AN ABSTRACT OF THE THESIS OF

PHILIP C. OWEN for the degree of MASTER OF SCIENCE

in Geology presented on June 8, 1977

Title: AN EXAMINATION OF THE CLARNO FORMATION IN THE VICINITY OF THE MITCHELL FAULT, LAWSON MOUNTAIN AND STEPHENSON MOUNTAIN AREA, JEFFERSON AND WHEELER COUNTIES, OREGON

Abstract approved: Redacted for Privacy

Dr. E. M. Taylor

This thesis is concerned with an area of 92 km^2 in the northern foothills of the Ochoco Mountains about 56 km east-northeast of Prineville in central Oregon. The rock units of the area consist of about 200 m of the Cretaceous Hudspeth and Gable Creek Formations; 1500 to 2200 m of the Clarno Formation, divided here into the Ross Flat Member, the Stephenson Mountain Member, and the Bear Creek Member; and 15 m of the red member of the John Day Formation.

The Ross Flat Member is composed of lacustrine volcaniclastic sediments, which have a maximum thickness of 200 m. This member is composed of interbedded sandstones, which often display graded bedding, and siltstones; subaqueous slump deposits which trend northwest are also found. The Ross Flat Member is interpreted to be the

near-shore deposits of a fairly large lake which received a high input of sediment.

The Stephenson Mountain Member is composed of 1200 to 1600 m of andesite flows, which lie concordantly on the Ross Flat Member. The widths of individual flows indicate that the flows moved to the northwest. In thin section there are three types of lavas: hypersthene-bearing basaltic andesites, pigeonite-bearing andesites or basaltic andesites, and hornblende-bearing or hornblende andesites, of which the hornblende-bearing andesites are the most common.

The Bear Creek Member appears to be a local unit and has a maximum thickness of 350 m. This member is angularly unconformable to the other members. In thin section the Bear Creek Member lavas are identical to those of the Stephenson Mountain Member. In the Stephenson Mountain area the base of the Bear Creek Member is composed of a 100-m-thick unit of rhyolite flows. There are two silicic extrusions which, if they are Clarno events, would also be part of the Bear Creek Member.

Intrusions in the area range in composition from basalt to rhyolite. Basaltic intrusions are rare. The area around Black Butte is intruded by a large number of hornblende andesite dikes; the age of these intrusions is equal to that of the Stephenson Mountain Member lavas. Andesite intrusions away from the Black Butte area can often be related to Bear Creek Member flows. With one exception, the Lawson Mountain sill, silicic intrusions are confined to the northern half of the area.

Chemical analyses indicate that the lavas from the area belong to a calcic suite which has low iron enrichment. The suite of lavas lies on the boundary between the tholeiitic and high-alumina series of Kuno (1966). Titania is low, and alumina is fairly high.

There are two major fold systems in the region, both of which are exposed in the area. The Mitchell Anticline, which trends to the north-northeast, is exposed in the southern half of the area. The Sutton Mountain Syncline, which occurs in the northwest corner of the area, belongs to an east-northeast-trending system.

Across the center of the area from east to west runs the Mitchell Fault. This fault has a horizontal displacement of 6360 m right laterally and a vertical displacement of 140 m south side up. The movement on the Mitchell Fault zone crumpled the crest of the Mitchell Anticline into a series of folds and caused the formation of several secondary faults.

An Examination of the Clarno Formation in the Vicinity of the Mitchell Fault, Lawson Mountain and Stephenson Mountain Area, Jefferson and Wheeler Counties, Oregon

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed June 8, 1977

Commencement June 1978

APPROVED:

Redacted for Privacy

Associate Professor of Geology
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Date thesis is presented June 8, 1977

Typed by Deanna L. Cramer for Philip C. Owen

ACKNOWLEDGEMENTS

I am in great debt to my advisor, Dr. E. M. Taylor, for his suggestions and comments during the preparation of this thesis and during the field work. He spent much time working through the various drafts of this manuscript under the press of time. I appreciate this very much.

I would also like to thank Dr. R. F. Lawrence, who joined the committee at the last minute as a replacement for Dr. Oles, Dr. H. E. Enlows, and Dr. K. F. Oles for their help during the course of this project.

I thank the following people for their comments and friendship while I have been out here: Bob Grundy, Larry Carpenter, Dave Knight, Dave Apple, Terry Svalberg, Jim Simpson, Pete Penoyer, Curt Haire, Lisa Paul, Lois Carda, Guy and Twila Dykstra, Paul and Judy Rutland, Marv and Phyl Halstadt, Al and Wendy Neim, the Don Kane family, the Elmer Bolche family, and the various members of the OSU Equestrian Club.

Finally I wish to thank my parents, who have footed the bill and provided much encouragement.

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AN EXAMINATION OF THE CLARNO FORMATION IN THE VICINITY OF THE MITCHELL FAULT, LAWSON MOUNTAIN AND STEPHENSON MOUNTAIN AREA, JEFFERSON AND WHEELER COUNTIES, OREGON

I. INTRODUCTION

The intent of this project was to make an examination of the stratigraphy and lithology of the Clarno Formation in order to clarify the nature of the movement on the Mitchell Fault. The Lawson Mountain-Stephenson Mountain area was selected because it had the greatest potential for unmapped features which might be matched on both sides of the fault, and because it is adjacent to the recently mapped Mitchell Quadrangle.

An area of 92 km^2 was studied in the Lawson Mountain and Stephenson Mountain 7.5-minute Quadrangles, located in the southwest corner of Wheeler County in central Oregon (Figure 1). The area is 56 km east-northeast of Prineville and 13 km west of Mitchell.

The area is accessible on ranch roads extending from U.S. Highway 26. The Ross Flat-Bear Creek road is the only secondary road that is maintained; other roads are in poor condition. All parts of the area are within eight kilometers of the highway or the Ross Flat road.

The area has a relief of one kilometer. The maximum elevation of the land surface is 1792 m at the top of

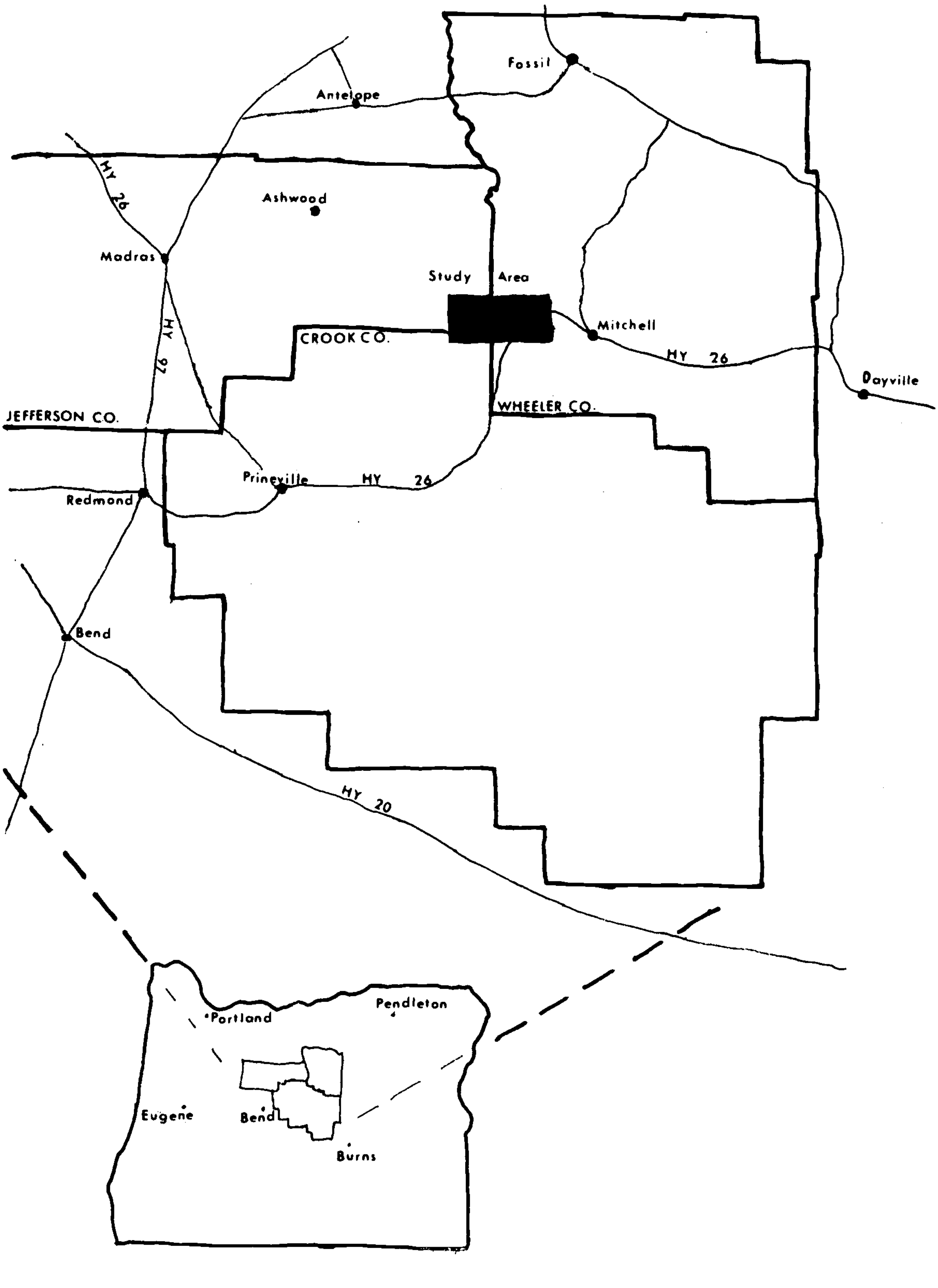

Figure 1. Location map of the study area.

Stephenson Mountain; the average elevation is 1000 m. Typical slopes are between 200 and 300 m/km.

Two tributaries of Bridge Creek, which flows into the John Day River, drain the study area: Bear Creek and the West Branch of Bridge Creek. Both creeks originate outside the area and are perennial. Neither creek receives a permanent water supply from the project area.

The area lies within the rain shadow of the Ochoco Mountains. The higher parts, those over 1300 m, receive enough precipitation to support a ponderosa pine woodland. In the lower areas this gives way to the juniper grassland so typical of the drier parts of eastern Oregon. Exposures of the rock units are excellent except in the denser parts of the woodlands and in areas which are farmed.

General Geology

The regional geologic section (Figure 2) consists of volcanic and sedimentary rocks, ranging in age from Late Cretaceous to Miocene, which were deposited upon a Permian metasedimentary basement. The basement rocks crop out in several places to the north and east of the study area.

The Late Cretaceous Formations, the Hudspeth mudstone and the Gable Creek conglomerate, rest unconformably on the basement rocks. Their exposed thickness is in excess of 3000 m in the vicinity of Mitchell. Within the project area the lowest tongues of these formations are exposed around

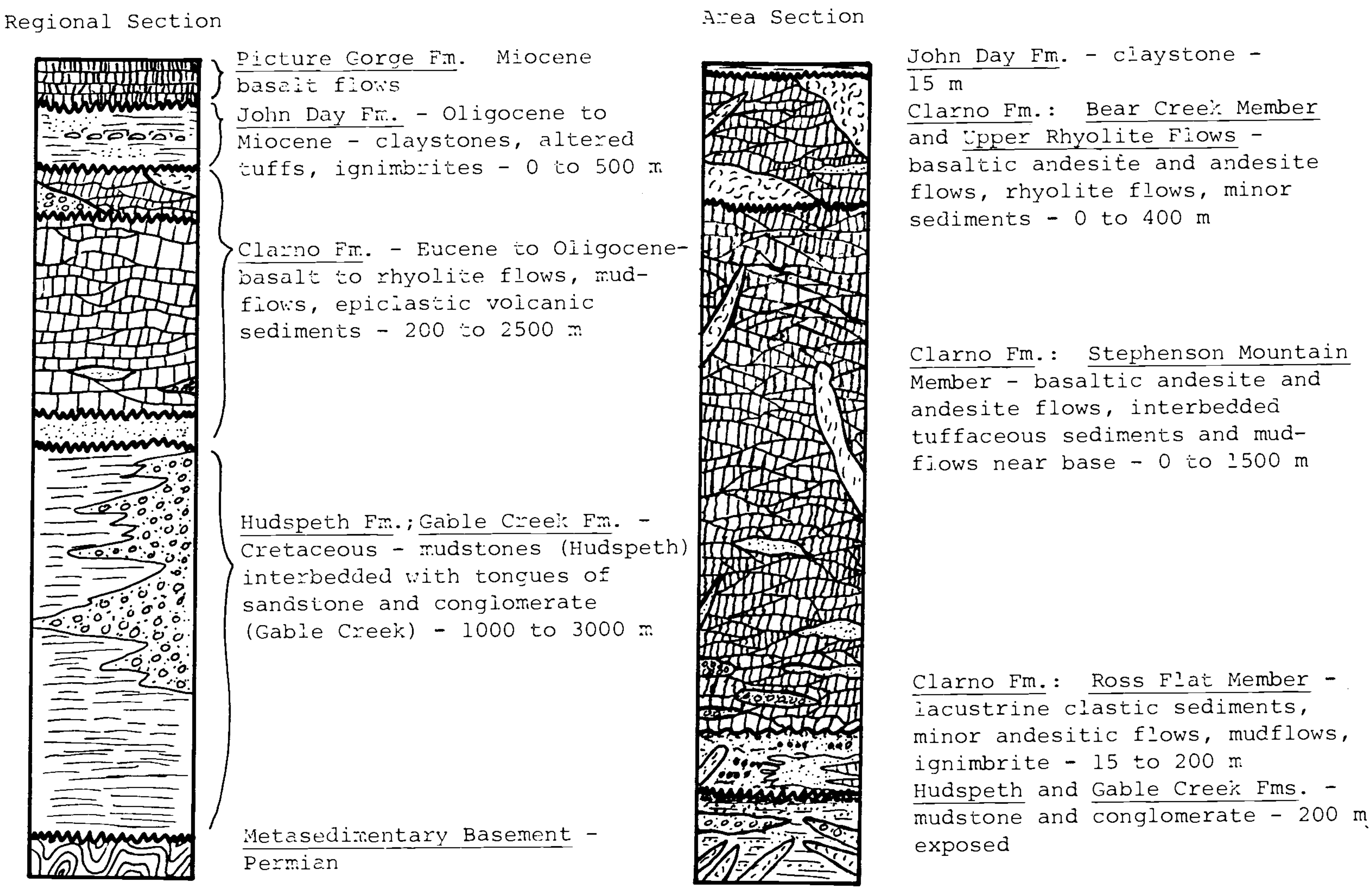

Figure 2. Generalized regional and area sections.

Black Butte in a section about 200 m thick.

Overlying the Cretaceous sediments uncomformably is the Eocene-Oligocene Clarno Formation, which crops out over most of the study area. This formation is composed of many types of volcaniclastic and volcanic rocks. Laterally and vertically the constituent lithologies of the Clarno Formation change in type, thickness, and relative proportions.

Within the project area the Clarno Formation is divisible into three major units. The lowest part of the Clarno section consists of 160 m of tuffaceous sediments and minor interbedded lava flows. Above the sediments is an andesite lava unit which averages 1400 m in thickness. At the top of the Clarno section are another andesite lava unit and a group of silicic flows; both units are unconformable to the lower units. The upper andesite unit is slightly less silicic than the lower andesite unit.

The Oligocene-Miocene John Day Formation is the youngest rock unit represented in the project area. Only a small part of the lowest member of this formation is present in the form of 15 m of tuffaceous claystone on the north edge of the area.

Elsewhere in the region the John Day Formation is overlain by the Picture Gorge Formation of the Columbia River Group. This formation crops out extensively to the north and south of the study area and has probably been removed from the area by erosion.

There are two major structures in the project area. The flanking folds of the Blue Mountain Anticline trend across the area in a north-northeasterly to east-north-easterly direction. These folds are offset 6360 m by the right-lateral Mitchell Fault.

Previous Work

The Clarno Formation was first described by Merriam (1901) in the region of Clarno, 50 km north of the project area. During the next 30 years several paleontological papers (Knowlton, 1902; Merrian and Sinclair, 1907; Chaney, 1927) were published which extended the boundaries of the formation and established an age of Late Eocene to Early Oligocene for the unit. Calkins (1902) made the first petrographic study of the formation.

Later, while the mines of the Horse Heaven Mercury District were in operation, a series of papers was written about the Clarno Formation in the District. This group of papers culminated in the report of Waters, et al. (1951). The units described in the report are surprisingly similar to the units found in the project area, although the District and the project area are separated by 12 km. Radiometric dating reported by Swanson and Robinson (1968) showed that the eruption of an unconformable upper andesite unit and some silicic extrusions occurred in the district 41.0 ± 1.2 m.y., an age too old for these rocks to be placed in the John Day Formation, and within the recognized age of the Clarno Formation.

Three theses involed with parts of the project area have been submitted by Masters candidates of Oregon State University (Swarbrick, 1953; Howard, 1955; Lukanuski, 1963). Because of a lack of suitable base maps and analytical facilities, the portrayal of stratigraphic relationships is poor in these theses. None of these candidates recognized the Mitchell Fault as a Clarno age event, although Howard (1955) recognized the faulting of the Cretaceous sediments by this structure. Swarbrick (1953) and Lukanuski (1963) did not map the upper group of flows.

The authoritative work about the Cretaceous sediments in the Mitchell region is that of Wilkinson and Oles (1968). They mapped the sediments within the project area and correlated the units with those of the type sections in the Mitchell Quadrangle. Wilkinson and Oles (1968) were the first to publish a map showing the faulting of the Clarno Formation by the Mitchell Fault within the project area.

Oles and Enlows (1971) published a description of the 15-minute quadrangle immediately to the east of the study area. In this bulletin they reclassify the Clarno Formation as a Group, divided informally into an Upper and a Lower Clarno Formation. The Upper Clarno Formation consists of mudflows and lava flows, with lesser amounts of vent agglomerate and tuffaceous sediments. The Lower

Clarno Formation, which the Upper Formation overlies unconformably, is composed of tuffaceous sediments and lava flows, with minor volcanic breccias. The Lower Clarno Formation is directly continuous with the rock units of the project area.

Enlows and Parker (1972) dated several units in the Mitchell Quadrangle by K/Ar radiometry. They found that the Clarno Formation ranges in age from 46 to 33 m.y., a time period which overlaps dates determined for the John Day Formation (Evernden, et al., 1964).

Oles and Enlows (1973) published a summary of the formation description in their bulletin (1971) and the data of Enlows and Parker (1972).

Novitski and Rogers (1973) reported that the Clarno Formation contains a calc-alkaline suite of volcanic rocks petrologically similar to those found in continental margin andesite belts.

Swandon (1969) and Robinson (1976) published small scale maps which include the study area. These maps are regional compilations of the data of many authors.

Procedures

The project area was mapped at a scale of 1:12,000 during the summers of 1974 and 1975. These data were transferred to the 1:24,000 scale map of this thesis (Plate 1). Aerial photographs of approximately 1:62,500 and

Figure 3. View eastward from Stephenson Mountain. Rhyolite dikes cut the hillsides in the foreground. Black Butte is in the upper right; Lawson Mountain is in the upper center; and Sheep Mountain is at the middle-left edge of the picture. The large valley cutting across in the middle distance is Bear Creek.

1:6,000 scales were used as an aid to the mapping. The thicknesses of the sedimentary units were determined by Jacob staff; the thicknesses of the lava units were calculated by geometric extrapolation. Strikes and dips were determined with a Brunton compass.

Major element analyses were performed on 29 of the more than 200 rock specimens collected during the field work. These analyses were supplemented by analyses of 14 rocks from within the project area or its near neighborhood previously collected by Dr. E. M. Taylor. Al_2O_3, FeO, TiO_2, CaO, and K_2O were determined by X-ray fluorescence spectrometry. SiO_2 was determined by both X-ray fluorescence and visible light spectrophotometry. MgO and Na_2O were determined by atomic absorbtion spectrophotometry. All iron was recorded as FeO; the analyses were performed on roasted rock powders and are H_2O free.

Approximately 140 thin sections were made for petrographic study of the rocks. Feldspar compositions were determined by the Michel-Levy method. In very fine grained specimens the X-ray diffractions of a cut piece of the rock were used to help determine the mineralogy.

The colors of the rocks were named in accordance with the Geological Society of America Rock Color Chart (1963).

Volcanic rock nomenclature for this thesis was based on the analytical data. The divisions arbitrarily set up were: basalt, 46-53 weight percent SiO_2; basaltic andesite, 53-58; andesites 58-65; dacite, 65-70; and rhyolite, 70+. Those rocks with less than 46 weight percent SiO_2 were classified by their mineralogy. Petrographically the rocks do not follow this classification; alteration of the rocks has changed the relative proportions of the oxides so that some low silica dacites are indistinguishable from the andesites and not at all similar to the main group of dacites. The term silicic andesites is here used to refer to these low silica dacites and the high silica andesites.

II. STRATIGRAPHY

Pre-Tertiary Rocks

Wilkinson and Oles (1968) formally described two formations of Albian to Cenomanian age which occur within the project area: the thinly laminated mudstones and siltstones of the Hudspeth Formation, and the poorly sorted sandstones and conglomerates of the Gable Creek Formation. These formations intertongue with each other in a pattern which was interpreted by Wilkinson and Oles (1968, p. 144) as the repeated progradations of delta-front gravels over pro-delta muds at the mouth of a high-energy river system. There are 11 progradations, which were numbered up from the Main Mudstone Member, a thick unit near the bottom of the sediment body. One Gable Creek tongue and two Hudspeth tongues are exposed in the project area. Wilkinson and Oles (1968) fully described the sedimentary structures and the lithology of these formations; because this thesis is concerned with the Clarno Formation, these features will not be described.

Hudspeth Formation

The two lowest tongues of the Hudspeth Formation, informally called the Main Mudstone and Tongue 2 herein, are exposed in the region extending from Black Butte to

Doolittle Flat, in the southeast corner of the project area. The Main Mudstone crops out in the West Branch of Bridge Creek Valley and on Doolittle Flat, at the crest of an anticline in each area. Tongue 2 is exposed in the intervening syncline.

Because the top of Tongue 2 and the bottom of the Main Mudstone are not exposed, the original thicknesses of these units cannot be determined in the study area. The tongues of the Hudspeth Formation taper to the northeast (Wilkinson and Oles, 1968, p. 143); these units should be thicker in the project area than they are in the measured sections to the northeast (Wilkinson and Oles, 1968, appendices). The Main Mudstone is 910 m thick near Tony Butte in the Mitchell Quadrangle. Tongue 2 is the equivalent of the formal Tongue 4-6, if the Gable Creek units on either side of the anticline of the West Branch Valley are the same. Formal Tongue 4-6 has a thickness of 43 m in the measured sections in the Mitchell Quadrangle (Wilkinson and Oles, 1968, appendices).

Where the Hudspeth units are held in place by intrusions, the mudstones form rounded hills. Elsewhere, the units form large valleys and pediments.

The Hudspeth Formation is fairly impermeable. Springs are not found in the mudstones, but occur where other units abut the land surface. The water that soaks into the Hudspeth units causes large slumps such as are found on the north-northeast side of Black Butte and at the southwest end of Doolittle Flat.

On hillsides grass grows more poorly on the Hudspeth units than on the other formations or on the alluvium (Figure 4). The slopes are mantled with an olive gray grus (5Y-3/2), which leaves the contacts of the other units with the Hudspeth tongues well exposed. In the flat areas the mudstones are covered with a more permiable soil, which makes these areas excellent for farming. The soil forms from the admixture of sheet-washed soils from other units with the soils forming upon the mudstones.

The contacts of the Hudspeth units with the Gable Creek Tongue are gradational in the project area; the siltstone laminations become coarser and thicker, and the mudstone layers thin and disappear. The contact is placed at the line of 50 percent sandstone or coarser.

The contact of the Hudspeth Formation with the Clarno Formation is abrupt and with significant angular discordance in the Doolittle Flat area. The paleosol which marks the contact in the Mitchell Quadrangle (Oles and Enlow, 1971) was not found, except in one small area; the contact is an abrupt change from mudstone to volcanic sandstone or siltstone.

Figure 4. Typical exposures of the Hudspeth and Gable Creek Formations, at the south side of Black Butte. The Hudspeth Formation forms a gray grus on which little grass grows. The Gable Creek Formation forms prominent cuestas. The hilltop is composed of the andesite of the Black Butte sill. The road is about seven meters across.

Gable Creek Formation

The Gable Creek Formation crops out on the east side of Black Butte and around the outcrop area of the Hudspeth Tongue 2. If the assumption is valid that both exposures are the same tongue, the unit is the Gable Creek Tongue 3 of Wilkinson and Oles (1968). The tongue is much more competent than the Hudspeth units, and it shows the structure into which the Cretaceous formations have been bent.

The thickness determined for the Gable Creek Tongue is very dependent upon where the unit is measured, because it thins to the southwest. The unit is 25 m thick in the Cougar Gulch area and 10 m thick in the SW¼ of SW¼ of Sec. 3, T. 12 S., R. 20 E., where the unit is covered by alluvium. Tongue 3 is 160 m thick in the Mitchell Quadrangle (Wilkinson and Oles, 1968, appendices).

The Gable Creek Tongue forms large cuestas (Figure 4). Trees and grasses grow readily on the dipslopes of the tongue, which indicates that water is available to the plants growing over the unit. Springs are commonly found where the Gable Creek Tongue is exposed in arroyos.

There are four previously unmapped areas where the Gable Creek Formation is exposed. Three of these areas are on the western side of Spring Gulch, near Ross Flat, where faulting has uplifted the formation to the surface. The fourth area lies north of the Mitchell Fault in the SE¼ of Sec. 26 and the SW¼ of Sec. 25, T. 11 S., R. 20 E., where a fault-surrounded block has been emplaced. The tongues to which these exposures belong could not be determined.

Clarno Formation: Introduction

Within the project area the Clarno Formation consists of three general map units, herein informally called the Ross Flat Member, the Stephenson Mountain Member, and the Bear Creek Member. The Ross Flat Member has a maximum local thickness of 200 m and is composed of volcanic sandstones, claystones, epiclastic volcanic breccias, lavas and an ignimbrite. The Stephenson Mountain Member is at least 1600 m thick in the western half of the study area and comprises the bulk of the Clarno Formation in this area. The Stephenson Mountain Member is composed of basaltic andesite to silicic andesite flows deposited without angular discordance upon the Ross Flat Member. The Bear Creek is a unit of basaltic andesite to silicic andesite flows, petrographically identical to the lavas of the Stephenson Mountain Member. The Bear Creek Member occurs as large lens-shaped bodies which lie unconformable to the rest of the Clarno Formation. The Bear Creek Member includes a 100-m-thick series of rhyolite flows underlying the top of Stephenson Mountain, and a small body of tuffaceous sediments. The greatest thickness of the Bear Creek Member in the study area is 350 m.

The bottom of the Clarno Formation is defined by an angular unconformity in the Mitchell Quadrangle (Oles and Enlows, 1971). The Cretaceous sediments have a ten-meter-thick paleosol between them and the Clarno Formation. In the project area neither the unconformity nor the paleosol are readily found; the unconformity is discerned by the overstepping of the Clarno Formation across the different Cretaceous units. The paleosol is found only in a short segment on the northwest side of Doolittle Flat where a lava flow is in contact with the Cretaceous material.

The top of the Clarno Formation was defined by Waters, et al. (1951) as the paleosol which separates the lower units of the Formation from the upper, unconformable units and the John Day Formation. Hay (1962) and Swanson and Robinson (1968) defined the top at the base of the first claystone unit of the John Day Formation. Swanson and Robinson (1968) showed that the upper units in the area of the Horse Heaven Mercury District were approximately 41 m.y. old, an age within the Clarno depositional period. In this thesis the top of the Clarno Formation is placed at the base of the first claystone unit above the Bear Creek flows or the silicic extrusions, which are tentatively placed within the Clarno Formation by this definition.

In many places to the north of the project area the Clarno Formation has been dated Late Eocene to Early Oligocene by fossils (Merriam, 1901; Knowlton, 1902; Merriam and Sinclair, 1907; Chaney, 1927, Evernden, et al., 1964). Howard (1955) reported that fossil plant material collected along the West Branch Valley was of the same age. The range of ages 46 to 34 m.y. published by Enlows and Parker (1972) shows a longer duration for the deposition of the Clarno Formation than had previously been assumed.

Clarno Formation: Ross Flat Member

Within the project area the sediments of the Ross Flat Member crop out in two locations. North of the fault the unit is exposed from Black Butte northeast long the West Branch of Bridge Creek Valley and extends 14 km northeast into Meyers Canyon in the Mitchell Quadrangle. South of the fault the member crops out from Ross Flat southwest into the Heflin Creek Valley and extends into the Lookout Mountain Quadrangle 12 km to the south (Swinney, et al., 1968). The total outcrop area of the Ross Flat Member within the study area is 12.2 km^2.

The sediments of the unit are easily eroded, but are slightly more resistant to erosion than the Hudspeth mudstones. The member is typified by large valleys containing very small cuestas formed by the harder subunits.

The contact of the Ross Flat Member with the Stephenson Mountain Member is angularly conformable. On a large scale the contact between the two members is gradational; the bottom 200 meters of the Stephenson Mountain Member are composed of interbedded lava flows and sediments. For convenience in the cartography, the top of the Ross Flat Member was mapped at the top of an ignimbrite which separates the main body of the sediments from the interbedded zone over the entire project area.

The Bear Creek Member comes in contact with the Ross Flat Member in the ridge separating Ross Flat and Doolittle Flat, and in the hills to the west of this ridge. The Bear Creek flows lie on top of a bevel of the Ross Flat sediments. The dip and stike of the flows is almost identical to that of the Ross Flat sediments on the ridge, but in the hills to the west of the flat the orientation differs by a maximum of 18°.

The Ross Flat sediments weather to a moderate yellowish brown (10YR-4/2). Fresh surfaces of the rocks range among greenish grays (5GY - 5G-6/1), light browns (5YR - 10YR-6/4 - 6/6), pale reds (5R - 7R-6/2 - 7/2), and pale to very pale oranges (10YR-7/2 - 8/2).

On the northwest side of the West Branch of Bridge Creek Valley, the Ross Flat Member, below the ignimbrite as defined earlier, is covered by a brownish red soil different from the appearance of the member everywhere else in the study area. This different soil has formed by the admixture by sheet washing of the weathering products of the Stephenson Mountain Member lava flows with the normal grus of the sediments.

Ross Flat Member: Local Marker Units

A system of marker beds, valid for the study area only, was developed to allow the observation of the variations of the member. The area over which the individual marker beds are usable varies widely, but these beds have enough continuity, and are distinctive enough, that the stratigraphic positions could be delimited in different areas. On the south side of the West Branch of Bridge Creek Valley and on the north edge of Ross Flat, the relative positions of several of the marker beds are so similar that it is probable that these two areas were contiguous and were displaced by the Mitchell Fault.

The following units were found useful as marker beds: the Spring Gulch sandstone near the bottom of the member, the Lawson Mountain mudflow, the laminated tuff, the purple tuff, and the West Branch ignimbrite at the top of the unit. Of these the laminated tuff is the least useful, because it is distinctive only in the covered area on the north side of the West Branch of Bridge Creek Valley, though it can be approximately located over much of the rest of the exposure area of the Ross Flat Member.

Spring Gulch Sandstone: The Spring Gulch sandstone is a thick, poorly-sorted unit which lies close to the bottom of the Ross Flat Member over most of the study area. The sandstone underlies the ridge separating Doolittle Flat from Ross Flat and forms the head and east side of Spring Gulch.

The unit can be traced to within 200 m of the Mitchell Fault at a point 1.6 km west of the summit of Lawson Mountain. In the West Branch of Bridge Creek Valley, the sandstone can be traced to within 200 m of the fault zone from the north. The exposure area within the West Branch Valley is small; the unit is covered by the rest of the Ross Flat sediments approximately 500 m from the fault.

The Spring Gulch sandstone in its outcrop pattern appears to be approximately 1.2 km wide and extends at least four kilometers in a northeasterly direction from the south edge of the project area to the Mitchell Fault and from the fault into West Branch Valley. The southeast edge of the sandstone is interbedded with mudflows and lava flows. The northwest edge of the unit splits into several better-sorted sandstone units interbedded with siltstone. The central portion of the sandstone has a maximum thickness of 40 m and consists of a prominent, ledge-forming unit (Figure 5), well-exposed in the upper part of Spring Gulch.

The position of the bed within the Ross Flat Member is dependent upon where a section is measured; the continuity of the exposures shows the equivalence of the units. At the southern edge of Ross Flat the sandstone is at the base of the member. To the northwest other units occur beneath the sandstone; the thickness of these sediments could not be measured accurately, but extrapolation of measurements made beyond the northwest edge of the Spring

Figure 5. Spring Gulch sandstone of the Ross Flat Member, exposed in a tributary valley of Spring Gulch, 1.6 km west of the summit of Lawson Mountain. This outcrop, near the southeast side of the unit, is 7.5 m thick. Finer and coarser subunits within the sandstone can be vaguely seen in a cut-and-fill structure. The pack is about 35 cm high.

Gulch sandstone indicate that the thickness is between 30 and 50 m.

The Spring Gulch sandstone shows many sedimentary structures. Those structures which show current direction, cut and fill channelling and cross-bedded laminations and beds, indicate that the flow was from the southeast to the northwest across the width of the sandstone body. Mud bodies, both in position and disoriented, are occasionally found in the unit.

The sandstone is poorly sorted; the grain size ranges from medium silt to pebbles (1/64 to 20 mm). There is little primary clay, except in the mud bodies. The cement is isotropic silica tinted gray with clay near the grains. The cement surrounds the grains; there is five to ten percent void space in the rock. The rock is in grain support.

The grains are composed of the following materials: andesite, 70 volume percent; basalt, 5 percent; devitrified volcanic glass, 5 percent; monomineralic grains, 20 percent. The andesite grains are greenish gray or yellowish gray, irregularly shaped, and subangular. The basalt fragments have a reddish brown color and are similar in form to the andesite fragments. The devitrified glass is a dark gray and contains small microlites of feldspar. The fragments of devitrified glass are more rounded than are the other rock fragments. The monomineralic grains are composed of plagioclase, pyroxene, hornblende, and quartz.

The plagioclase, pyroxene, and hornblende grains, which comprise 5 percent of the rock together, are smaller than 1.0 mm and have an angular form. The quartz grains comprise 15 percent of the rock. These grains are usually rounded or well rounded and have a size larger than 1.0 mm. The shape and large size make it probable that the quartz grains were derived from the Cretaceous sediments.

Lawson Mountain Mudflow: On the northern side of Ross Flat the Lawson Mountain mudflow lies approximately 136 m beneath the top of the member. The unit lies 15 m above the Spring Gulch sandstone and 63 m below the purple tuff. In the West Branch of Bridge Creek Valley, where the member can be measured from the Spring Gulch sandstone to the purple tuff, the mudflow lies about 22 m above the Spring Gulch sandstone and about 72 m below the purple tuff.

The mudflow is a narrow, long unit whose outcrop pattern trends approximately N. 30° W. The bed can be traced discontinuously for 0.75 km across the valleys of the tributaries of Spring Gulch, about 1.6 km west of the summit of Lawson Mountain, to within 200 m of the Mitchell Fault. On the north side of the fault the unit crops out approximately 300 m from the fault zone, in the SE¼ of SE¼, Sec. 25, T. 11 S., R. 20 E., and can be traced 1.0 km to the northwest to the center of the section. The unit is about 25 m wide and 12 to 18 m thick. Of all the mudflows found in the Ross Flat Member, the Lawson Mountain mudflow was the only one found in the vicinity of the Mitchell Fault; the other mudflows seem to be restricted to an area nearer to the edge of Spring Gulch sandstone.

The mudflow is an unstructured assemblage of andesitic and basaltic rock fragments supported in a matrix of clay and fine sand-size grains of plagioclase, hornblende, pyroxene, and quartz (Figure 6). The size of the rock fragments ranges from medium sand to boulders (1/4 mm to 1.5 m).

A high degree of alteration is usually present in the mudflow. The whole rock is often colored a greenish gray (5G-6/1) by chlorite (?). The clasts are a moderate greenish yellow (5GY-5/2) among the andesites and a dusky reddish brown (5YR-4/2) among the basalts. Isotropic and faintly birefringent silica occurs as cavity fillings.

Laminated Tuff: On the north side of the West Branch of Bridge Creek Valley, the laminated tuff is a distinctive four- to six-meter-thick unit which is useful in the determination of the local structure (Figure 7). In the rest of the study area, the unit is an 8 to 12 m zone amidst the sandstones and siltstones of the member. The laminated tuff lies approximately 100 m below the top of the member and 27 m below the purple tuff. The laminated tuff weathers into 0.25-cm-thick slabs which are easily followed in float.

Figure 6. Lawson Mountain mudflow, exposed in a tributary valley of Spring Gulch, 1.6 km west of the summit of Lawson Mountain. Basalt and andesite boulders and cobbles are in an unstructured clay and sand matrix. The hammer is about 30 cm long.

Figure 7. Laminated tuff, exposed on the north side of the West Branch Valley. The distinctive pieces of the tuff appear as a useful marker horizon in this part of the study area. The hammer head is about 15 cm wide.

The tuff weathers to a light brownish yellow (5Y-6/2) and feels like chalk. The unit has well-developed bedding planes which in thin section are more clay-rich than the rest of the rock. The bedding planes are approximately 0.02 mm thick and weather to a darker brown than the rest of the rock. The induration of the rock varies within the unit; the part which crops out through the mantling soil on the north side of the West Branch Valley is the hardest part of the unit.

The laminated tuff is a siltstone in which the amount of silicification is the primary variable. The rock is composed of fine to very fine silt (1/64 to 1/256 mm) cemented by silica and clay. Rock fragments, phenocryst fragments, and devitrified glass constitute 90 to 95 percent of the rock; clays comprise the rest. The silica cement fills the interstices between the grains and forms almost 10 percent of the rock in the silicified zones.

Purple Tuff: The purple tuff is a 12- to 25-cm-thick bed of highly indurated, siliceous tuff. The color of this bed is a light purplish gray (5RP-7/2), which on weathering turns to a moderate brownish yellow (10YR-5/3). This bed with its distinctive color is the only one of its kind found in the stratigraphic sections of the Ross Flat Member. The bed lies 73 m below the top of the member in the northern Ross Flat section.

The purple tuff forms a ledge on the slopes where it crops out. There is a preferential direction of fracture which splits the bed into 2.5-cm-thick, planar blocks. Hand specimens of the purple tuff have the "ring" of a very tightly bound rock when struck and have the appearance of an extremely hard clay. Nothing crystalline or granular is visible in the rock even when it is viewed under a binocular microscope. Slabbed pieces show a vague, contorted bedding.

Thin sections show that the rock is composed of extremely fine glass fragments held together by silica. Very little devitrification has occurred. Clay obscures the textures other than those of the quartz, which forms 0.01 mm veins and nodules.

West Branch Ignimbrite: The West Branch ignimbrite crops out along the contact of the Ross Flat Member with the Stephenson Mountain Member in the West Branch Valley. To the east of the study area the unit forms the caprock of numerous small buttes across the floor of the West Branch Valley. In the Ross Flat area the ignimbrite is exposed discontinuously around the southern side of Lawson Mountain, on the ridge to the north of the Bear Creek Ranch headquarters, and in the Heflin Creek Valley.

The ignimbrite forms 3- to 14-m-high cliffs, which display crude columnar jointing. The rock weathers to a light brownish yellow (10YR-5/3) from a light yellow

(5Y-8/2), its fresh color. The vertical zonation described by Ross and Smith (1961) was not found; only the lower central welded zone and the glassy bottom occur in the study area. The glassy bottom, which is a vitrophyre, is found in very few places; the best development of this part is found at the notch between Lawson Mountain and the Cougar Gulch intrusion. The vitrophyre in this place contains preserved *Equisetum* stems.

The ignimbrite contains 35 percent lithic fragments (andesite, 65 percent; flattened pumice, 15 percent; sediments, 10 percent; and andesitic scoria, 10 percent), 5 percent sanidine crystals, and 60 percent devitrified glass shards. An analysis by Oles and Enlows (1971) shows that the ignimbrite is a rhyolite which contains a high amount of potassium.

Microscopically the West Branch ignimbrite has the typical eutaxitic texture of welded tuffs; the glass shards molded themselves around the more solid fragmental materials and crystals as the unit settled. The glass is now completely devitrified into small axiolites. Plagioclase is not present in the rock other than in the extraneous material. There are some areas of hematite which have the shape of hornblende crystals. Calcite is present as a replacement of the sanidine crystals and of small areas of the groundmass. The lithic fragments are relatively fresh and contain little replacement material.

Ross Flat Member: General Lithology

Other than the marker beds, the Ross Flat Member contains two basic types of sediments, sandstones, and silt/claystones. Each type has variation in grain size and grain composition. Both types are cemented by silica minerals and are impossible to disaggregate without the destruction of the grains. The following description was made from the examination of hand specimens and thin sections; because this examination could not be three dimensional as a sieve analysis could, the size, shape, and sorting information is approximate.

Over large parts of the outcrop area these two lithologic types alternate regularly (Figure 8) and form a ledge and slope topography on the hillsides and stream bottoms. The changes from one type of sediment to the other is usually abrupt; gradational contacts are rare. The regularity of the bedding is interrupted by rare, coarse sandstone or conglomerate beds which occur at random throughout the member.

The size range of the sandstones extends to medium pebbles (10 mm); the most common size is fine to very fine sand (1/4 to 1/16 mm), which is found in the regular bedding. The sorting is dependent upon the grain size of the sediment. The fine sandstones are well sorted; the coarser units are poorly to very poorly sorted. The rounding, also dependent upon grain size, is poor in all but the finest

Figure 8. Regular interbedding of sandstones and siltstones in the Ross Flat Member, exposed in a tributary valley of Spring Gulch, 1.6 km west of the summit of Lawson Mountain. Three sandstone/siltstone pairs are visible; the third sandstone bed is overlain by a coarser slump unit. The hammer at lower left is 30 cm long.

sandstones. All the sandstones contain little primary clay and are in grain support. The cement is isotropic silica, which fills the interstices between the grains.

The large-scale shapes of the sandstone beds vary considerably. Exposures permitting, the fine sandstones can be traced over large areas and have the appearance of a sheet. The coarser units are more local, in cross section less than 50 m wide, but these units can be exposed over great distances if the land surface cuts at a slight angle to the length. The coarse units that can be traced are all long in the direction N. 40° W.

Structures in the sandstones are common, but not often well developed. The platy grains are usually oriented parallel to the bedding of the unit. Graded bedding within a sandstone bed is common, although the top silt and clay layers usually found in graded beds (Bouma, 1959) are usually not present or are very thin. Internal bedding and laminations are very common. There are some loading and current structures in the finer sandstones, but these structures are often poorly developed, which precludes directional determinations in any but a general sense for the current structures. The load structures are sole markings and flame structures; the current structures are cross bedding, small cut and fill channelling, and drag markings. Biotic perturbation is common in the finer units; preserved roots and filled borings are present in many units. The borings appear as non-directional, sharply-defined clay channels in the sandstone. The lack of bifurcation, the small size, and the lack of preferred direction make it probable that these borings were made by an animal.

The grains of the sandstones consist of volcanic rock fragments, phenocryst fragments from the volcanics, and reworked sediments from the Cretaceous formations (Figure 10). The volcanic rock fragments comprise between 70 and 90 percent of the grains. The percentage of the phenocryst fragments in the units is dependent upon the coarseness of the particular unit, because the phenocrysts of the source rocks have a maximum size of 1.0 to 2.0 mm. The maximum percentage of phenocryst fragments found is 25 percent of the rock. The grains from the Cretaceous sediments are more common in the strata near the bottom of the member than higher up, but the sedimentary grains never comprise more than 10 percent of the rock.

The most common rock type of the fragments is andesite. The grains are grayish green (10GY-6/2) to yellowish gray (5Y-6/3) from the alteration of the groundmass. The grains have two forms: a hyalophitic, pilotaxitic grain similar to the groundmass of a lava flow, and a vesicular, hyaline grain derived from pyroclastic accumulations. In all the andesite grains the glass is devitrified and the ferromagnesian minerals are replaced by hematite/chlorite/

calcite/silica intergrowths. Andesite fragments comprise 80 to 95 percent of the rock fragments. The basaltic grains are altered to a mass of hematite and silica which contains vesicles and plagioclase microlites. Silicic fragments, which constitute 5 to 15 percent of the rock fragments, are composed of flow-banded, devitrified glass. The silicic fragments do not have phenocrysts. The color of the silicic fragments is a pinkish gray (5R-7/1).

The phenocryst fragments are plagioclase, hornblende, and pyroxene. Plagioclase, an andesine or a labradorite, is the most common; pyroxene is rare. The fragments are broken and never have long crystal faces.

The grains from the Cretaceous sediments are composed of silica in the form of chert or quartz. The sediment grains are more rounded than the other types of grains and are aggregated in the coarser units.

The claystones are subdivisible into very fine grained siltstones (less than 1/64 mm grain size) and silicified claystones. The siltstones are easily eroded; the claystones form ledges. The siltstones and the less silicified claystones are a yellow brown (5Y-5/3). The more silicified claystones are an orange-pink (5YR-7/2). Fossilized wood, stems and leaves, filled burrows, and root fillings are common features of both rock types.

The siltstones have component grains similar to the coarser grained sediments, but they contain between 30 and

50 percent monomineralic grains. The rock is the most weakly cemented type of the Ross Flat sediments. The siltstone beds are usually massive, but thin-bedded units are present.

The silicified claystones are composed of devitrified glass and clay (Figure 9); in thin section and hand specimen the rocks resemble a dirty chert. There is often a discontinuous, convoluted banding which is related to the amount of clay present. Veins and nodules of chalcedony form a network in the rock. In thin section vague shard-like forms are visible, but they are difficult to distinguish accurately. The claystones appear to be beds of fine ash silicified by the release of silica from the devitrification of the glass in the shards.

Ross Flat Member: Lateral Variations

The main change in the character of the Ross Flat Member across the project area is found in the sediments of the lowest part of the member: the Spring Gulch sandstone, the units it overlies, and the units lateral to it. The rest of the member changes less markedly across the project area than this part does. Because the changes are poorly exposed in the West Branch of Bridge Creek Valley, the description will use the Ross Flat area exposures.

The character of the sediments in the lowest part of the member changes between the western and eastern sides

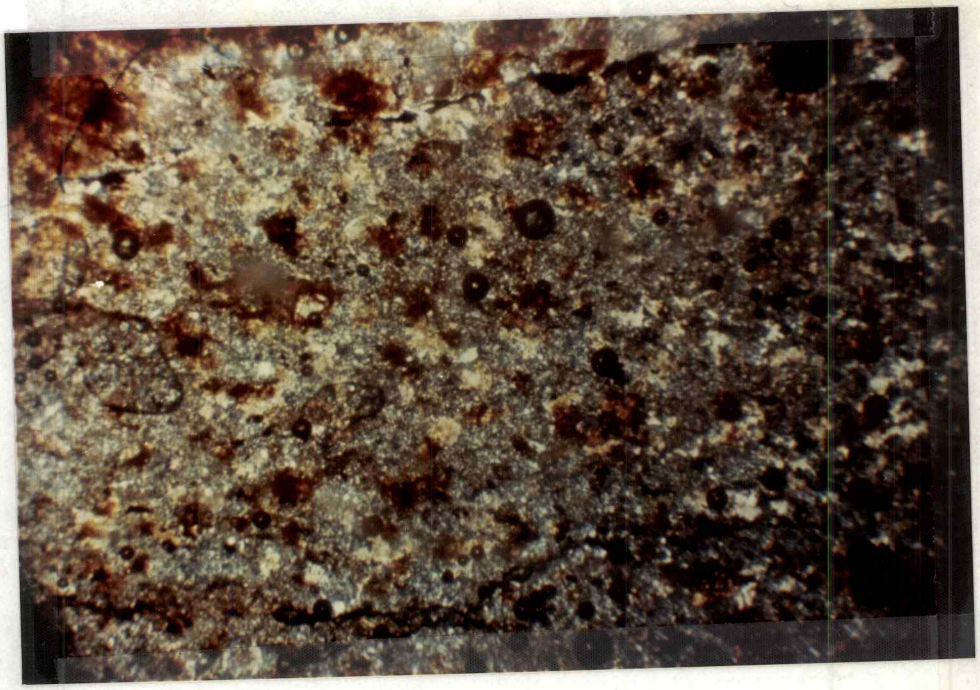

Figure 9. Fine grained, altered siltstone from the Ross Flat Member. The grains are composed of devitrified glass partially replaced by calcite and hematite. There is some recrystallization of the silica minerals into cavity-fillings and minor replacements. The dark rimmed circles and the dark bordered areas at the right are bubbles. Width of field is 1.3 mm. Cross polarized light.

of the study area across the width of the Spring Gulch sandstone. The outcrop trend of the Spring Gulch sandstone is approximately centered upon a line running N. 30° E. from the center of the south boundary of Sec. 5, T. 12 S., R. 20 E. The Spring Gulch sandstone forms the bottom of the member along and to the southeast 0.6 km of this line. The exposures of the lowest part of the member to the southeast of the Spring Gulch sandstone are scarce, but the area to the south and east of Lawson Mountain contains a lava flow and a 20 m thick unit of siltstone. The siltstone is thin-bedded to thinly laminated and contains preserved *Equisetum* stems and other plant material. The lava flow lies across the contact of the Spring Gulch sandstone with the siltstone; the lava flow tongues into the Spring Gulch sandstone and covers over the siltstone at the opposite sides. On the northwestern side of the Spring Gulch sandstone, the base of the Ross Flat Member is composed of interbedded claystones and siltstones, which wedge out under the Spring Gulch sandstone and thicken to the northwest. The displacement of the Cretaceous sediments to the surface by some faults on the west side of Spring Gulch shows approximately 30 m of sediments under the Spring Gulch sandstone at the north edge of Sec. 5, T. 12 S., R. 20 E. The Spring Gulch sandstone divides into many thinner units interbedded with siltstone on its northwest edge. The thickness of the lowest part of the Ross Flat Member

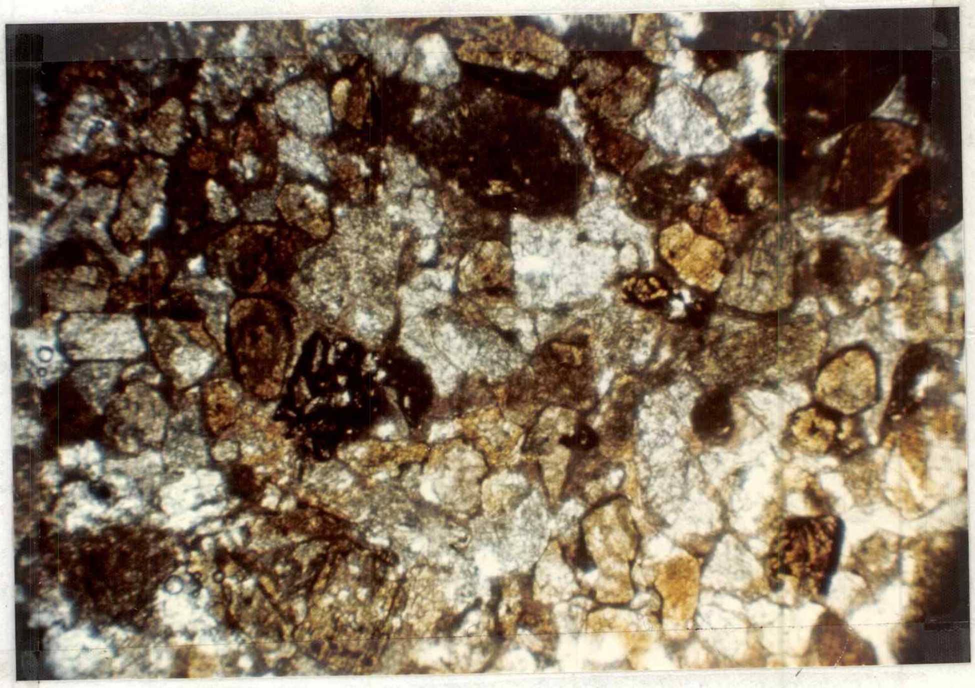

Figure 10. Medium grained sandstone of the Ross Flat Member. Grains of vitric andesite (black with laths of plagioclase), altered andesite (brownish, dappled grains showing some plagioclase or light greenish, rough grains), hornblende and pyroxene (clear, light yellow grains) and plagioclase (clear, rough, colorless grains) are in a loose grain-support texture with a silica cement. The silica cement is clouded with clay near the grain boundaries, but the cement is clear further away. Width of field is 4.1 mm. Plane polarized light. Section is very thick (about 0.15 mm).

increased from 20 m at the east side of Lawson Mountain to 70 m at the west side of Spring Gulch. The lowest part of the member is not exposed in the study area west of the Spring Gulch valley system.

The top of the lowest part, at the top of the Spring Gulch sandstone in the central Ross Flat area, marks a change in manner of deposition of the member. The regularly bedded sandstones and siltstones start at this point and complete the sections in the Lawson Mountain, Ross Flat, and Bear Creek Ranch headquarters areas. The coarser units of sandstone and conglomerate are not found more than 0.5 km from the northwestern edge of the Spring Gulch sandstone. The thickness of the middle part ranges from 40 m at the eastern side of Lawson Mountain to 110 m near the Bear Creek Ranch headquarters. There is less sandstone in the western part of the outcrop area of the Ross Flat Member.

The West Branch ignimbrite, at the top of the member, marks another change in the depositional history. The ignimbrite may thin to the northeast; the thinning observed may be an illusion caused by the scarce outcrops and the local variations of thickness. In the West Branch Valley the ignimbrite is 5 to 10 m thick; in the Ross Flat area the unit is 8 to 14 m thick; and in the area of the Bear Creek Ranch headquarters the unit is 18 to 35 m thick.

Ross Flat Member: Environment of Deposition

The key to the environment of the Ross Flat Member is the Spring Gulch sandstone. This northeast-trending prism of poorly sorted sandstone has structures indicative of an energetic wave or current system. To the northwest the Spring Gulch sandstone changes into interbedded sandstones and siltstones, which have the structures of deposition by density currents; to the southeast the sandstone becomes locally a unit of siltstone and lava flows. These features fit the shore of a large body of water. The siltstone on the southeastern side indicates an area of tranquil water behind the shore. The supply of sediments to the sandstone body must have been moved by longshore currents within the study area; fluvial sediments do not occur in the lowest part of the member in or near the study area.

The middle part of the Ross Flat Member shows that sediments which would normally be found offshore from the beach zone overstepped the sediments of the lowest part. The sediments of the middle part indicate that the local environment was tranquil except when density currents passed through. All types of density currents, from turbidity currents to grain flows to mudflows, slumped to form the sandstones and conglomerates of the middle part. Although the types of sediments indicate that there was much water over the study area, preserved tree stumps and plants show that the water level varied considerably over long periods of time.

The West Branch ignimbrite was emplaced on dry ground over a slightly hummocky surface. In part the variations in the thickness of the ignimbrite result from the topography of the area. The local vitrophyres occur where the ash was deposited on water or wet ground.

Clarno Formation: Lava Units

The lava flows of the Clarno Formaion are divisible into two units, named herein the Stephenson Mountain Member and the Bear Creek Member. The Stephenson Mountain Member is a 1.2- to 1.6-km-thick unit of basaltic andesite to silicic andesite flows which is conformable to the Ross Flat Member. The Bear Creek Member is a unit of basaltic andesite to silicic andesite flows which is discordant to the rest of the Clarno Formation. The Bear Creek Member flows tend to be thicker than the flows of the Stephenson Mountain Member.

Stephenson Mountain Member

The Stephenson Mountain Member crops out on both sides of the Mitchell Fault. To the north of the fault the member is exposed in a band completely across the study area. The unit extends to the northeast continuously for 30 km. To the north and west the unit has not been mapped to its limits. To the south of the fault the Stephenson Mountain Member crops out around the headquarters of the Bear Creek

Ranch and beneath Lawson Mountain. The total area in which the member is exposed is 39.4 km^2, of which 1.5 km^2 is south of the Mitchell Fault. Within the project area the Stephenson Mountain Member is the primary constituent of the Clarno Formation.

The flows of the member are moderately resistant to erosion. The flows form a series of cuestas with a local relief of 70 m. Large cliffs are rarely formed by the flows, in part because the flows are thin, and in part because the flows are rapidly eroded to scree (Figure 11).

The flows weather to a dusky brown on the rock surface and in the soil formed over the lava. The composition of the lava affects the weathering color; the more silicic flows weather to a more grayish color, and the less silicic flows weather to a more reddish brown color.

The Stephenson Mountain Member supports an open forest of junipers in the lower parts of the project area, and a dense forest of ponderosa pines in the highlands. Springs are common in the areas underlain by the unit, because there is an interconnecting joint system among the flows.

The contact of the Stephenson Mountain Member with the Ross Flat Member is angularly conformable and has little relief. With the Bear Creek Member the Stephenson Mountain Member has a maximum divergence 31° in the Stephenson Mountain area. The Bear Creek Member flowed across an eroded

Figure 11. Typical exposures of the Stephenson Mountain Member, exposed one kilometer northwest of the summit of Lawson Mountain. The view is from the south edge of the Sheep Mountain domes toward the southwest.

surface of the Stephenson Mountain Member similar in morphology to the land surface today.

The Mitchell Fault and the overlapping John Day Formation make the thickness of the Stephenson Mountain Member difficult to measure. The closest approximation of the thickness is measured from the contact with the Ross Flat Member in the West Branch Valley northwest across the strike of the member to the John Day Formation contact. Slumping of the lavas over the contact and a change of dip of 58° complicate the measurement. The unit is 1200 m thick in this section; projections of the contact with the Ross Flat Member suggest that the member is at least 1600 m thick in the Stephenson Mountain area.

The bottom two hundred meters of the Stephenson Mountain Member consist of flows interbedded with mudflows and tuffaceous beds. The mudflows weather to a yellow orange soil; the lithology is visible in the stream bottoms only. The tuffaceous beds weather to a moderate reddish brown soil; the material from which these beds are derived is not exposed. The mudflows and the tuffaceous units average ten meters in thickness.

The andesite flows of the unit average eight meters thick and range from 1.6 to 1.8 m. Throughout the outcrop area of a flow, the thickness of that flow is nearly constant. Laterally, the flows are often traceable for 0.5 km; one flow in the West Branch Valley crops out over a distance of 1.8 km.

The flows have few structures other than jointing. Most commonly the flows have a one- to ten-centimeter-spaced, platy jointing parallel to the bottom of the flow (Figure 14). Within a single flow the spacing of the jointing changes little. Well developed columnar jointing is not common; normally the columns are 45 to 130 cm across and extend through the depth of the flow. The width of the columns changes gradually from place to place. The upper surface of the flows usually has a one to two-centimeter-spaced jointing which extends a maximum of 25 cm into the flow. This jointing abruptly changes direction every few meters, and apparently is caused by the folding and shearing of the congealed skin of the flow while the flow was moving. The upper surface of the flows is usually slightly hummocked; other surface features such as pressure ridges are absent. The upper portions of some of the flows are amygdaloidal.

Bear Creek Member

The Bear Creek Member crops out to the south of the Mitchell Fault from the area of the Bear Creek Ranch headquarters to the west edge of the study area. Remanents of the member cap the hills to the south and east of the ranch headquarters. The full extent of the member in the region is not known, because the unit has not been mapped. North of the fault the member occurs as the filling of a valley prior to the modern Bear Creek Valley and as the capping rocks of Stephenson Mountain. The member continues to the north of the study area as the main constituent of a group of hills. The outcrop area of the member within the project area is 26.6 km^2.

The lavas of the unit range from basaltic andesites to silicic andesites; in the Stephenson Mountain area the base of the member consists of a 100-m-thick unit of rhyolite flows, and to the southeast of the Bear Creek Ranch headquarters the unit contains a tuffaceous sandstone body. The groups of flows on either side of the Mitchell Fault may not have the same source vents, and are placed within the same rock unit because of their stratigraphic relationship with the rest of the Clarno Formation.

The andesitic flows of the Bear Creek Member are more resistant to erosion than are the flows of the Stephenson Mountain Member. The flows commonly form 12- to 20-m-high cliffs (Figure 12). The lavas weather to moderate browns (5YR-3/4). The vegetation that grows upon the Bear Creek Member is similar to that of the Stephenson Mountain Member.

The contact of the member with the other units of the Clarno Formation is angularly unconformable in most places. Near the Bear Creek Ranch headquarters the strike diverges from that of the Stephenson Mountain Member by 20°. The base of the rhyolite flows covers a cuesta surface of Stephenson Mountain Member flows; the strikes of the Bear

Figure 12. Bear Creek Member exposed in the upper Dodds Creek Valley, at the south edge of the study area. At least five flows are visible on the mid-range ridge; the bottom flow caps the nearer butte. Light-colored ridge in the foreground is the West Branch ignimbrite. Between the ignimbrite and the butte is an exposure of the Stephenson Mountain Member outside the study area.

Creek flows are similar to those of the Stephenson Mountain Member, but the dips are from 8° to 17° less steep. In the lower Bear Creek Valley the Bear Creek flows lie almost parallel to the floor of the valley; the Stephenson Mountain Member flows dip about 15° more steeply and strike 24° more easterly. The Bear Creek Member is in contact with the Ross Flat Member in the hills to the southeast of the Bear Creek Ranch headquarters. The maximum divergence found was 18°.

Within the project area the Bear Creek Member has a maximum thickness of 350 m along the north edge of the area about 2.4 km west of Bear Creek. The unit thins to the south and becomes intracanyon to the Stephenson Mountain Member. The extent to which erosion has thinned the member could not be determined. To the south of the Mitchell Fault the thickness of the member is obscured by two anticlines and a heavy growth of forest. An estimate of the maximum thickness is 260 m.

At the head of Spring Gulch there is a 30-m-thick unit of tuffaceous sediments within the Bear Creek Member. The unit is highly weathered, but it stands out because the soil formed from it is a yellow orange (5YR-6/6). Of the sediments themselves only crumbly, clay-rich pieces can be found, which indicate that the sediments are coarse-grained, poorly-sorted, volcanic sandstone.

The rhyolite flows of the Bear Creek Member form a prominent cliff on the sides of Stephenson Mountain (Figure 13) and form the walls of the Stephenson Creek Valley. There are at least three flows, each about 30 m thick. The rhyolite varies in color from white to pale red (5R-6/2) and weathers to a pale yellowish brown (10YR-6/2).

The rhyolite flows form 20- to 30-m-high cliffs split by vertical joints spaced eight to ten meters apart. Local lens-shaped vitrophyres separate the flows in the low places on the surface covered by the flow. Analyses show that the vitrophyres are composed of material from the lower flow. Flow banding is common near the lower margins of the flows. The banding was dragged in places into recumbent folds, which indicate that the flows moved to the northeast. The upper portions of the flows contain vugs.

The Bear Creek Member andesite flows are 12- to 25-m thick; on the average the Bear Creek flows are twice as thick as the Stephenson Mountain Member flows. Jointing in the flows is very poorly developed. There is usually an incipient jointing, a plane of weakness to weathering and stress, which is parallel to the base of the flow (Figure 14). This jointing is spaced on an interval of 10 to 18 cm, but the spacing is thinner among the folded flows. Columnar jointing appears as a one- to five-meter-spaced vertical jointing. Shallow joints, apparently related to

Figure 13. Rhyolite flows on the southeast side of Stephenson Mountain. A road crosses the middle of the picture from the right edge. Three flows are visible.

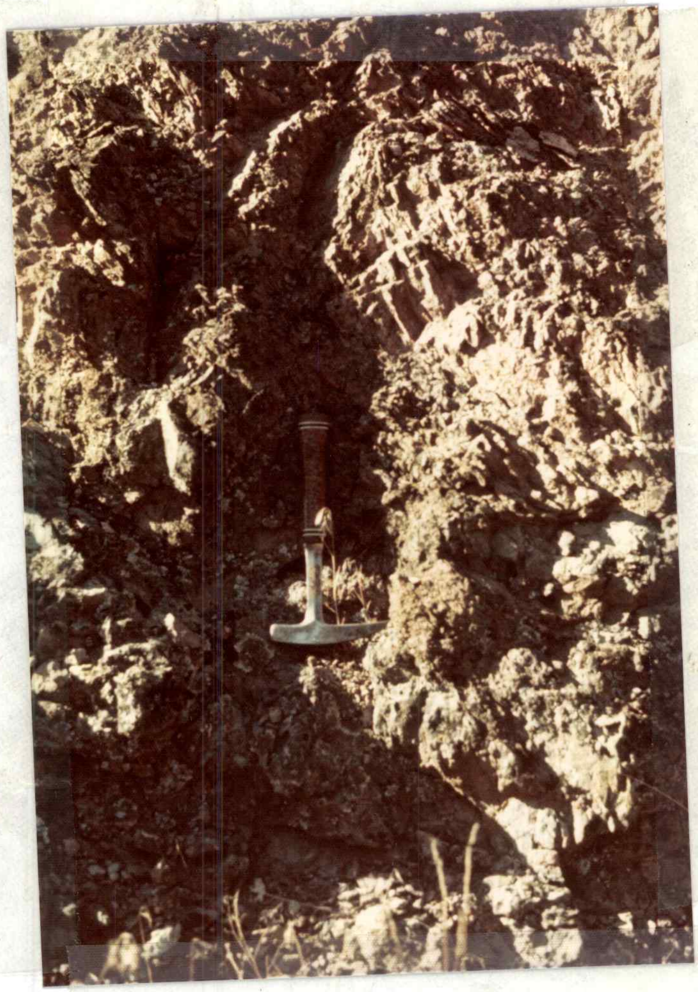

Figure 14. Jointing in an andesite flow. The most prominent jointing, and the most commonly observed, is parallel to the base of the flow, and in this picture this jointing dips into the page and to the left. A vertical jointing is also visible. The hammer is 30 cm long.

the movement of the flow, are common in the upper surfaces of the flows. Large vesicles and amygdules are found in some flows.

Petrography of the Clarno Andesitic Lavas

There are two types of andesitic lava found in the study area. The more prevalent of the two is a hornblende-bearing andesite which contains between 60.0 and 64.8 weight percent SiO_2. Where this type of flow is porphyritic, its phenocrysts are feldspar, hornblende, clinopyroxene, magnetite, and, rarely, biotite. The other type of lava is an andesite or a basaltic andesite containing between 55.7 and 60.0 weight percent SiO_2. The phenocryst assemblage in the porphyritic lavas of this type is feldspar, two pyroxenes, magnetite, and in the less silicic rocks, olivine.

The andesite lavas of the Clarno Formation are almost always porphyritic with phenocrysts a maximum of 5 mm long. The mafic phenocrysts are often clumped into glomercrysts with a maximum diameter of 12 mm. Typically the porphyritic lavas are composed of 10 to 15 percent phenocrysts. Pilotaxitic orientation of the feldspar phenocrysts is common, although eddying effects during the flowing of the lava obscure the alignment locally. The lavas have glassy groundmasses. Alteration changes the normally dark gray (N-3) lavas to a dark greenish gray (5G-3/1) or a dark brownish gray (5Y-3/1). Severe alteration turns the rocks to a moderate brown (10YR-4/2) and gives the rock a slightly saccnaroidal appearance.

Thin sections show that the groundmass of the lavas is pilotaxitic and hyalophitic. The glass, which is usually in some stage of devitrification, comprises 40 to 85 percent of the groundmass; plagioclase constitutes 60 to 80 percent of the crystalline groundmass. The other phases which may appear in the groundmass are clinopyroxene, hornblende, magnetite, and apatite; the mafic silicates are the major phases of this group.

The plagioclase in the groundmass is in small euhedral laths which reach 0.1 mm in length. Within a single flow the size of these crystals is fairly constant. The anorthite (An) content of the groundmass plagioclase is in the range An_{50-54} (labradorite) in the basaltic andesites, An_{46-52} (andesine or labradorite) in the intermediate andesites, and An_{34-46} (andesine) in the silicic andesites.

The mafic minerals, clinopyroxene, hornblende, and magnetite, form small equidimensional crystals which have a maximum size of 0.05 mm. The clinopyroxene and hornblende crystals are subhedral; the magnetite is in euhedral crystals. Hornblende is found in the more silicic andesites only.

In the phenocrysts the plagioclase crystals have strong normal or oscillatory zoning. The central portions of the crystals are often partially resorbed. At the edges of the crystals the anorthite content is close to that of the groundmass feldspar. The central parts of the crystals range from An_{62-68} (labradorite) in the basaltic andesites, to An_{56-64} (labradorite) in the silicic andesites. The crystals are euhedral or subhedral and average three by two millimeters in size. The plagioclase is invariably twinned by the carlsbad and albite laws, but not by the pericline law.

Hornblende occurs as phenocrysts in lavas which contain more than about 60 weight percent silica (Figure 15). The crystals are euhedral and elongate in the direction of the C crystallographic axis. The hornblende is clear and pleocroic, faint green to faint brown, and has a negative optic sign. These features occur in hornblende; however, the faint color is atypical. The hornblende crystals do not show reaction textures with the groundmass. Simple and polysynthetic twins occur rarely. The hornblende crystals, with a maximum size of one by two by eight millimeters, are often the largest phenocrysts in the flow.

Pyroxene occurs as phenocrysts in all the flows, but it is much less common in the flows which contain hornblende. There are three types of pyroxene found in the flows; augite, pigeonite, and hypersthene. The augite

Figure 15. Hornblende, plagioclase, and a small pyroxene phenocryst in an altered, hornblende-bearing andesite flow of the Stephenson Mountain Member. The elongate hornblende crystal encloses magnetite grains and blebs of devitrified glass. The pyroxene grain, viewed nearly parallel to its "C" crystallographic axis, is partially enclosed (located near the upper left corner of the hornblende crystal). The groundmass is colored brown by hematite and chlorophaeite/saponite. The groundmass glass is now completely devitrified. Width of field is 4.1 mm. Plane polarized light.

crystals are euhedral with a size of one by one by three millimeters. The crystals in the more silicic flows are rimmed by a 0.02 mm layer of brownish pyroxene optically identical to the main part of the crystal. Augite occurs in flows of all compositions. In some intermediate andesites, those with an SiO_2 content between about 58 and 62 weight percent, pigeonite is found. The pigeonite crystals have a form similar to that of the augite, but the rim of optically identical pyroxene is thicker. In the basaltic andesite flows hypersthene is present instead of pigeonite. The hypersthene crystals are faintly pleochroic and have a subhedral form. The crystals of hypersthene are less common than those of augite (Figure 16) and are found primarily in the larger glomerocrysts.

Olivine, usually entirely replaced by iddingsite, occurs in the less silicic basaltic andesites. The only place where the olivine/iddingsite pseudomorphs are found is in the centers of glomerocrysts, where the olivine apparently was protected.

Magnetite occurs as phenocrysts in euhedral crystals with a maximum size of 1.5 mm. The magnetite crystals are the only phenocrysts which show a complete size range between that of the groundmass and that of the main phenocrysts.

Devitrification of the glass forms an assortment of minerals not found in the rocks originally. Silica

Figure 16. Clinopyroxene, orthopyroxene, and plagioclase phenocrysts in a Bear Creek Member basaltic andesite flow. The plagioclase laths are bent because of folding in the neighborhood of the flow. Both types of pyroxene are surrounded by slightly disoriented, similar pyroxene; however, the twinning affects the border. Width of field is 4.1 mm. Cross polarized light.

minerals, chlorite, epidote, and a brownish, low-relief material tentatively identified as chlorophaeite or saponite, are often found in minute crystals or as replacements. X-ray diffraction studies often show peaks for tridymite or cristobalite. Quartz fills vugs and veins. Zeolites are not common, but stilbite was found in one vuggy rock, and some of the devitrified glass contains zeolites of unknown type.

The feldspar crystals are often altered in part to calcite, epidote, clay (Figure 17), and, in severe alteration, a symplectite-like intergrowth with potash feldspar. The hornblende is changed to chlorophaeite/saponite, magnetite, or hematite, and chlorite in the more altered rocks, but shows little alteration otherwise. All the pyroxene types are altered to chlorophaeite/saponite, amphibole, and hematite, and the excess calcium is taken up in the formation of calcite. The magnetite alters to hematite.

Petrography of the Bear Creek Rhyolite Flows

The rhyolite lavas contain 71 to 75 weight percent SiO_2. In part the greater amount of silica in some of the flows arises from secondary deposition of quartz.

The flow banding of the lavas is spaced at 2.0 to 2.8 mm intervals (Figure 18). The rocks are glassy, but they are usually altered to a procellanous appearance. Secondary silica and orthoclase have been deposited between the

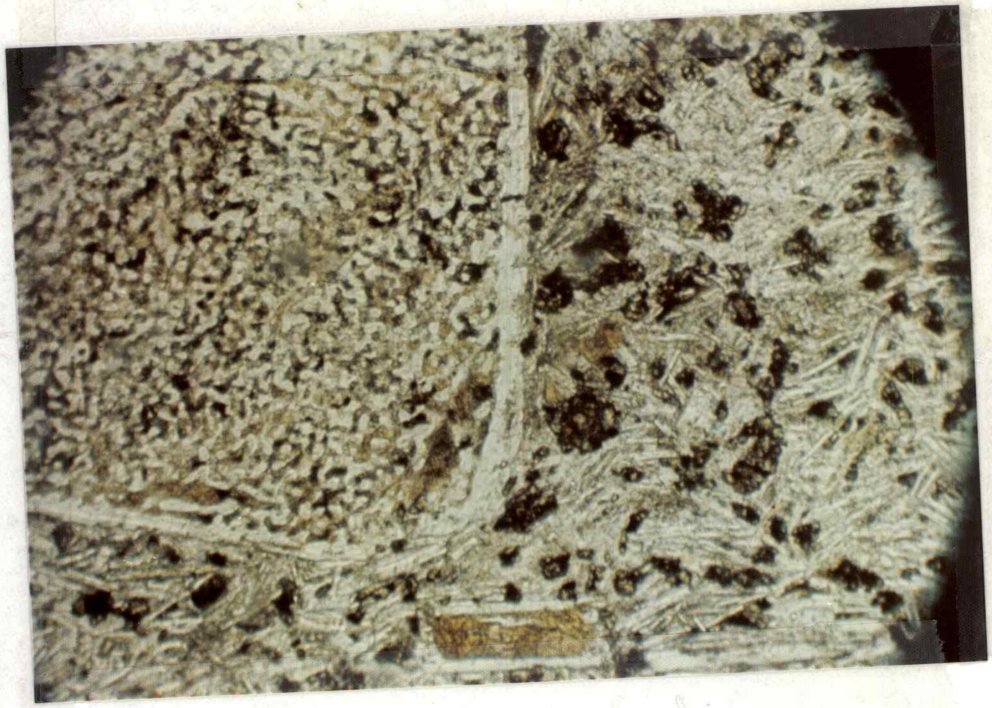

Figure 17. Alteration of plagioclase crystals in a Bear Creek Member andesite flow. The alteration, confined to the more calcic interiors of the crystals, has formed chlorite, chlorophaeite/saponite, and minor epidote in a vermicular texture. The groundmass is composed of pyroxene, plagioclase, and magnetite grains in devitrified glass. Width of field is 1.3 mm. Plane polarized light.

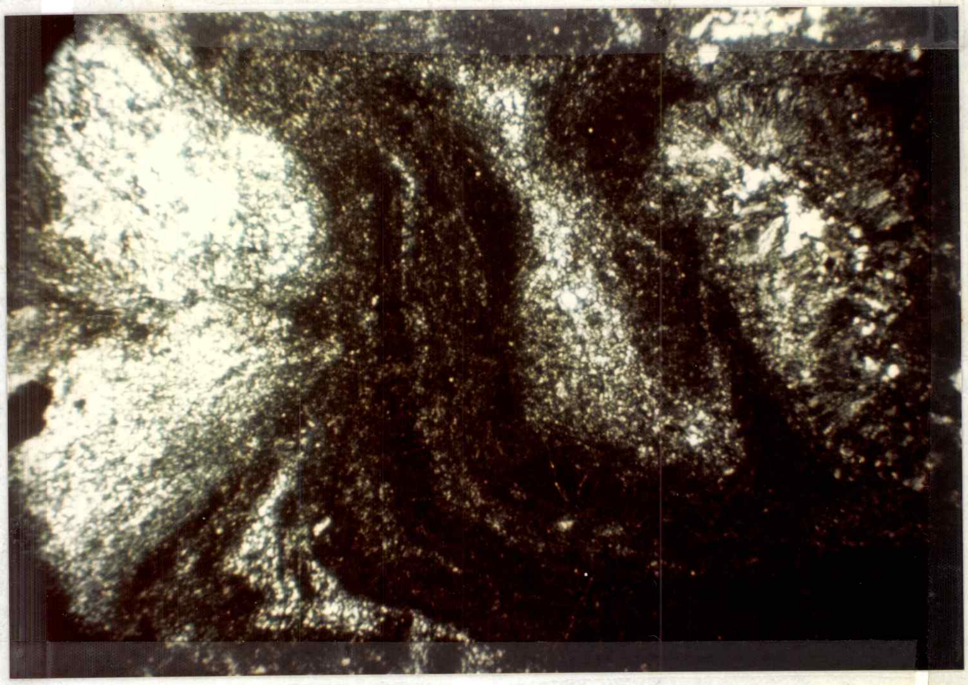

Figure 18. Photomicrograph of the flow banding in a Bear Creek Member rhyolite flow. The devitrified glass of the lava occurs in the dark, fine-grained areas. The coarse-grained areas are composed of secondary silicates: quartz, orthoclase, and albitic plagioclase. The transition zone between the coarse and fine areas indicates that recrystallization of the devitrified glass occurred during the deposition of the secondary minerals. Width of field is 4.1 mm. Plane polarized light.

bands. Sparse phenocrysts of sanidine, quartz, and plagioclase comprise less than two percent of the rock by volume.

Microscopically the rocks consist of devitrified glass, sanidine, tridymite (?), biotite, and albite/oligoclase (An_{8-15}). The glass has formed spherulites and axiolites with a random orientation relative to the banding. Alteration has formed hematite, which gives the rocks an orange cast. Hornblende was not recognized in the thin sections of the flows themselves, but it is present in the vitrophyres.

Clarno (?) Silicic Extrusions

There are two extrusive silicic bodies in the project area which cannot be placed within the Clarno Formation with complete confidence: the Sheep Mountain extrusions and the Spring Gulch extrusion. The Sheep Mountain extrusions are a 2.9 km^2 group of hornblende-bearing rhyolite and dacite domes and flows located in the north-central part of the study area. The domes form a triple-peaked mountain which rises 300 to 400 m above the valleys at its sides (Figure 19). The mountain has a layered appearance when it is seen from a distance, which is the result of the rectangular jointing of the rock. The domes are layered parallel to their original edges. The outside edges which still remain are a breccia of silicic blocks glued by the lava of the domes. There are some extraneous blocks in

Figure 19. Sheep Mountain from the west (upper left). The layered appearance is caused by jointing. The northern dacite dome appears more separate in this picture than it appears on the mountain itself. At the middle right is the end of one of the Spring Gulch rhyolite flows. The andesite flows of the Bear Creek Member in the bottom of the Bear Creek Valley dip much less than the andesite flows of the Stephenson Mountain Member on the ridge above them. There is a rhyolite dike in the left foreground valley.

the breccia near the base of the domes. Inside the breccia the lavas of the domes are moderately altered and have a granular appearance. The altered rocks have a lower resistance to erosion and weathering than either the breccia or the lavas of the main part of the domes. The bulk of the domes consists of hard, reddish purple (5RP-5/2) rock, with a jointing spaced at 12 to 35 cm.

The domes rest upon the cuesta surface of the Stephenson Mountain Member flows with approximately the same angular unconformity as the Bear Creek Member flows. In the places where the domes and the Bear Creek flows abut, the Bear Creek flows show themselves older with a ten meter alteration zone along the contact.

The north summit of Sheep Mountain has a lava compositionally different from the rest of the domes (analysis SH-NS *vs*. SH-2, appendices). In appearance the rocks of the north summit are similar to the rocks of the main part of the mountain, but the north summit rocks contain more hornblende phenocrysts. Chemical analyses show that the lava of the north summit is a dacite which has significant differences in its content of CaO, FeO, and Al_2O_3 from the lava of the rest of the domes.

To the east 0.8 km from the main summit of Sheep Mountain and to the west 1.6 km from the summit are some silicic flows which are also unconformable to the Stephenson Mountain Member. Parts of both groups of flows are covered by Bear Creek flows, which indicates that part of the Sheep Mountain volcanism is within the time period of the Clarno Formation. The eastern flows lie proximate to a dike of rhyolite which extends eastward from the base of Sheep Mountain. Analyses show that rocks from both groups of flows are nearly identical (SH-LF, RFR-5 appendices), and that both groups are chemically similar to the north summit lava. The flows average 20 m thick and have a more reddish color than the dome lavas. The flows appear to be more glassy than the dome material.

Thin sections of the Sheep Mountain dome lavas show that the rock is composed of a pilotaxitic mass of oligoclase microlites and hematite pseudomorphs of hornblende crystallites, comprising 30 percent of the groundmass (Figure 20). Phenocrysts constitute 0.5 percent of the rocks; sanidine, zoned oligoclase, quartz, and hornblende replaced by hematite are the phenocrysts. The glass, which forms the bulk of the rock, is not devitrified.

Glass comprises 90 percent of the flow rocks. Flow banding is conspicuous; some of the bands are rich in hematite. The microlites are composed of the same minerals as those in the dome lavas, but the oligoclase is more calcic. Phenocrysts are not present in the flows.

The rhyolite extrusion of Spring Gulch forms the caprock of two buttes to the west of Spring Gulch and the filling of a valley on the western side of the buttes. The

Figure 20. Hornblende-bearing rhyolite of the main Sheep Mountain dome. The needles of hornblende are in a random array in the devitrified glass of the groundmass. Phenocrysts other than hornblende are not present. Width of field is 1.3 mm. Plane polarized light.

flows have been eroded to about half their original area; to the north of the main part of the flows, there is a small remanent of another valley-filling flow, and at the junction of the two forks of Bear Creek lies another piece of the rhyolite flows. Beneath the flows is a silicified ash bed, colored green by alteration. The ash bed is 25 m thick to the east of the flows, where it fills a valley in the Stephenson Mountain Member lavas. The ash bed contains much foreign material; the bulk of the bed material is a glassy rhyolitic ash.

At the bottom of the flows on the southern side of the buttes there is a four- to six-meter-thick vitrophyre. The vitrophyre crops out beneath the flows to the south of a line of intrusions which penetrate the flows. The vitrophyre is a very dark gray (N-3) and is composed of two percent phenocrysts in an unstructured glass. Sanidine, hornblende, and quartz are the phenocrysts.

Above the vitrophyre lies the main body of the flows. The lower parts of the flows are banded and have secondary quartz filling the spaces between the bands. Above the banded zone is an amygdaloidal layer, which has cavities of maximum size 0.8 mm. The top of the flows is covered by a weathered layer, which has a texture similar to a finely vesicular pumice.

The main parts of the flows vary from a reddish purple (5RP-5/2) to a light red (5R-6/2) intermixed with the white of the secondary quartz. The rhyolite at the top of the buttes is a pinkish gray (10R-7/2).

Phenocrysts in the flows are quartz, sanidine, and rare biotite. The largest crystals are 1.0 mm long; the average size is 0.5 mm. Hornblende was not found in the main body of the flows, but the weathered rhyolite at the top of the buttes has some hematite areas which resemble the crystal shape of hornblende.

Chemical analyses show that the Spring Gulch rhyolite flows are not chemically similar to the Sheep Mountain extrusions (analyses SH-2, SH-NS vs. VB-V, appendices). The dissimilarities in the alkalis, calcium and titanium components are too great for weathering to have introduced such variation. More similar are the Spring Gulch extrusions to the Bear Creek Member rhyolite flows (analyses STM 1,2,3, appendices), although they appear unrelated in the field.

The Spring Gulch rhyolite flows do not abut Bear Creek Member flows or John Day Formation material. The sold indication of the age of the flows is that they are older than the andesite intrusion, which places the flows probably within the Clarno volcanic time period.

John Day Formation

The John Day Formation is a unit of water-laid tuffs, shallow-water sediments, and ignimbrites of Late Oligocene to Early Miocene age. The formation is divided by Robinson (1976) into nine subunits (after Peck, 1964) in the area of Ashwood, 40 km west of the study area, but this division cannot be applied to the eastern side of the outcrop area of the John Day Formation. Instead, the formation is divided into three members (Hay, 1962): a red lower member, a green middle member, and a yellow-brown upper member. The red member is the only part of this formation present in the study area.

The unit is a thin wedge about 15 m thick at the area boundary (Figure 21). Two subunits comprise the member: a basal zone which takes its color from the rock type beneath it, and a red claystone. Both units are very poorly indurated and erode rapidly in heavy rains. Plant life grows where there is an alluvial cover on the member.

The contact between the John Day Formation and the Clarno Formation is marked by a paleosol which formed upon a rugged Clarno surface (Oles and Enlows, 1971). If the John Day Formation was ever so extensive, a relief of over 500 m existed in the Sheep Mountain area.

The basal subunit in the study area has the appearance of a paleosol; pieces of bedrock become smaller with

Figure 21. John Day Formation to the east of Sheep Mountain. The white unit is silicified tuff which lies north of the study area. The red claystone is in the study area. The Picture Gorge Basalt overlies the upper member of the John Day Formation on Sutton Mountain in the background.

increasing distance from the contact. The color of this subunit is taken from the material over which it lies; dark red (7R-3/6) over the basaltic andesites, dark reddish brown (10R-3/4) over the andesites, and pale purple (5P-7/2) over the silicic lavas. The change of colors over adjacent bedrock types indicates that this unit formed in place.

The claystone above the base has a color that approximates the weighted average of the colors of the basal unit, a dark red (5R-4/5). The unit is composed of silty clay. When the rains wet the claystone, the unit turn into a sticky gumbo. Drying causes a contraction within the claystone which forms a highly fractured, crumbly surface. Hay (1962) proposed that the claystone units of the John Day Formation are sheetwash deposits along the edges of the depositional basins.

To the north of the project area the lithology of the John Day Formation changes to white silicified tuffs interbedded with red and light brown claystones. This part of the formation shows channelling and large scale cross-bedding, and is interpreted by Hay (1962) to be the near-shore deposits of the lake basin.

Quaternary Deposits

Four categories of near-recent to recent deposits are recognized in the project area. Quaternary alluvium is here used for stream valley sediment and flat area soils. Talus deposits indicate scree slopes composed of large angular rock fragments with or without a matrix material. Fan deposits are composed of material similar to the alluviam, but which radiate from a source or form a bajada, and which are at a higher level than the parent streams at present. Landslide deposits are large slump units containing large blocks which have slid out of position, or units of soil-like material which have covered lower strata by down-slope movement.

Quaternary Alluvium

The alluvium in the stream valleys is a very poorly sorted, unconsolidated conglomerate. The large clasts reflect the source areas of the stream. The primary process involved in the formation of these deposits is the phenomena of flash flooding. The summer rainfall is typified by local, extremely heavy downpours, the runoff of which, confined to the stream valleys, forms a body of flowing water whose competence is extremely high. Effectively, the flash floods are a very liquid mudflow. When the flood waters reach an area where the constriction of the flow is removed, the sediment load is dumped, forming an unstructured deposit. In the Gage Creek Valley the rate of deposition by flash floods far exceeds the rate of erosion by the normal stream flow. The creek is presently confined to a narrow gully cut into about 20 m of alluvium. The Mazama ash forms a discontinuous white band found in many places in the alluvium.

In large flat areas such as Ross Flat, thick soils cover the bedrock. The slopes of these areas are low enough that sheet wash and rill formation are slow processes. These flat areas are the farm land of the region.

Quaternary Talus Deposits

The talus deposits are active scree slopes composed primarily of large rock fragments. The deposits form on the slopes below large cliff-forming rock units, such as the Black Butte summit block, Lawson Mountain, and the hills to the south of the Bear Creek Ranch headquarters. When the cliff above the talus is worn back to a more gentle slope, the talus deposit stabilizes; the interstices between the rock fragments fill with soil. Only the larger talus slopes were mapped.

Quaternary Fan Deposits

Where a stream debauches from a valley into a large flat area, the loss of competence by the stream deposits a cone-shaped body of sediments. On the north side of Sheep Mountain the remains of such a fan are exposed. The creek which formed the fan has now cut down below the level of the fan, and left it to be dissected by sheetwash and rillwash. Only the western half of the fan remains, as a wedge-shaped deposit of unconsolidated alluvium overlying the John Day Formation. The deposit is ten meters thick near Sheep Mountain, and it thins toward the north.

Quaternary Landslide Deposits

There are two types of landslide deposits in the study area. The most common type occurs when a body of loose material creeps downhill, incorporating other materials and homogenizing itself as it moves. Often, after these deposits have stabilized, they form large areas which are level enough to farm, but which are non-arable because of the large amount of boulders which they contain. The active slides have a hummocky surface which is distinctive on aerial photographs.

The second type of landslide occurs where a large block has moved downslope as a unit. These slides have features which are usually seen in fault zones, such a slickensides and drag folds. The slides are discerned by the anomalous dip of the block and the overlapping of materials lower on the slope.

III. INTRUSIVE ROCKS

The intrusive rocks of the project area are subdivided by composition, with the exception of the intrusions located in the central part of the Mitchell Anticline near Black Butte. The Mitchell Anticline intrusions are described as a group because these intrusions are variously altered, but petrographically similar rocks. Representative analyses of most of the rock types are presented in the Appendix (Tables 5-8).

Basaltic Intrusions

Intrusions of basaltic composition have two forms: small plugs of agglomerate and short, thin dikes. There are three agglomerate plugs in the study area; two of the plugs are adjacent to the Sheep Mountain domes, and the third plug is to the northeast of Lawson Mountain. The two plugs near Sheep Mountain are wedge-shaped bodies which intruded along the margin of the domes. The plugs have altered the nearby rhyolite to clay. The plug by Lawson Mountain measures 30 m by 60 m, and has a dike projecting from it to the north-northwest for a distance of one kilometer. This plug and dike intrude vertically through the lava flows of the Stephenson Mountain Member.

The three agglomerate plugs have identical lithologies, all composed of greenish black (5G-2/2), angular blocks in a matrix of purplish red (5RP-6/3) lava. With the exception of some rare pieces which resemble distorted bombs and scoria, the shapes of the blocks are not recognizable as those of pyroclastic material. All sizes of blocks from coarse sand to boulders (2 mm to 0.7 m) are present in the agglomerate.

In thin section the agglomerate blocks appear hyaline to microcrystalline. Microlites of calcic labradorite (An_{64-68}) and pyroxene, and crystallites of magnetite comprise less than seven percent of a block. There is some devitrification of the glass into chlorite, hematite, and feldspar (?).

The matrix around the blocks contains less than two percent microlites in glass stained red by hematite. The glass is slightly altered, and has an index of refraction greater than Lakeside (1.540).

There are five dikes of basaltic composition in the study area; all are located in the Ross Flat area. The basalt dikes are found easily in the field, because they weather to a moderate reddish brown (5YR-5/4) soil. There are three petrograhic types represented by the dikes.

In the central part of Ross Flat there are two dikes of porphyritic basalt. The southern of the two extends for 0.3 km along the eastern side of Spring Gulch and is between 0.5 and 1.2 m thick. The dike dips 75° to the east. The more northerly of the two trends in a northwesterly direction along a valley to the east of Spring Gulch. The dike veers due west and crosses Spring Gulch about 0.1 km north of the road crossing. The total length of this dike is 1.0 km; the width ranges from 1.5 to 8 m. The northwest trending section of this dike dips 70° to 80° to the east; the west trending section is vertical.

The porphyritic basalt of these dikes contains phenocrysts of calcic labradorite (An_{65-70}), augite, and magnetite. About 70 percent of the rock is groundmass, composed of grains of feldspar, pyroxene, and magnetite in devitrifying glass. Between five and ten percent of the rock has been replaced by calcite, located in and near the feldspar. Hematite, chlorophaeite, and iddingsite (?) are additional alteration products. Analysis USG-1 in the appendices shows the composition of this type of basalt.

The second type of basaltic rock, found in a dike which cuts an andesitic intrusion in the upper part of Cougar Gulch by Lawson Mountain, is a porphyritic olivine-bearing basalt. This dike is 0.2 km long and averages three meters in thickness. It was intruded vertically into the intrusion and the adjunct Ross Flat sediments.

The basalt of this second type does not contain plagioclase as a phenocryst, but has large olivine and augite crystals. The olivine is 95 percent replaced by iddingsite; the pyroxene is about 60 percent replaced by the same material. The phenocrysts comprise about 15 percent of the rock.

The groundmass of the olivine-bearing basalt is composed of labradorite (An_{64-68}), augite, and magnetite crystals surrounded hyalophitically by devitrified glass. Calcite veins and replacements comprise over ten percent of the rock. Chlorite, hematite, and chlorophaeite are also found in the groundmass. Analysis CG-DI (Appendices) shows the composition of this rock type.

The third type of basalt, a nonporphyritic unit, is found in a dike to the southwest of Doolittle Flat, at the southern boundary of the study area, and in a dike approximately 1.5 km west of Spring Gulch, to the south of the Mitchell Fault. The dike to the southwest of Doolittle Flat can be traced in the Hudspeth mudstones for a distance of 0.2 km in the direction N 30 W. The dike averages two meters in thickness. The dike to the west of Spring Gulch trends about N 30 E, and can be traced from the zone of the Mitchell Fault to the bottom of the local stream valley to the southwest, a distance of 0.4 km. This dike ranges from three to four meters thick.

Petrographically the third type of basalt is an altered hyaline basalt. Microlites comprise about 40 percent of the groundmass; the rest is devitrified glass. Calcite, magnetite, and chlorophaeite are common alteration products.

Andesite Intrusions: Mitchell Anticline Intrusions

Black Butte and the hills to its north and west are intruded by a complex group of andesitic and minor "lamprophyric" dikes. There are three petrographic types of andesites, informally referred to here as the white type, the pink type, and the blue type after the fresh surface colors. These types intergrade with each other and in thin section appear to be the alteration products of similar material after differing processes. This division of the rock types is primarily one of convenience; it was derived for the separation of the different intrusive bodies in the field.

White Type

The white type constitutes the bulk of the intrusive rocks in the Black Butte area. The type comprises the rocks of the top of Black Butte, two plugs, and nine sills. The sill which forms the top of Black Butte is the only large intrusive body on the eastern side of the Mitchell Anticline in the project area.

The Black Butte sill is 200 m thick in its central part. The intrusion lies above the Gable Creek Tongue except on the western side of the sill where it connects to the plugs. The Gable Creek strata are not deformed by the intrusion. The sill has thick columnar jointing spaced on an interval of 2.5 to 3.8 m and canted about 15° to the southeast.

On the west side of Black Butte are two plugs, separated by a 20 m thick body of mudstone which is possibly a block slumped into the liquid lava at the time of intrusion. The western of the two plugs has an oblong shape approximately 600 by 120 m. The edge of the eastern plug crops out from under the Black Butte sill. Both plugs are altered to friability; the plugs form a light gray, treeless area on the west side of the butte where a valley has been cut (Figure 22).

There are at least nine sills of the white-type rock on the western side of the Mitchell Anticline. The sills are 15 to 35 m thick and range from 0.6 to 1.6 km in length. Throughout their lengths the sills form hogbacks or breaks in the slopes of the hillsides. The sills are inclined more steeply in the center of the anticline than on the limb, but they all dip to the northwest. The sills are often jointed on a scale of three to five centimeters parallel to their borders.

The white-type rocks vary in color on fresh surfaces from light olive gray (5Y-6/1) to pale yellowish brown (10YR-6/2). Weathering and an increasing state of alteration deepen the colors to olive gray (5Y-5/1) and pale orange brown (7YR-5/2).

Figure 22. Black Butte from the west. The western plug is visible across the base of the mountain, and the sill of the top of the butte shows its columnar jointing. In the foreground is the large, blue-type dike. A pink-type dike is barely visible behind the tree top at the lower left.

The rocks of the white type are difficult to study in thin section, because they have all been altered to some extent by devitrification and calcite replacement. The alteration has changed the chemical compositions of the remaining minerals. The chemical analysis of the Black Butte sill may not be a good indication of the composition of the original lava because of this alteration (analysis EMT-52, appendices).

The white-type rocks are all hornblende-bearing andesites. Phenocrysts in the rocks are andesine or labradorite (An_{46-54}), hornblende, and magnetite. The plagioclase is largely replaced by calcite, which possibly makes the anorthite determination spurious. The hornblende crystals are no longer present; in some rocks there are cavities or large calcite crystals with the shape of hornblende crystals, and in other rocks the hornblende remains as a mass of hematite, calcite and chlorite. The magnetite occurs in various stages of conversion to hematite.

The groundmass of the white-type rocks is completely devitrified and partially replaced by calcite. The original microlites are sometimes represented by their outlines of fine clay and hematite. There is some quartz present in the groundmass in the form of small, irregular blebs. The amount of quartz varies from three to ten percent of the rock; the amount of calcite varies from 10 to 60 percent of the rock.

Pink Type

With the exception of one large dike, the pink type is a local variation, which occurs as offshoots and margins of the thicker white sills and in thin places in the white sills. The transition from the white type to the pink type often occurs over distances of less than three meters.

The large dike of the pink type crops out from the Mitchell Fault to the northeast of Black Butte west-southwest to the Gage Creek Valley and from there south-southwest to the boundary of the project area, a distance of 5.6 km. The thickness of the dike varies from 18 to 35 m. The dike is visible from a long distance, because the soil that forms from it is a light orange pink (5YH-7/2) which contrasts strongly with the grays of the Hudspeth mudstones. The large, pink dike dips toward the axis of the Mitchell Anticline and cuts through some of the dikes of the white type. The large dike is not clearly younger than all the white dikes, for some of the contacts are diffuse, which suggests a contemporal origin among the various dikes.

Hand specimens of the pink-type rocks show that the unit is composed of two petrographic types. The offshoot and margin rocks are speckled like a fine sandstone, or lineated with short discontinuous stripes. The dark speckles and stripes are composed of carbonate and hematite. The rock of the large dike appears to be the same material as that which comprises the white type but the rock of the large dike has more disseminated hematite. All the pink-type rocks vary from pale reds (10R-6/2) to light browns (5YR-6/4).

Microscopically, the offshoot/margin rocks are composed of glass and have only secondary and devitrification minerals visible (Figure 23). X-ray diffration studies show prominent quartz, feldspar, and calcite peaks on most of the offshoot/margin rocks, but some rocks do not produce feldspar peaks. Hematite is scattered throughout the rocks, but it is concentrated in the calcite.

The rocks of the large dike are petrographically similar to those of the white-type sills. Silicification has been the dominent replacement process, rather than the formation of calcite. The rocks are holocrystalline; the groundmass consists of irregular blebs of quartz and laths of plagioclase. The hornblende is completely replaced, and the crystal form has been obliterated. The analysis of the rock from Gilchrist Butte is representative of the rock from the large dike (analysis EMT-62, appendices).

Blue Type

The blue-type rocks are found in one large sill on the west side of Gage Creek, and in several small dikes on the east side of that creek. The sill on the west side is 35 m thick and forms a prominent cliff. The sill dips to the west, but it is not parallel to the sills of the white type.

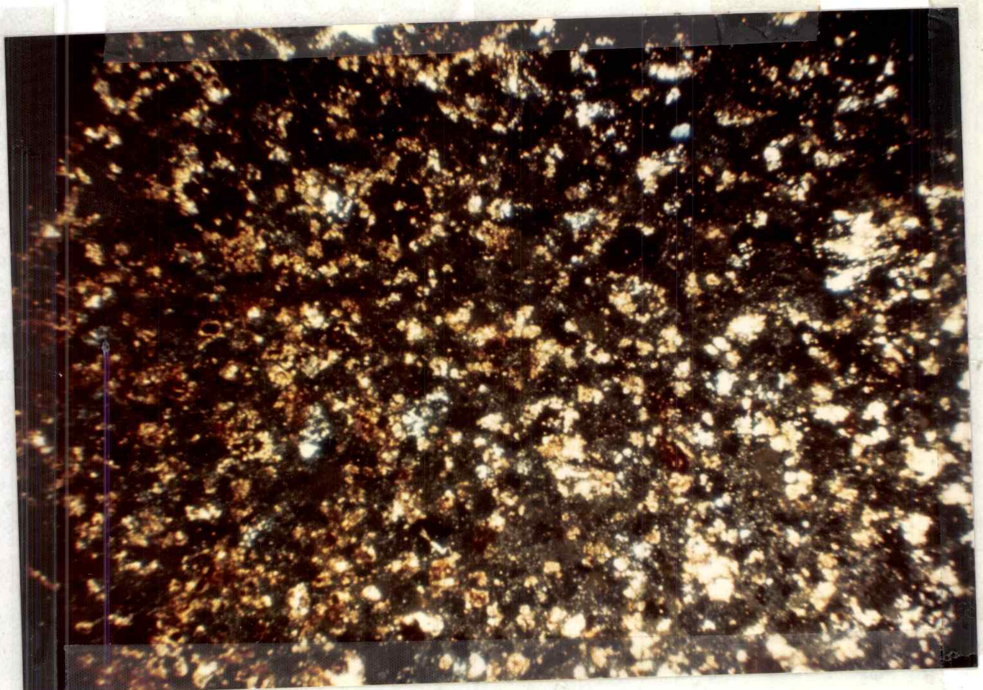

Figure 23. Altered vitric andesite of a offshoot, pink type dike. The glass is slightly devitrified and contains replacements of calcite/hematite, quartz and plagioclase. Width of field is 4.1 mm. Cross polarized light.

The sill is jointed on an interval of 1.0 to 1.5 m. The dikes on the east side of Gage Creek are all vertical. These dikes vary from 1.2 to 6 m in thickness and are not traceable for more than 100 m. The dikes form small hog-backs.

The rocks of the blue type are a dark bluish gray (5B-4/1) to a medium light gray (N-6) color on their fresh surfaces. Weathered surfaces are a dark yellowish brown (10YR-4/2). The rocks appear very finely crystalline in hand specimens; plagioclase is the only recognizeable mineral.

The blue-type rocks are holocrystalline in thin section. The mafic minerals are magnetite and a chlorite/calcite replacement of hornblende. The plagioclase has changed and grown secondarily, for the crystals are anhedral and untwinned. The anorthite content is variable on a local scale and is difficult to measure accurately; extinction-determined compositions vary between An_{38} and An_{84}. The groundmass is a mass of quartz, feldspar and calcite blebs.

"Lamprophyre"

The "lamprophyre" is a minor group of rocks which occur as pods in the pink type rocks, as margins to bodies of mudstone in contact with the pink-type rocks, and as small dikes located near the large dike of the pink type. The name "lamprophyre" stems from Howard (1955), who

who named the rock a kersantite. Field usage at the O.S.U. Geology Camp has retained the general name to the present time.

The lamprophyric material occurs in small bodies, usually one to three meters in diameter. The dikes are larger units, but they are less than 20 m long and between 0.3 and 1.5 m wide. The lamprophyric bodies are not prominently exposed and are often difficult to find.

Along the edges of the block of mudstone which separates the two plugs on the west side of Black Butte, there are many small, irregular bodies of the lamprophyric material. These bodies thicken and thin without a distinct pattern, and in some places disappear entirely. To the inside of the bodies and occasionally surrounding them is a peculiar brownish rock rich with darker brown blebs. The rock resembles an argillite; it is aphantic, but it is not glassy. The blebs are texturally similar to the main part of the rock. Within the brown rock lies the mudstone of the Hudspeth Formation, which is altered to a neutral gray in places.

Approximately one kilometer to the west of the summit of Black Butte, there is a pink-type dike which contains pods of "lamprophyre," the brown rock, and baked mudstone. The types of pods are scattered at random. The pods average 0.6 m in diameter; pods smaller than 0.2 m are not present. There is a greater abundance of "lamprophyre" in the smaller pods (Figure 24).

In an arroyo on the south side of West Branch Creek, about 0.3 km northeast of the mouth of Gage Creek, the only occurrence of the lamprophyric material separate from other intrusions crops out as a 0.6 m wide, 20 m long dike. The large dike of the pink type crops out approximately six meters above the lamprophyric dike.

Fresh surfaces of the lamprophyric rocks are medium gray (N-5). Phenocrysts of biotite are the only discrete mineral; veins of microcrystalline calcite are common. Weathering changes the color to a moderate yellowish brown (10YR-4/2).

Microscopically (Figure 95) the lamprophyric rocks contain about 12 percent biotite phenocrysts, which are lath shaped and have a maximum length of 2.5 mm. The groundmass is composed of biotite, magnetitie, quartz, and a mineral with tabular crystals, a low birefringence, and a moderate angle, negative 2V, tentatively identified as andalusite. The minerals are unoriented. There is much secondary calcite, 15 percent on the average, and some secondary quartz, about 3 percent. The calcite has replaced all the other minerals without preference. Analysis EMT-68 (appendices) shows the composition of the "lamprophyre."

Figure 24. Pink type dike containing pods of "lamprophyre," argillite (?), and baked mudstone, exposed 1.0 km west of the summit of Black Butte. The "lamprophyre" is in the brownish black pods like the large pod in the upper left. The baked mudstone pods are lighter gray and have a marked fissility. The argillite, difficult to discern in this picture, is a slightly darker brown than the surrounding lava. The dark brown band in the central part of the picture is not argillite. The hammer is 30 cm high.

Figure 24. Pink type dike containing pods of "lamprophyre," argillite (?), and baked mudstone, exposed 1.0 km west of the summit of Black Butte. The "lamprophyre" is in the brownish black pods like the large pod in the upper left. The baked mudstone pods are lighter gray and have a marked fissility. The argillite, difficult to discern in this picture, is a slightly darker brown than the surrounding lava. The dark brown band in the central part of the picture is not argillite. The hammer is 30 cm high.

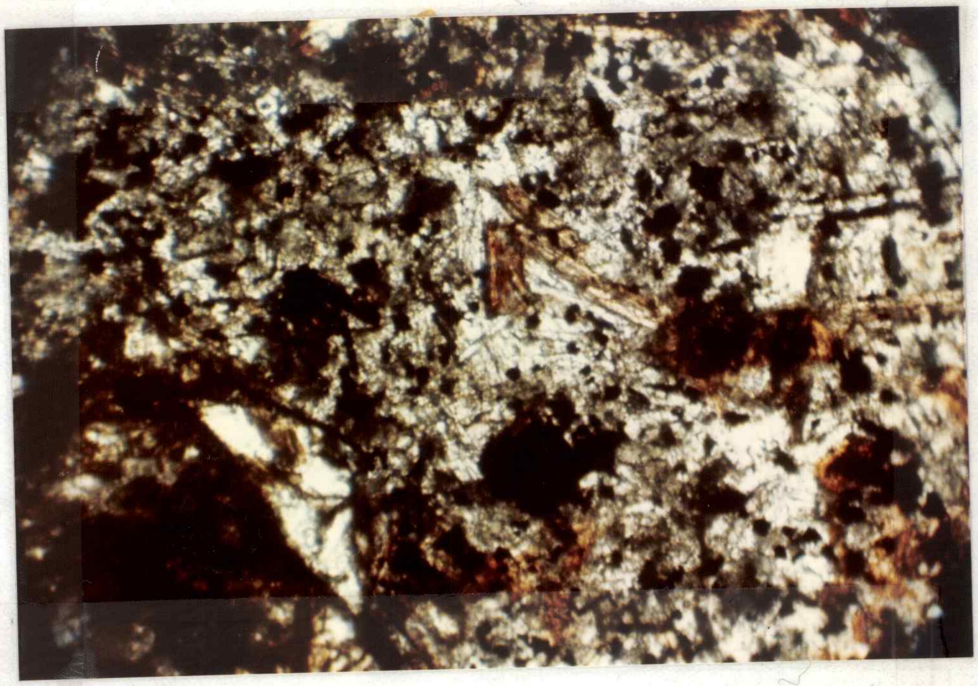

Figure 25. "Lamprophyre:" an altered, biotite andalusite (?) hornfels. The biotite is easily distinguished by its tan to dark brown variations in color. The andalusite appears as slender prisms of higher index than their surroundings. Quartz, magnetite, and calcite (secondary) are also present, but the quartz and calcite are difficult to distinguish. The crystal at the lower left is probably a replaced andalusite porphyroblast. Width of field is 4.1 mm. Plane polarized light.

The white-type and the blue-type rocks are the least altered of the groups of intrusions; both of these types are severely altered with the addition of much silica and carbonate. The biggest difference between the two types is the oxidation state of the iron. The white type has all the iron in the ferric state; the magnetite and the mafic silicates have all been changed to hematite intergrowths. In the blue type the alteration has left the magnetite unchanged and converted the mafic silicates to chlorite; some of the iron remains in the ferrous state. The blue-type dikes and sill are stratigraphically lower in the Hudspeth Formation than are the white- or the pink-type intrusions; the difference might be related to a weathering episode prior to the present one or to ground water circulation.

The pink-type rocks are the most highly oxidized of the Mitchell Anticline intrusions. Disseminated hematite is associated with the devitrification of the glass and the alteration of the feldspars. By their occurrence the glassy offshoot and margin rocks are chill zones. Less devitrification has occurred in these chilled rocks than has occurred in the other Mitchell Anticline intrusions; the fresh glass may be due to a lower permiability in these border rocks.

The "lamprophyre," located at the contacts of the Hudspeth Formation with the large dike of the pink type and in included bodies in the other intrusive units, is properly named a biotite hornfels. The calcite in this unit is secondary and not usable in the naming of the rock. The biotite, quartz, and, tentatively, andalusite are common middle-grade metamorphic minerals formed in pelitic rocks; the apparent lack of feldspar precludes the rocks from the lamprophyric group of igneous rocks.

Andesite Intrusions: Other Intrusions

There are ten plugs of andesitic rock located away from the central part of the Mitchell Anticline. One of these plugs, the Cougar Gulch Intrusion, is composed of altered hornblende andesite similar to rocks of the white type Mitchell Anticline intrusions in its mineralogy and alteration. Seven of the plugs are composed of petrographically similar hornblende-bearing andesites. The other two intrusions are dissimilar to each other and to the other intrusions in the project area.

Hornblende Andesite Intrusion

The Cougar Gulch intrusion is a 600 m diameter plug at the east end of Lawson Mountain. The plug is oblong in outline. The intrusion of the plug bent up the surrounding sediments to a vertical orientation.

Hand specimens of the Cougar Gulch intrusion are a yellowish gray (5Y-7/2), and consist of plagioclase and hornblende phenocrysts in a microcrystalline groundmass. The hornblende crystals reach 1.0 cm in length, but are very thin, less than 0.5 mm wide. The hornblende phenocrysts are altered to a reddish brown. Pilotaxitic orientation of the hornblende parallels the sides of the plug.

In thin section the Cougar Gulch plug has marked similarities with the Mitchell Anticline intrusion rocks (Figure 26). The calcite alteration of the rock is less pervasive in the Cougar Gulch plug than in the Mitchell Anticline intrusions, but the devitrification of the groundmass glass is complete; the mafic minerals are replaced; and secondary silica is ubiquitous. The phenocrysts, oligoclase and replaced hornblende, have irregular borders, indicating that the plagioclase is also probably altered. The oligoclase has an anorthite content ranging from An_{14} to An_{26}, which is more albitic than the plagioclase on the Mitchell Anticline intrusions. The hornblende has been replaced by hematite, calcite, and quartz; the crystal form is still visible. The groundmass, like those of the rocks of the Mitchell Anticline intrusions, is a complexly interwoven mat of potash feldspar (?), silica, and plagioclase; the microlite outlines of the original groundmass are not visible.

Hornblende-bearing Andesite Intrusions

There are seven intrusions of chemically and petrographically similar hornblende-bearing andesite in the study area. One of these intrusions connects directly to a Bear

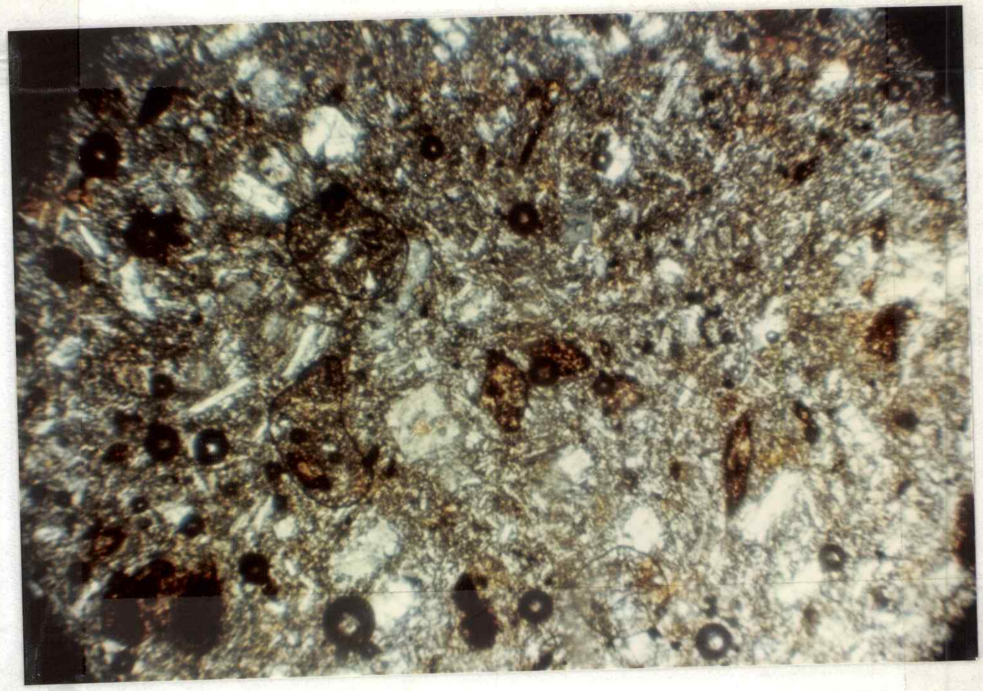

Figure 26. Hornblende andesite of the Cougar Gulch intrusion. The hornblende has been replaced by a hematite/calcite/quartz intergrowth, but the original form of the crystals remains. The other phenocryst is plagioclase in an untwinned form in many places. The groundmass consists of plagioclase, quartz, calcite, and hematite. There are bubbles on both sides of the rock slice. Width of field is 4.1 mm. Cross polarized light.

Creek Member flow. Four intrusions distort Bear Creek flows or cut the Spring Gulch rhyolite extrusion; these intrusions are Bear Creek age or younger. The other two plugs occur in the West Branch Valley and were intruded into the Ross Flat Member.

Near the north border of the project area, Stephenson Creek makes a bend to the east (boundary Sec. 23 and 24, T. 11 S., R. 19 E.); at the bend is an oblong plug which was intruded through the Bear Creek Member rhyolite flows. The plug has a maximum diameter of 400 m. The top of the plug joins a Bear Creek andesite flow of nearly identical composition. The connection does not have pyroclastic material near it; the altered andesite of the plug gradually turns into the fresher andesite of the flow. The flow is indistinguishable from the normal andesite flows of the member.

On the ridge separating Stephenson Creek from Flannery Gulch there is a small plug, which is about 70 m in diameter. The intrusion of this plug formed a bulge in the overlying Bear Creek rhyolite flows, which, stressed, have been eroded away. The flows on top of the hill to the east of the plug are not connected to it, but they may have been vented from it, for the flow rocks are petrographically similar to the rock of the plug.

Near the junction of the forks of Bear Creek, about 1.5 km northwest of the Bear Creek Ranch headquarters, there are three hornblende-bearing andesite intrusions (Figure 27). The intrusions are in a rough line, trending east-northeast. The intrusions form striking monoliths which rise up to 40 m over the surrounding area. The easternmost plug is 2.2 km long and varies between 6 and 140 m in width. The plug cuts the Spring Gulch rhyolite extrusion. The center plug is connected with the western plug by a one- to two-meter-wide dike. The center plug has been partially carved away by Bear Creek, which has formed a loop in the middle of the plug. The southern edge of this plug forms a ridge, which contains several dikes concentric to the plug. The western plug has the form of an imbricated dike system; each dike is marked by a small pair of horizontal columns. A plug of rhyolite has intruded along the north side of the western plug. Two dikes of andesite extend west from the main intrusion. The western and central plugs together are 1.6 km long. The western plug averages 100 m in width; the central plug has a maximum width of 30 m. The dike between the western and central plugs cuts an outlying piece of the Spring Gulch rhyolite flows.

There are two intrusions of hornblende-bearing andesite in the West Branch Valley. Hill 3079 and the hill to its immediate north (east border Sec. 25, T. 11 S., R. 20 E.) contain two different intrusions; Hill 3079 is composed of hornblende-bearing andesite, and the hill to the north is composed of pyroxene-phyric basaltic andesite. The form

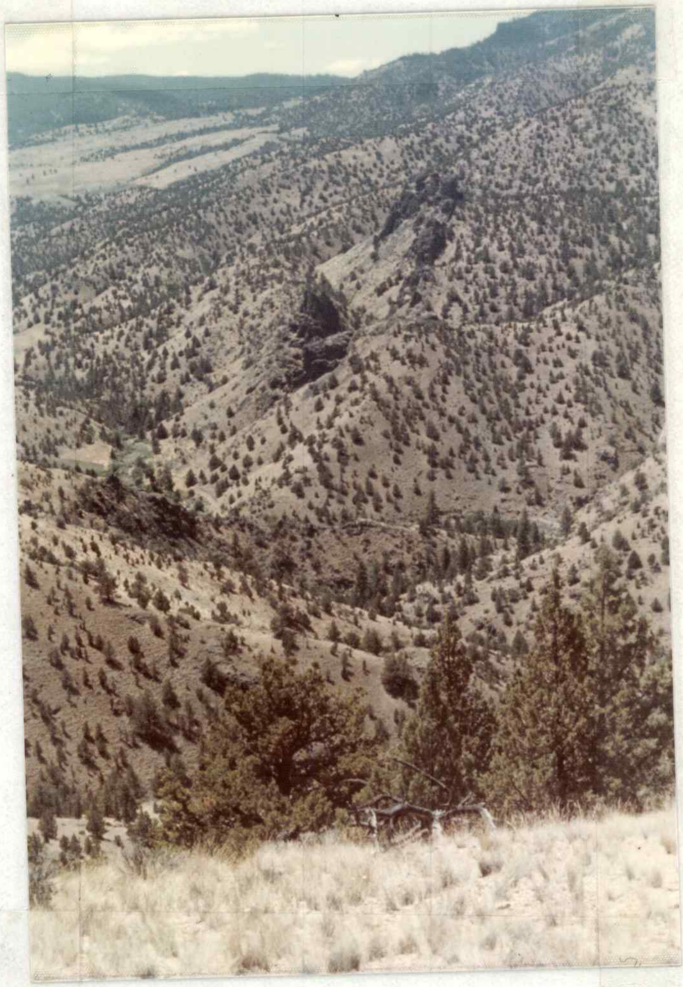

Figure 27. Western part of the junction intrusions. A part of the eastern half of the group is to the left of the central tree top. The break in slope next to the fields in the upper left marks the approximate trace of the Mitchell Fault.

of the Hill 3079 intrusion is not apparent; the upper part of the body is missing, and the relations of the bottom of the intrusion are obscured by small slumps. The body appears to be a sill. The body is 160 m wide and 50 m thick. There are several satellite plugs of identical rock in the area, and the intrusion itself has two dikes intruded around its southern half. The plug has joints at 0.5 to 1.2 m intervals.

The other hornblende-bearing andesite intrusion is located one kilometer west of Hill 3079. This intrusion is an elongate, highly altered sill. Several lobes extend through the bedding of the Ross Flat Member from the main part of the intrusion. There is a three-meter-spaced jointing parallel to the sides of the sill and a cross jointing spaced at five meter intervals.

The rocks of all seven of these intrusions are a dark to very dark gray (n-2 - N-3) where they are fresh. Alteration usually changes the color to a dark greenish gray (5GY-4/1) or a pale yellowish brown (10YR-5/2). The plug at the bend of Stephenson Creek is a pale red (5R-5/2), because the iron in it has been oxidized into hematite. Feldspar crystals are the only phenocrysts seen in the hand specimens. There are between 10 and 15 percent phenocrysts in these rocks.

Under the microscope the groundmass is very fine grained and, in most of the intrusions, composed of devitrified glass, microlites of plagioclase and pyroxene, and crystallites of magnetite. There is a size hiatus between the groundmass crystals (less than 0.1 mm) and the phenocrysts (1 to 4 mm). The phenocryst phases are plagioclase, pyroxene, hornblende, and magnetite. The plagioclase is a normally zoned to slightly oscillatory zoned labradorite (An_{56-60}) with an andesine edge (An_{46-50}). Augite and pigeonite are the pyroxenes; both types are rimmed by a brownish zone which has the same optic figure as the main part of the crystal (Figure 28). The hornblende does not have a rim and is pleochroic, faint green to faint brown. Plagioclase comprises 70 to 80 percent of the phenocrysts; hornblende forms 10 to 15 percent; clinopyroxene forms 5 to 10 percent; and magnetite forms 5 percent.

Alteration has devitrified the glass to a feldspar/silica intergrowth in most of the rocks. The plagioclase is recrystallized in some of the rocks into an unzoned, occasionally untwinned, andesine. Calcite, chlorite, and chlorophaeite/saponite replace the mafic minerals in the more highly altered plugs. The Hill 3079 sill and the Stephenson Creek - Flannery Gulch plug are composed of the freshest rock; the Bear Creek junction intrusions and the large sill in the West Branch Valley are the most altered intrusions. The compositions of these rocks are shown in analyses VB-I, JT-4, BUR-3, DR-2, and HWB-1 (appendices).

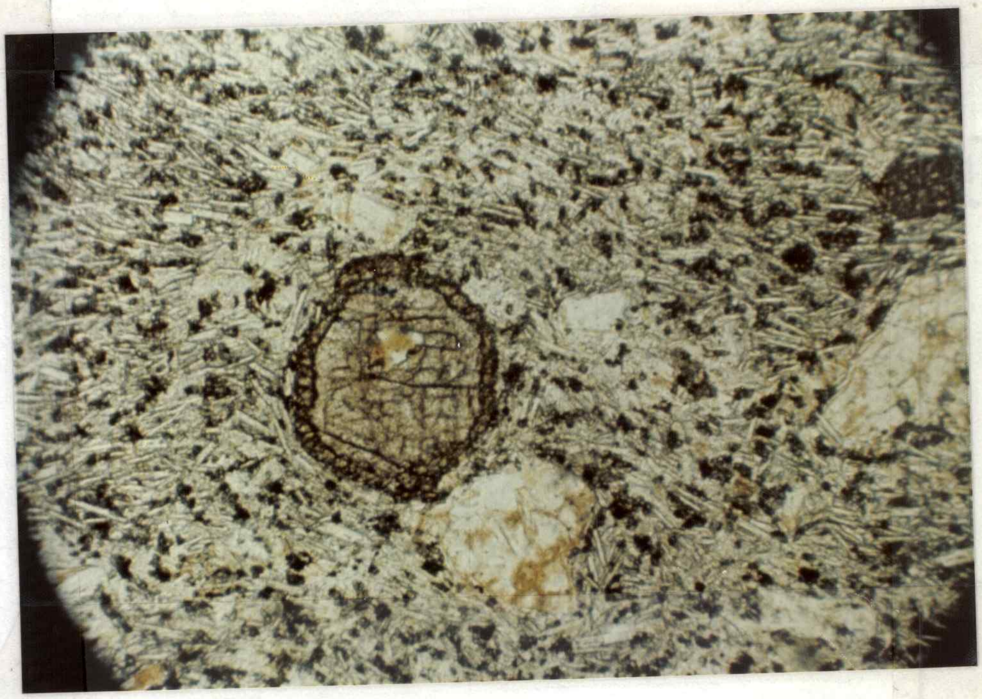

Figure 28. Rimmed augite in the hornblende-bearing andesite of the western junction intrusion. By its interference figure the rim is composed of pyroxene of the same composition as that of the main part of the crystal. Often the orientation is also the same. Altered plagioclase comprises the other phenocrysts; the groundmass is composed of plagioclase, augite, and magnetite in devitrified glass. This mineralogy and texture is found in all the hornblende-bearing andesite intrusions. Width of field is 1.3 mm. Plane polarized light.

Altered Pyroxene-phyric Basaltic Andesite Intrusion

To the north of Hill 3079 about 0.1 km there is a 300 m by 600 m plug of basaltic andesite which has been bisected by the West Branch Creek. The plug forms a 130 m high butte; as exposed by the creek, the intrusion is fan-shaped. Columnar jointing, aligned perpendicular to the edges of the dikes in a braided dike system, is spectacularly developed in the plug (Figure 29). The basaltic andesite of the plug is similar to the basaltic andesites of the western part of the project area, but flows of basaltic andesite are not found near the plug (cf. analyses HWY-2 and R-2, appendices).

The rock of the plug is a medium dark gray (N-4), and contains one-millimeter phenocrysts of altered pyroxene. Under the microscope the rock consists of moderately altered augite and pigeonite in a coarse groundmass of pilotaxitic labradorite (An_{54-60}) (Figure 30). The mode of the rock is 60 percent plagioclase, 20 percent pyroxene, 15 percent altered glass, and 5 percent magnetite. Much of the pyroxene is altered to chlorophaeite and calcite; the plagioclase contains irregular replacement bodies of calcite. The glass is devitrified into a sub-microscopic mat of faintly birefringent crystals.

Porphyritic Hornblende Andesite Intrusion

A small plug of porphyritic hornblende andesite forms a butte one kilometer west-southwest of the summit of Lawson

Figure 29. Double intrusion at the east edge of the study area. Hill 3079 is the butte to the right of the plug. Hill 3079 is composed of hornblende-bearing andesite; the butte in the foreground is composed of pyroxene-phyric basaltic andesite. The staircase appearance of the foreground butte is caused by columnar jointing.

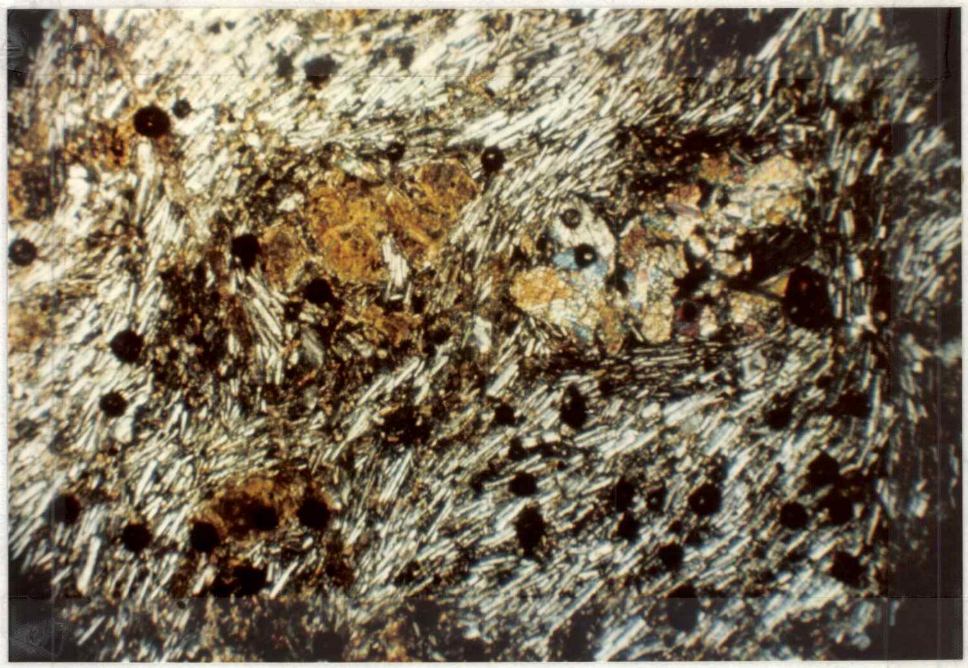

Figure 30. Pyroxene-phyric basaltic andesite of the Hill 3079 plug. Phenocrysts of augite and pigeonite, some altered to chlorophaeite and calcite, rest in a groundmass of pilotaxitic plagioclase, augite, magnetite, and devitrified glass. The round, black objects are bubbles; the shaped, black objects are magnetite. Width of field is 4.1 mm. Cross polarized light.

Mountain. The plug is oval with diameters 140 m and 80 m. There is a rectilinear jointing on an interval of 10 to 15 cm. Although the andesite of the Ross Flat plug is modally unlike the flows of the study area because of the concentration of its phenocrysts, the intrusion has chemical similarities with both the hornblende-bearing andesite intrusions and the pyroxene-phyric basaltic andesite intrusion (analyses RFI-1 vs. HWY-2, VB-I, HWB-1; appendices).

The fresh rock of the Ross Flat plug is a dark brownish gray (5YR-3/1), which weathers to a dark yellowish brown (10YR-4/2). The rock contains 35 percent phenocrysts; the minerals present are labradorite (An_{52-60}), augite, hornblende, and magnetite. The labradorite has oscillatory zoning, and the augites are surrounded by a brownish rim as is typical of the andesitic rocks of the area. The hornblende crystals are the largest phenocrysts with a maximum size of five millimeters; the rest of the phenocrysts are about three millimeters across. The groundmass is composed of dark brown glass which contains 25 percent microlites of labradorite and augite. The rock is very fresh compared to the typical rocks of the study area; the glass is still isotropic, and the rock contains less than one percent calcite overall.

Silicic Intrusions

There are three silicic intrusive groups in the study area: a large dacite sill which comprises Lawson Mountain, a quartz-bearing rhyolite plug to the southwest of Sheep Mountain, and seven rhyolite dikes and a rhyolite plug on the southeast side of Stephenson Mountain. The Lawson Mountain sill was intruded before the movements of the Mitchell Fault, which places this unit in the time period of the Clarno Formation. The other two intrusive groups are very late events of the Clarno Formation or possibly very early events of the John Day Formation.

Lawson Mountain Sill

The Lawson Mountain sill is 2.0 km long, 0.5 km wide, and, originally, more than 120 m thick. The northern edge of the sill abuts the Mitchell Fault zone; beneath the sill around its southern edge lies a unit of andesite flows tentatively placed with the Stephenson Mountain Member. The top of the intrusion has been removed by erosion.

The sill is chemically similar to a plug in the Mitchell Quadrangle (NW¼ of NW¼, Sec. 28, T. 11 S., R. 21 E.; analysis EMT-59 *vs*. EMT-73, appendices). The distance which these two intrusions are offset along the fault zone nearly matches the amount of displacement indicated by the Ross Flat sediments, which indicates that the Lawson Mountain sill was probably intruded prior to the movements on the fault zone.

The Lawson Mountain sill lies concordantly upon some andesite flows. Because the flows lie conformably upon the West Branch ignimbrite of the Ross Flat Member, these flows are placed with the Stephenson Mountain Member. The unit of flows is 20 to 25 m thick under the entire length of the Lawson Mountain sill.

The sill shows well developed columnar jointing in most of its outcrops. The ridge line of Lawson Mountain divides the columns into two groups which dip away from each other. The average width of the columns is 20 cm; the maximum width is 45 cm. The jointing can be traced in places through the depth of the intrusion with little change in orientation.

The rock of the sill contains three percent phenocrysts in a medium gray (N-5), glassy groundmass. Weathered surfaces vary in color from light gray (N-7), to pale reds (10YR-6/3) and light browns (5YR-5/6).

Under the microscope the rock is a mass of devitrified glass which contains phenocrysts of andesine (An_{34-36}), orthoclase, and altered hornblende (?). The groundmass contains few ghosts of plagioclase microlites, but it contains many relicts of hornblende. Alteration has transformed the mafic minerals into hematite and chlorophaeite/saponite. In some places the rock of the sill has been brecciated and the cracks filled with silica.

The Lawson Mountain sill may actually be an extrusive dome or flow. The unit is here called a sill because the columnar jointing is so well developed on such a fine scale, and because the sill lies concordantly upon the lava unit beneath it, unlike the other silicic extrusive units in the area. If the Lawson Mountain unit were extrusive, it would be the earliest silicic lava produced in the study area.

Plug Southwest of Sheep Mountain

The plug to the southwest of Sheep Mountain is a 0.8-km-diameter, circular body. Spring Gulch is deflected 0.3 km east by the southern border of the intrusion and has a smaller deviation at the north edge. The plug forms a 90-m-high butte.

The plug is zoned concentrically. Surrounding the intrusion, in places forming a 1.0- to 1.5-m-high wall, there is a glassy, dike-like, border zone which has the same phenocryst assemblage as the central part of the plug. The border zone is vertical wherever it is found. Inside the border is a weak, clay-rich zone through which the creek flows. In the center is the main part of the plug, a medium gray (N-5) rock which contains phenocrysts of quartz, orthoclase, and plagioclase.

In thin section the feldspars, orthoclase and zoned oligoclase (An_{22-28}), are in two-millimeter euhedral to subhedral crystals; the quartz crystals are in two-millimeter euhedra which are slightly corroded (Figure 31). The groundmass contains many small needles of a hematite/calcite replacement of hornblende and rarer laths of plagioclase in a matrix of devitrified glass. The rock of the border zone is similar to that of the central part, but the groundmass is less devitrified, and the rock contains minor amounts of chlorite.

On the southeast side of the plug an altered body of andesite is exposed. The jointing of the andesite and its contacts are oriented parallel to those of the other flows around the plug. The andesite has been altered to a grayish orange (7YR-7/4). The andesite body has pilotaxitic plagioclase (andesine, An_{34}, unzoned) phenocrysts and microlites. The groundmass is devitrified and recrystallized into relatively large blebs (0.1 mm maximum). There is much disseminated hematite and chlorophaeite/saponite; primary mafic silicates were not found.

Stephenson Mountain Intrusions

There are seven rhyolite dikes and one rhyolite plug exposed on the southeast side of Stephenson Mountain. With the exception of a small northwest-trending dike near the bend plug on Stephenson Creek, the dikes all trend to the northeast. The dikes range up to 3.2 km in length and vary from 1.0 to 45 m in width. The plug is a small, glassy body intruded into the western Bear Creek junction

Figure 31. Quartz phenocryst in the rhyolite plug to the southwest of Sheep Mountain. The crystal, though coroded, has retained a prismatic shape, viewed end on. There are a few holes in the section at the lower right. Crystallites of hematite after hornblende are visible to the left of the quartz crystal. Width of field is 4.1 mm. Cross polarized light.

intrusion. The dikes often branch; a common source for the group seems probable.

The slopes underlain by the dikes are a pale orange or a pinkish white (5YR-10YR - 6/2) which contrasts strongly with the dusky browns and moderate browns of the andesite flows (Figure 32). The fresh surface colors of the rhyolite range from black (N-1) in the vitrophyres and obsidians through olive greens (10Y-4/2), pale yellowish browns (10YR-6/3), and pale reddish purples (5RP-7/2) to white (N-10).

The rock types in the dikes occur in a seemingly random pattern. The thinner places in the dikes tend to be more glassy,but bodies of vitrophyre, porcellain-like glass, or vesicular rhyolite can occur anywhere. In some places vertical striations are found along the edges of the dikes where projections in the wall have left grooves in the stiff lava.

Where the dikes are porphyritic, the phenocrysts are less than 1.0 mm long. A maximum of 15 percent phenocrysts occurs in these rhyolites. Quartz, sanidine, and albite (An_{6-10}) are the minerals occurring as phenocrysts. Biotite and hornblende are very rare in the rhyolites; the few crystals of biotite found may have been secondarily formed.

The groundmass of the rhyolites is a mass of altered crystals, always comprising less than five percent of the rock, and devitrified glass, recrystallized into spherulites

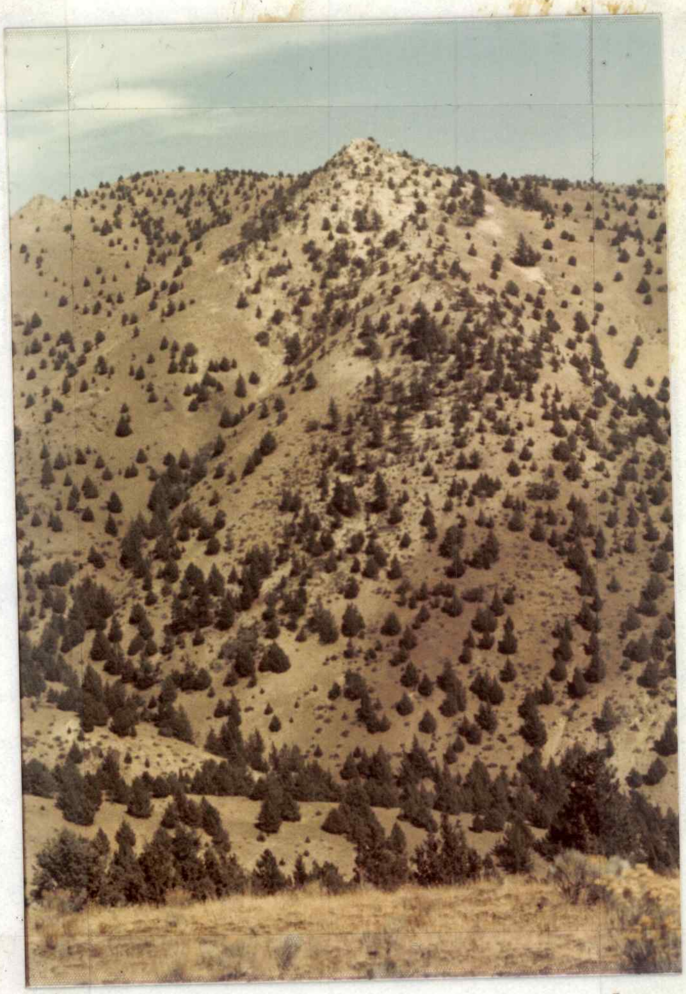

Figure 32. Dike on the east side of Flannery Gulch. The dark area at the lower right part of the hillside is some andesite flows which separate two parts of the dike. The light rock at the left edge of the skyline is a piece of the Stephenson Mountain rhyolite flows.

and minute crystals (Figure 33). Veins and blebs of quartz and small crystals of tridymite and cristobalite are common in these rocks, and these minerals show invariable on X-ray diffraction records. Hematite colors the more altered rocks.

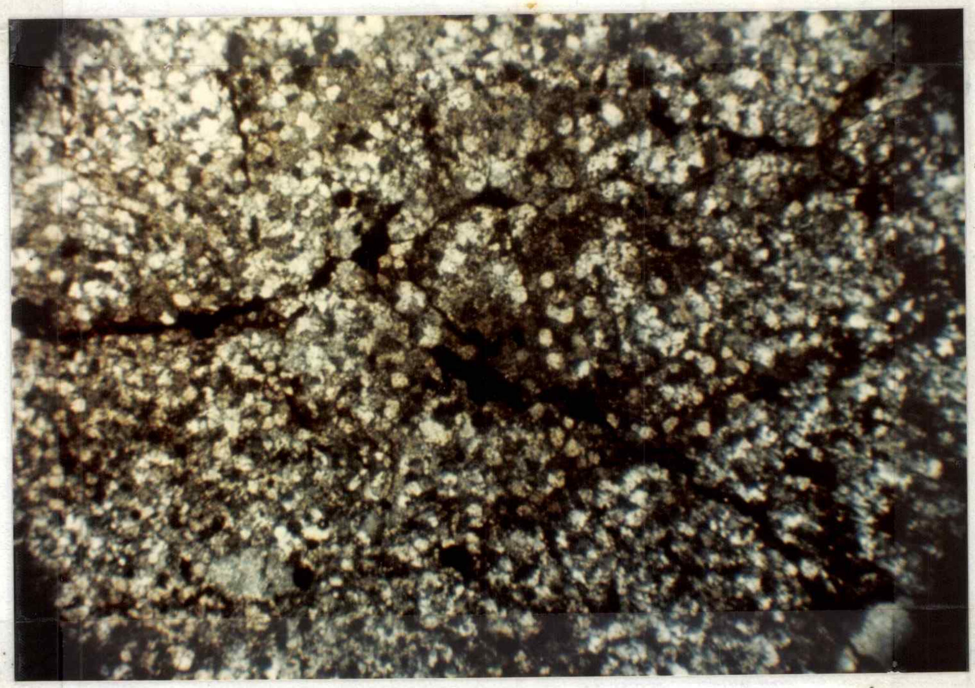

Figure 33. Rhyolite from a Stephenson Mountain dike. The glass has devitrified into a polygonal texture indicative of secondary recrystallization processes. The mineralogy is quartz, orthoclase, and albitic plagioclase. There is some hematite visible in minor veins. Width of field is 4.1 mm. Cross polarized light.

IV. CHEMICAL VARIATION

Chemical analyses are the primary method by which volcanic rocks can be compared with one another. Variations in the cooling history and the mode of emplacement of the rocks can make petrographic comparisons of lavas and intrusions unreliable, primarily because of chilling and differing partial pressures of water and oxygen. The main use of petrography in the naming of rocks is in the assigning of varietal names. By chemical analyses volcanic rocks can be placed into groups based upon the composition of the material as it was emplaced, before the near-surface changes in the cooling chemistry had their effects. However, post-cooling alteration of volcanic rocks causes changes in the compositions which are difficult to interpret.

The basic difficulty which alteration causes lies in the type of data which the analysis provides. Analyses are commonly presented in the form of weight percentages of the major element oxides. Because the percentages must add up to approximately one hundred, a change in the amount of any one component causes an opposite change in all the others. The addition of major amounts of a component which is not normally analyzed causes an incomplete analysis; the addition of carbonate, sulfide, and hydrate are the most common examples of this. The problem of changing components is alleviated by analyzing large numbers of rocks and comparing them on variation diagrams. A second problem caused by shifting components occurs because differences in the gram molecular weights of the oxides bias the changes in favor of the heavier elements; if Na_2O is replaced by K_2O, the analysis will gain potash at the expense of the other components, because the potash weighs approximately 1.5 times as much as the soda. Conversion of weight percent analyses to molecular percentages is a seldom used method of removing the weight bias.

If few elements were involved, the effects of alteration could be easily determined; in volcanic rocks alteration involves all the major oxides, carbon dioxide, water, the oxidation potential, the acidity, and occasionally sulfides. As a result, the course of alteration is almost impossible to predict from a chemical analysis.

The only effective method of producing chemical analyses which portrays the emplacement composition of the lava is to analyze the least altered rocks available. The examination of a rock in thin section yields the information most readily; low levels of alteration are easily missed by macroscopic inspection or chemical tests. In general, devitrification of the groundmass glass indicates that alteration has occurred, even if the crystalline part of the rock does not show changes. Changes in the crystals indicate a more advanced stage of alteration; normally the pyroxenes and the calcic centers of the plagioclase phenocrysts show the alteration first. The rocks with altered crystals are usually more altered than is desirable for analyses. In the project area, however, there are very few rocks which are not altered beyond this criterion. The least altered specimens consistent with widest variety of petrographic types and a few more altered rocks were analyzed for this study. The alteration of these rocks shows in the scatter of the variation diagrams (Figures 34-37), especially in the Na_2O and K_2O diagrams. The analyses which probably reflect best the emplacement composition of their lavas are VB-SW, JT-13 (Table 1), BCB-1 (Table 2), VB-V (Table 3), HWB-1 and RFI-1 (Table 6) (appendices).

The alteration of the rocks of the study area follows a pattern in its early stages. Although the amounts of the changes vary, calcium, magnesium, sodium, and potassium are removed from the rocks and the amount of silica is increased. Petrographically these changes are shown by the devitrification of the glass. Further alteration may follow many different paths, which are dependent upon the composition of the lava and the environment in which it lies. The alkalies and calcium are very mobile, but they tend to be enriched in as many rocks as they are depleted, and they seem to be changed only locally. Iron is mobile in its reduced state; ferric iron tends to be concentrated. Magnesium tends to be removed from all types of rocks.

Aluminum and titanium are seldom affected by alteration; the differences in their amounts are the result of changes in the amounts of the other components. The alteration involving silica appears related to the composition of the original rock; silica is gained in rocks with more than 58 percent silica and, on little evidence, is lost in rocks with less silica. An indicator of the changes in the amount of silica is the iron - magnesium index (FeO/FeO+MgO) of Wager and Deer (1959), which parallels the changes. This index is useless above approximately 70 percent silica, because the magnesium is present in very small amounts relative to iron. The parallelism is probably caused by a similarity in the conditions which deposit or remove silica and the conditions which remove magnesium or remove iron.

Variations of the Major Elements Relative To Silica

The Harker diagrams (Figures 34-37) show that the andesites and silicic rocks of the project area follow a single trend line. The biotite hornfels does not fit these lines (silica percentage 44.5, the farthest left point on the diagram), especially in the TiO_2, K_2O, and Al_2O_3 diagrams. The two basaltic rocks (analyses CG-DI and USG-1, appendices) do not fit as well as the other rocks, but these rocks are altered enough to make these variances reasonable.

A plot of CaO and total alkalies against SiO_2 shows the SiO_2 percentage at which the CaO and total alkalies are equal, which is called the Peacock index (Figure 37a). The Peacock index of the rocks of the project area is 63, which places the rocks in the calcic rock series (Peacock, 1931). If the field boundaries of Kuno (1966) are placed on this diagram, the plot of the total alkalies lies on the boundary of the high alumina series and the tholeitic series.

The triangular alkalies - iron - magnesium diagram of Wager and Deer (1939) (Figure 38) shows a low amount of iron enrichment over the enrichment of the alkalies. The plots of the points are probably shifted away from the magnesium corner by alteration, which would make some of this iron enrichment secondary, but the rocks which are probably the freshest show some iron enrichment. The rocks of the modern Cascade Range, the nearest similar body of rocks, do not show this iron enrichment (Williams, 1942; Rollins, 1976; Dyhrman, 1976; Nockolds, 1954).

Concerning the analyses themselves (in the appendices), the rocks of the study area have some traits which are also characteristic of the high alumina series. The titania content of these rocks (Figure 34a) is about constant at 1.00 to 1.10 weight percent in the andesites and less silicic rocks; the content is never greater than 1.25 weight percent. In the rocks with more than 65 weight percent silica, the TiO_2 content decreases with the increase of silica. A low titania content is a characteristic of volcanic rocks found behind convergent plate boundaries (Pearce, 1976). The alumina content (Figure 37b) of the rocks of the study area ranges from about 16 to 18 weight percent, an amount which is higher than that found in andesitic rocks from non-subduction regimes (Carmichael, *et al.*, 1974). The alumina trend also changes, at about 65 weight percent, to a decreasing line.

Variation of the Amounts of Lavas Relative to Silica

Andesite with a silica content of 58 to 65 weight percent comprises volumetrically the majority of the lavas and intrusions in the project area. Probably 90 percent of the Stephenson Mountain Member, 60 percent of the Bear Creek Member, and 75 percent of all the volcanic rocks in the project area are composed of this rock type. Basaltic andesites, rocks with between 53 and 58 percent SiO_2, comprise the remaining 10 percent of the Stephenson Mountain Member, 30 percent of the Bear Creek Member, and 13 percent overall. Silicic rocks containing more than 65 percent silica account for 10 percent of the Bear Creek Member and 12 percent of the whole area. Basaltic rocks constitute less than one percent of the rocks in the study area. This predominance of andesitic material is a common feature of the volcanics found behind convergent plate margins; the abundance of silicic material indicates that upper crustal material probably was assimilated by the magma generation system and erupted both as homogenous mixtures and as discrete lavas (Carmichael, *et al.*, 1974), although rubidium - strontium isotopic data would be necessary to demontrate this.

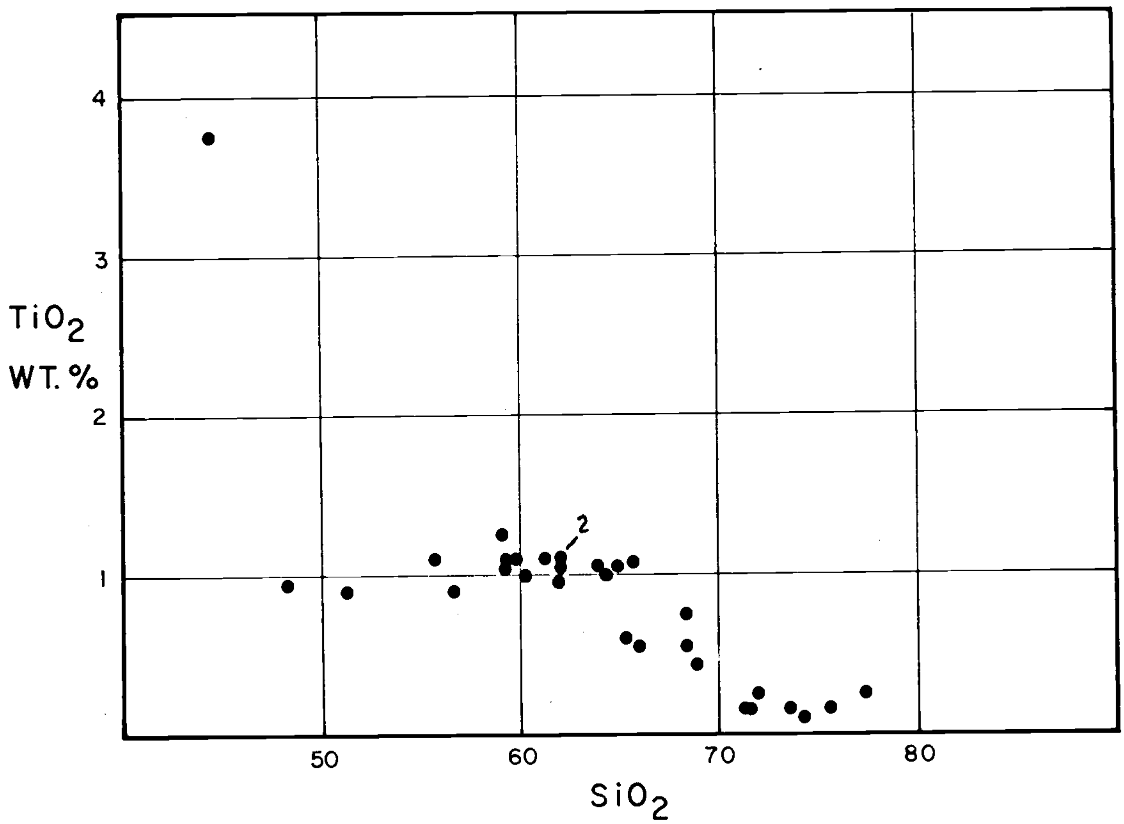

Figure 34a. Harker diagram of titania.

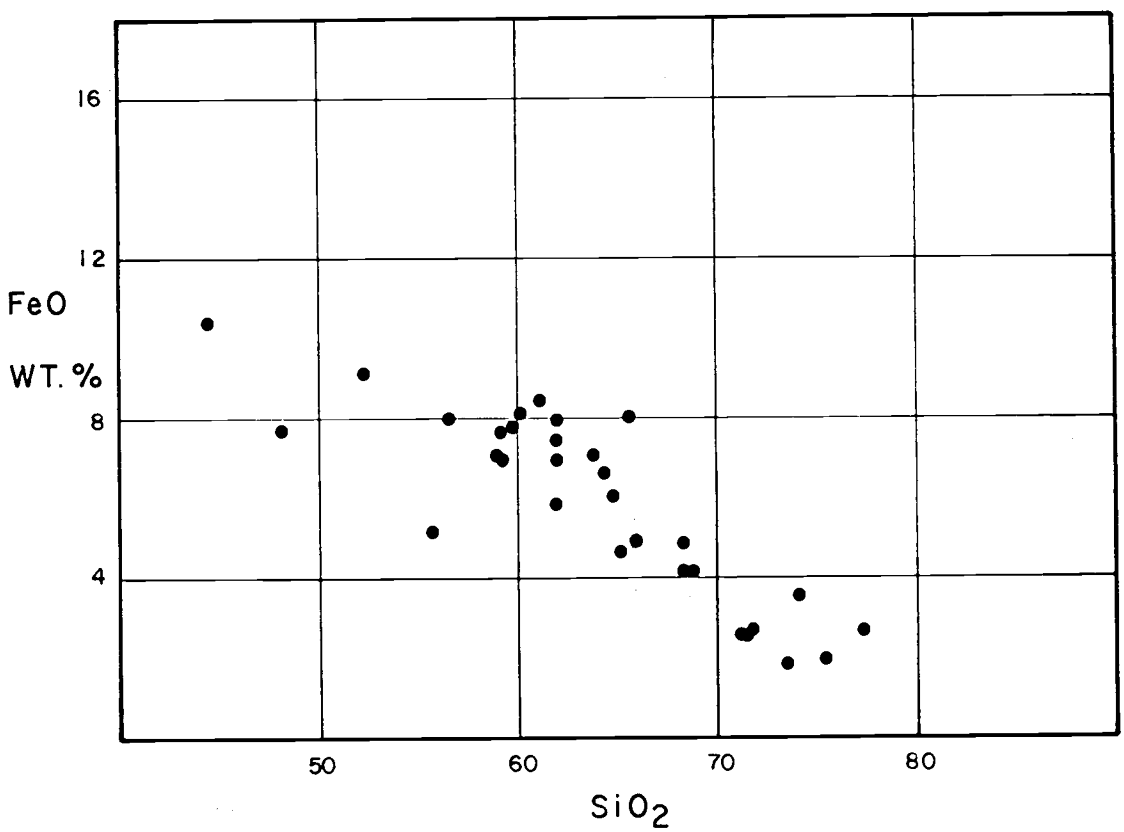

Figure 34b. Harker diagram of total iron.

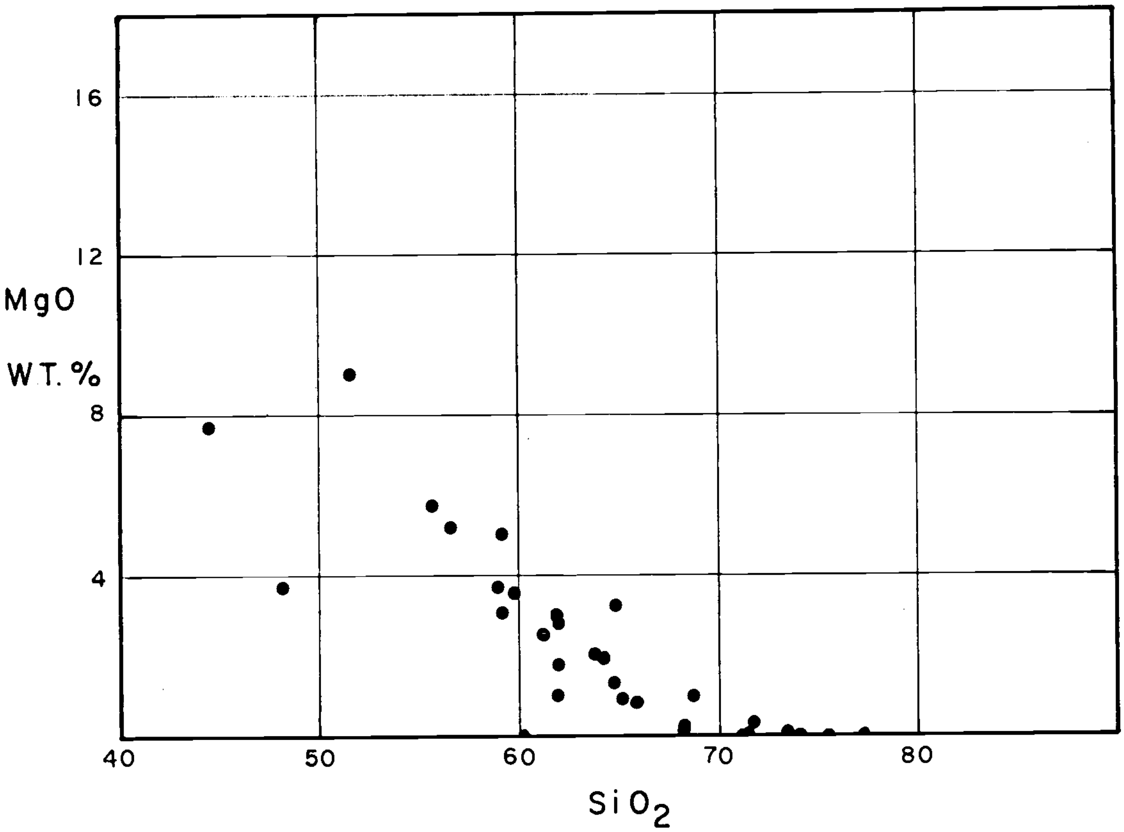

Figure 35a. Harker diagram of magnesia.

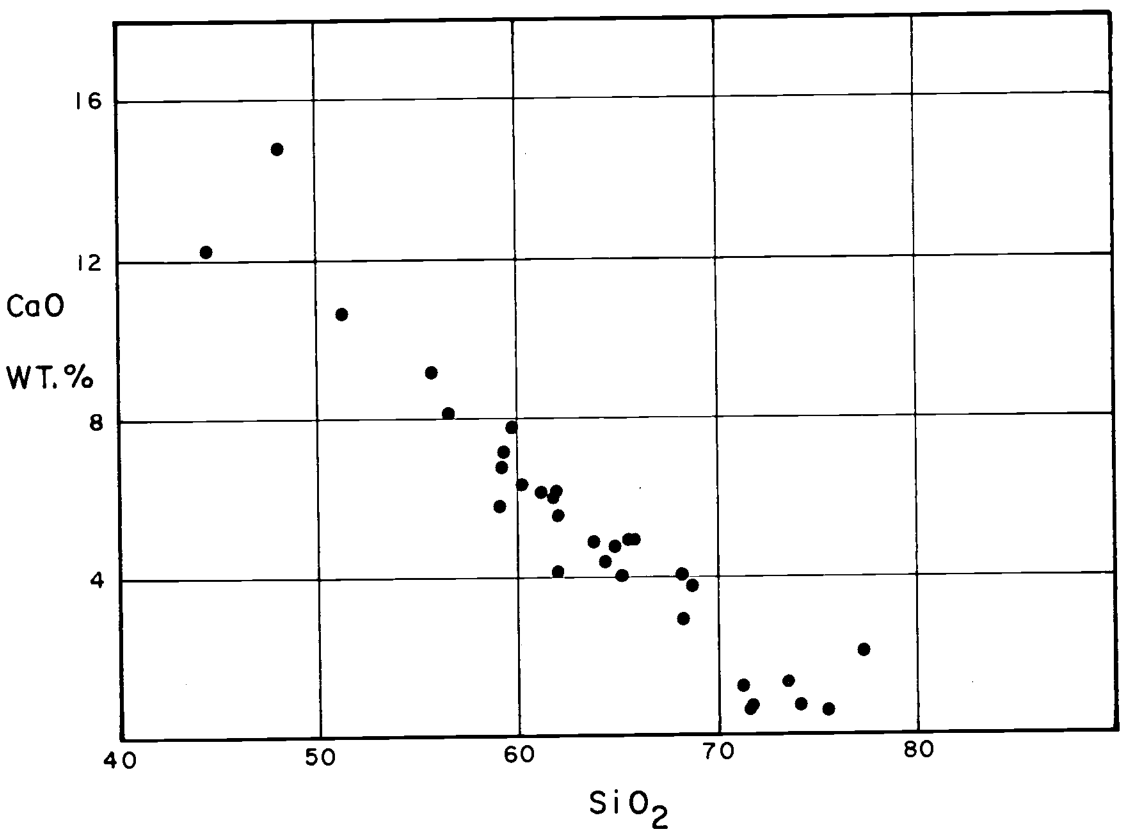

Figure 35b. Harker diagram of lime.

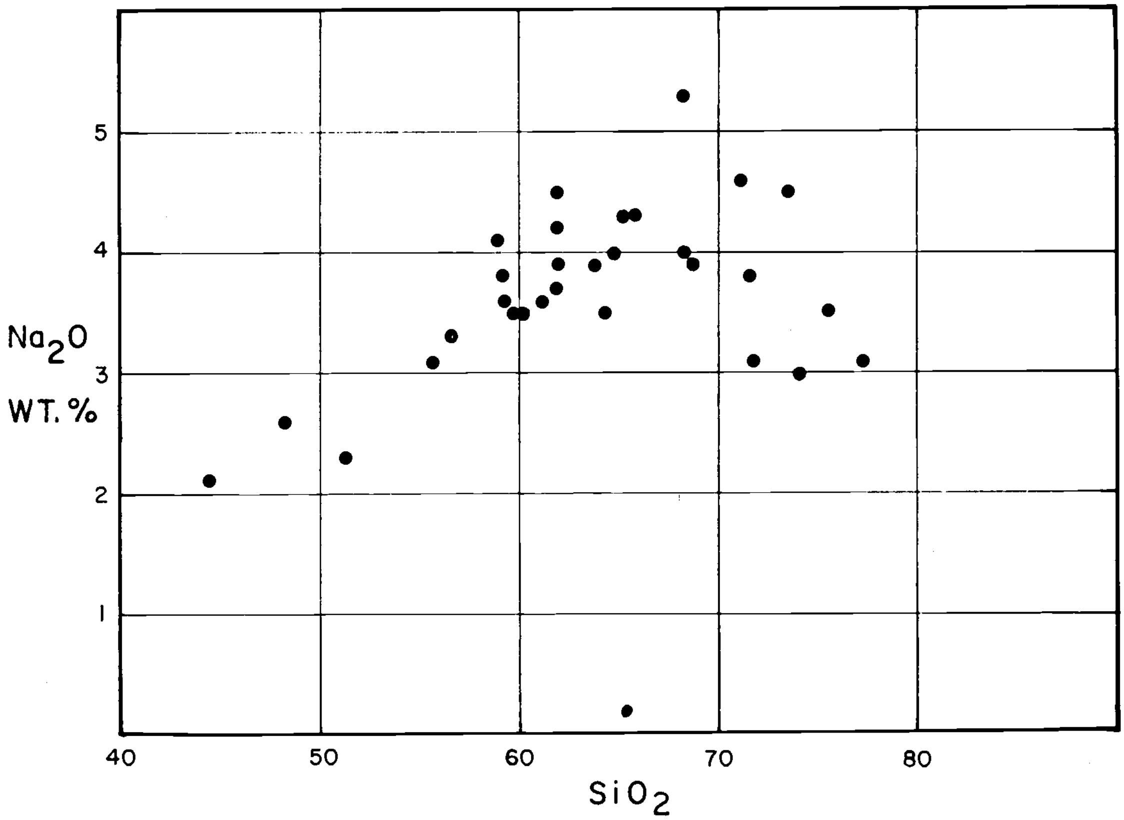

Figure 36a. Harker diagram of soda.

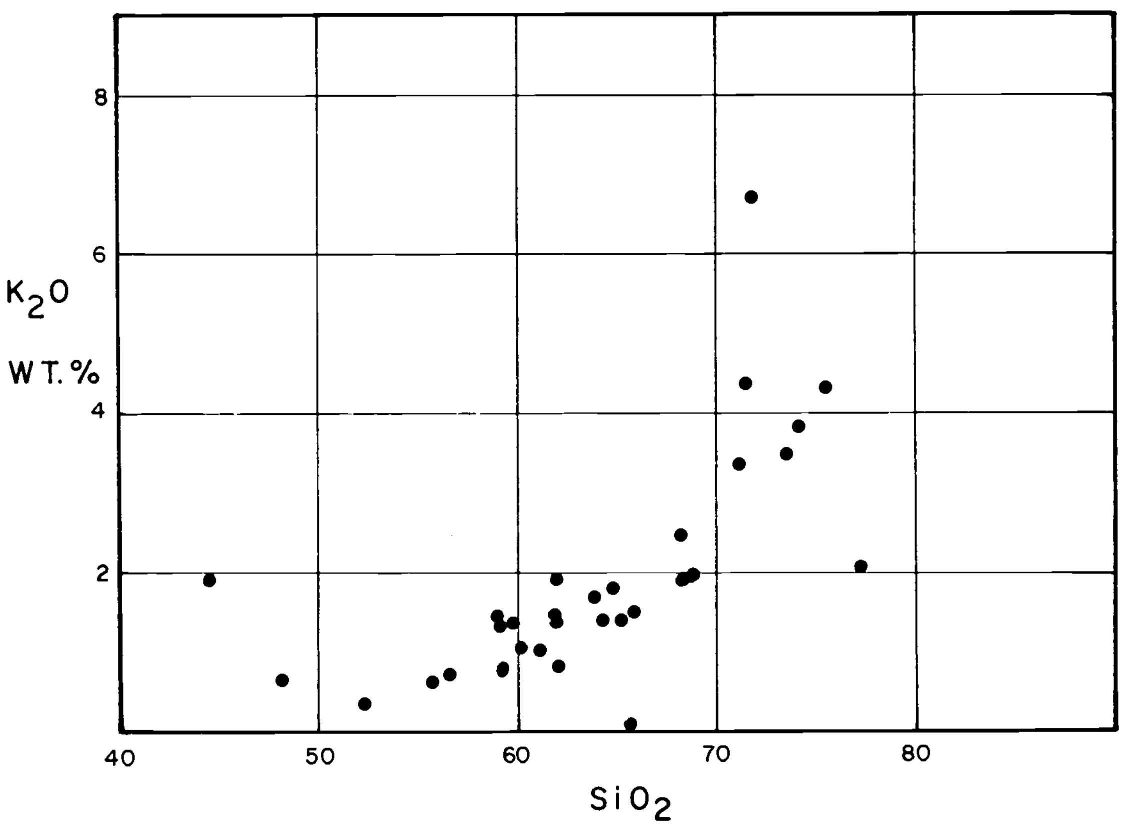

Figure 36b. Harker diagram of potash.

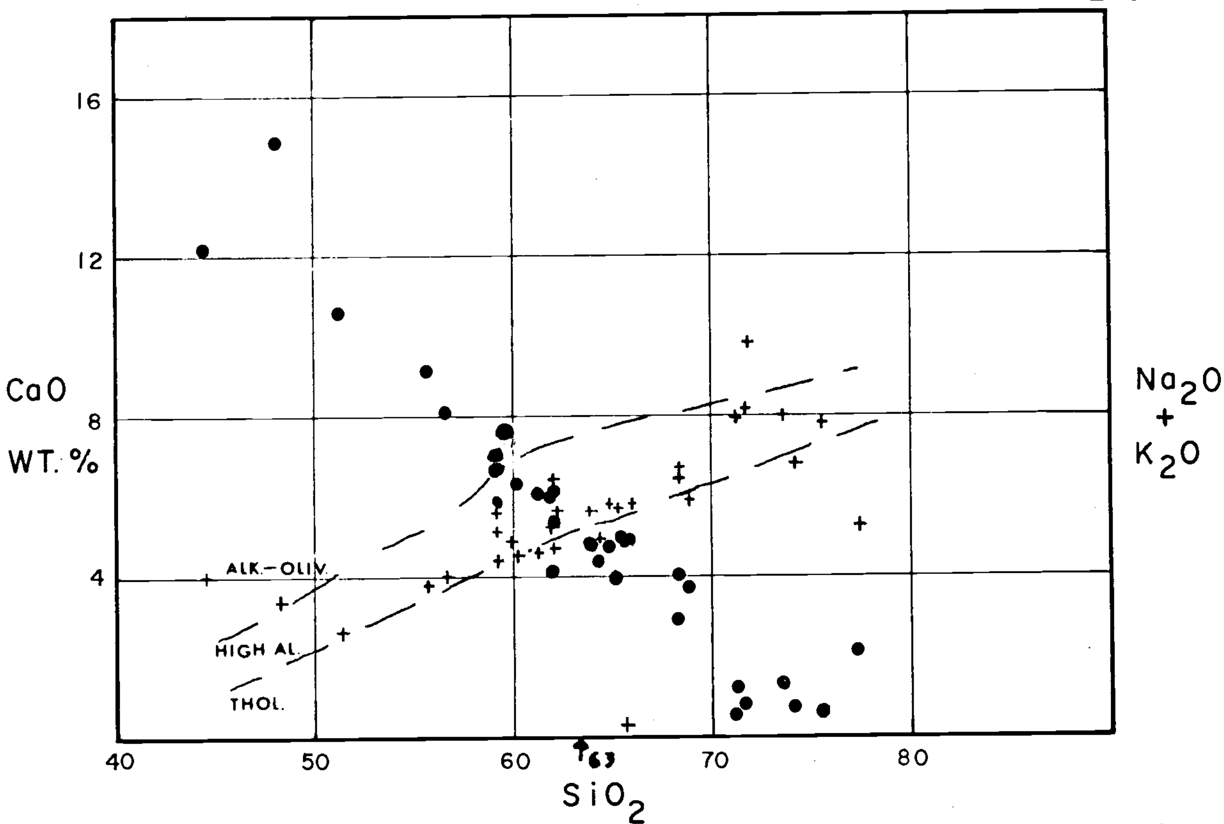

Figure 37a. Peacock index diagram with Kuno (1961) boundaries.

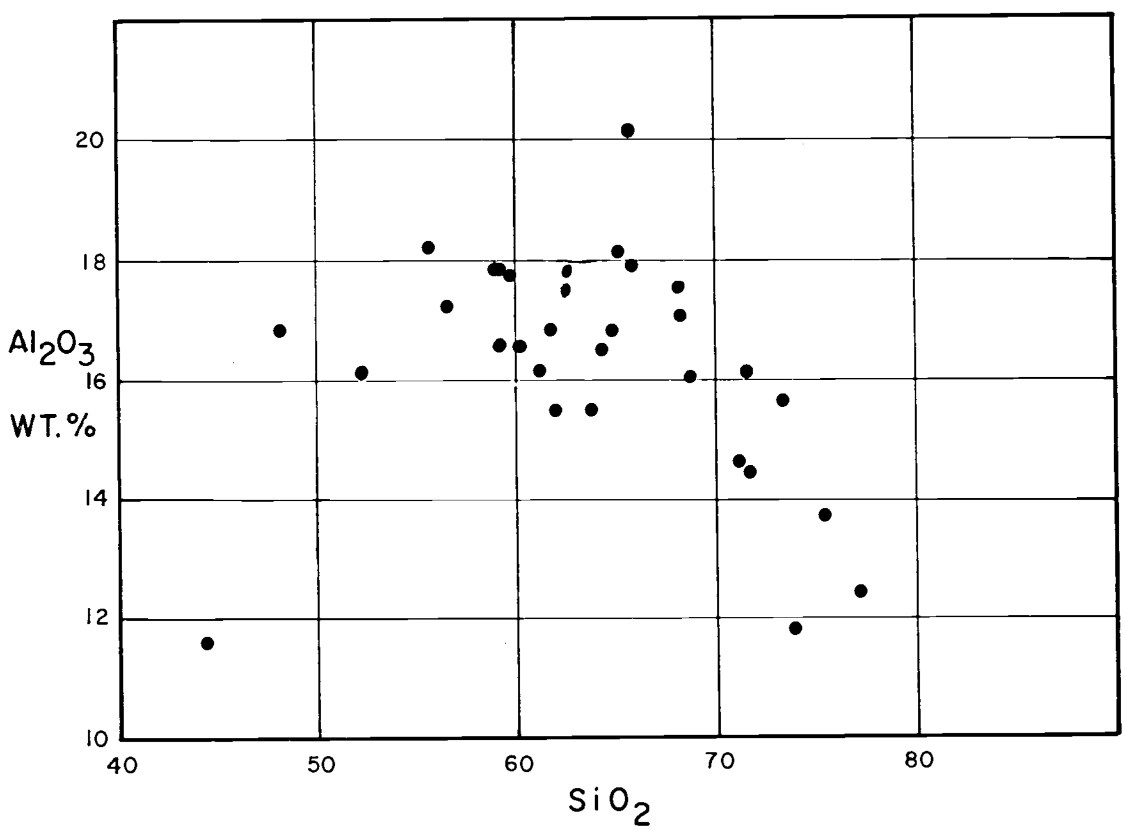

Figure 37b. Harker diagram of alumina.

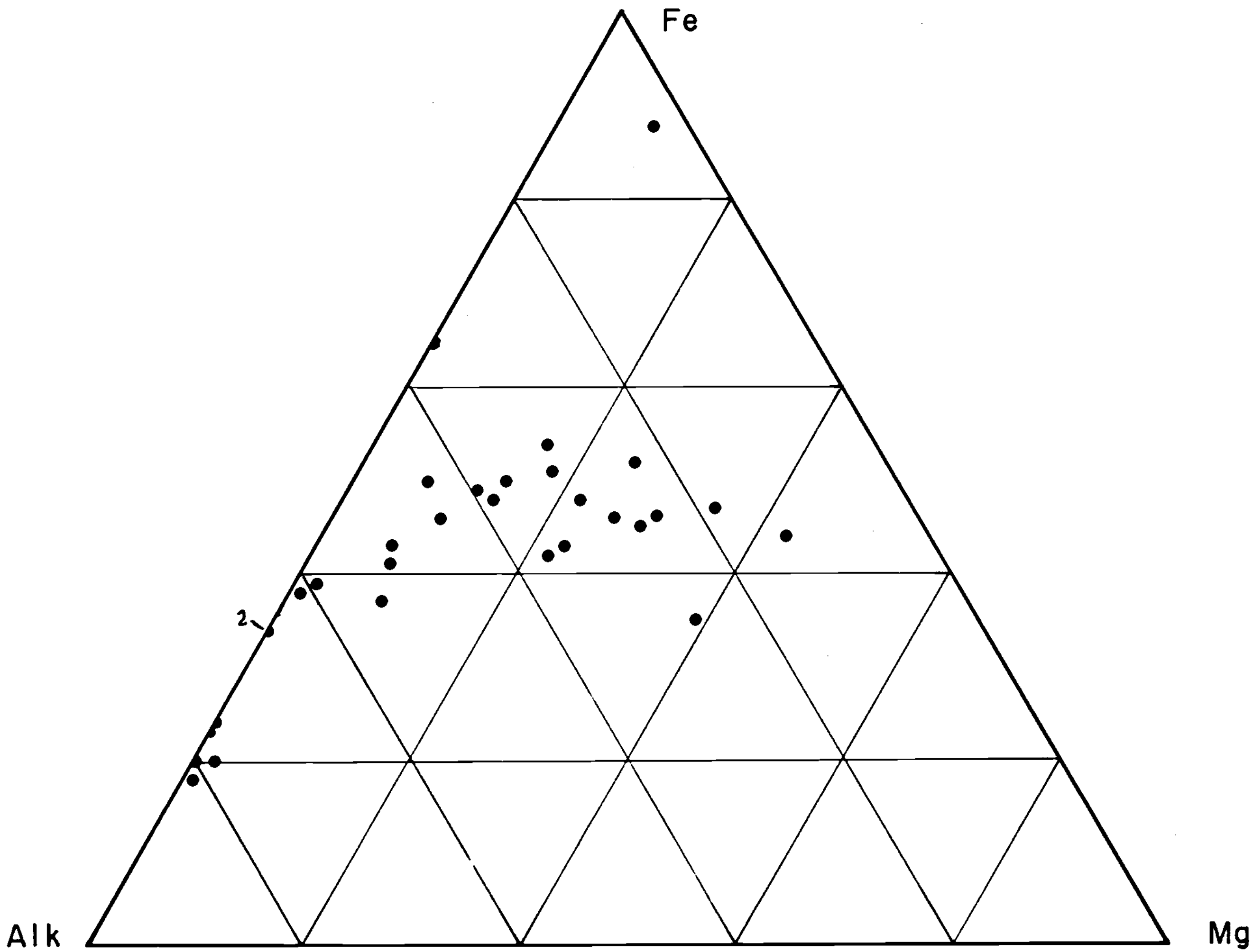

Figure 38. A'FM diagram showing low iron enrichment.

V. STRUCTURE

The rocks of the project area have been deformed by the large-scale folding of the Mitchell Anticline and the Sutton Mountain Syncline, and by the movements on the Mitchell Fault and its subsidiaries. There is one fold, in the West Branch Valley, which is probably cogenetic with faulting in the Sargent Butte area in the Mitchell Quadrangle (Oles and Enlows, 1971); this faulting may be the result of stresses generated by the Mitchell Fault or, possibly, the Richmond Fault of Fisher (1967). Slumping has created some areas of apparent faulting, but these "faults" do not have structural significance and cannot be traced away from the slumps.

Folds

Because lava flows tend to have large initial dips, the strikes and dips shown on the lava units of the map (Plate 1) show a distorted picture of the folding in the project area. Reliable indicators of the initial dips were not found in the lavas; flow to the northwest is indicated by the narrow width of the majority of the Stephenson Mountain Member flows in the outcrops which cut across this direction. The direction of slope indicated by the Ross Flat sediments is downward to the northwest. If the 46 m.y. radiometric date of the White Butte intrusion (Enlows and Parker, 1972) shows that the Mitchell Anticline intrusions are nearly equivalent in age to the Stephenson Mountain Member lavas, the vents over these intrusions would be the most probable local source of the flows. The present dips of the Stephenson Mountain Member flows would thus be the sum of the initial dips of the flows and the inclination from the folding of the area; the folding indicated by the dips of the flows would plunge irregularly or would have an axial surface that was anomalously bent and tilted. The Bear Creek Member lavas, having different source vents, would have a primary divergence from the orientation of the lavas of the Stephenson Mountain Member and a different component of inclination from the folding. These components in the dips could not be resolved for either member other than in a relative sense; the changing dip of the Bear Creek rhyolite flows, for example, probably reflects changes in the slope of their course, but the tilting of the whole area cannot be resolved from these dips.

Sutton Mountain Syncline and West Branch Monocline

The Sutton Mountain Syncline is the main structure found north of the Mitchell Fault. The axial trace of this fold trends east-northeast from the summit of Stephenson Mountain to the north border of the study area approximately one kilometer west of Bear Creek, in the middle of Section 19, T. 11 S., R. 20 E. the fold shows an apparent plunge to the east-northeast; the amount of plunge varies from about

3° at the summit of Stephenson Mountain to about 25° in the Stephenson Creek Valley. On the southeast limb of the syncline, transitional to the Mitchell Anticline six kilometers to the east of the study area, the flows have a maximum dip of 36°, except where they are affected by the West Branch Monocline.

The West Branch Monocline is a northeast-trending flexure which has its zone of maximum dip on the north side of the West Branch Valley. This fold occurs between the Mitchell Fault and Sargent Butte, which is three kilometers east of the northeast corner of the study area. There is a suggestion of faulting along the West Branch Valley, because the Ross Flat Member plots anomalously too thick in cross sections of the valley; physical evidence for faulting was not found, and the folding and alluvial cover precluded accurate measurement of the section across the valley floor. The presence of this monocline only between the Mitchell Fault and Sargent Butte suggests that this flexure was formed as a secondary feature of the Mitchell Fault; however, Oles and Enlows (1971) show that another major fault, named the Richmond Fault by Fisher (1967), runs to Sargent Butte from the northeast, and this fault may have had some effect on the monocline.

Mitchell Anticline and Related Folds

To the south of the Mitchell Fault, the rock units have been bent into several folds within the study area; the anticlinal axial traces are located in the Gage Creek Valley west of Black Butte, on Doolittle Flat, on the west side of Spring Gulch, and on the western side of the Dodds Creek Valley. Synclines occur between the anticlines, but will not be discussed here. The axial traces of these folds trend north-northeast to northeast. The amplitude of the folding decreases away from the Mitchell Fault zone; the folds between the east side of the Gage Creek Anticline and the west side of the Spring Gulch Anticline cannot be traced much to the south of the study area (Swarbrick, 1953; Wilkinson and Oles, 1968). The Dodds Creek Anticline may also die out south of the project area, for it comes very difficult to locate the fold at the south border of the area.

The axial trace of the Gage Creek Anticline trends north-northeast from the south border of the study area, at the middle of Section 2, T. 12 S., R. 20 E., to the north end of the plugs at Black Butte, where the trace bends to a northeasterly direction and is thence traced to the Mitchell Fault. There is some uncertainty about the form of the fold and the position of the axial trace because the mudstones of the Hudspeth Formation do not show the structure; the form must be deduced from the Gable Creek strata and the Mitchell Anticline instrusions. The strata and the instrusions dip more steeply near the fault than at the south border of the study area, and the intrusions veer to the northeast near the fault zone, probably because of dragging of the units by the movement on the fault.

The axial trace of the Doolittle Flat Anticline runs from the southwest corner of Section 4, T. 12 S., R. 20 E., approximately northeast to Lawson Mountain. The north end of this anticline and the syncline to its east were deformed by the intrusion of the Cougar Gulch plug. The two vertical faults on the east side of the anticline, which have displacements of less than five meters, were probably formed as a result of this deformation, although they could possibly have formed as secondary features of the Mitchell Fault. The deformation shows primarily as a bend of the axis of the Doolittle Flat Anticline to the west and as a slight bend to the east of the axis of the syncline.

The west limb of the Spring Gulch Anticline is much wider than the east limb; in aerial photographs the Spring Gulch Anticline appears as a wrinkle in the side of the Doolittle Flat Anticline. The axial trace of the Spring Gulch Anticline runs from the southwest corner of Section 5, T. 12 S., R. 20 E., north-northeast to the Ross Flat-Bear Creek Ranch road in the middle of Section 32, T. 11 S., R. 20 E. This anticline plunges to the north-northeast slightly. Three faults cut the fold; the sharpness of the folding decreases at each fault away from the Mitchell

Fault zone. The syncline to the east of the Spring Gulch Anticline cannot be traced beyond the southernmost fault.

The axial trace of the Dodds Creek Anticline can be traced from the south border in the center of Section 2, T. 12 S., R. 19 E., north-northeast to the Mitchell Fault in Section 35, T. 11 S., R. 19 E. The thick flows of the Bear Creek Member and heavy forest growth obscure this fold near the south border of the study area; the distance to which this fold extends south of the study area was not determined. The Dodds Creek Anticline plunges (apparent plunge) to the north-northeast at 15° to 20°.

To the south of the project area, Swarbrick (1953) mapped two anticlines. One of these anticlines trends to the southwest from Doolittle Flat and is the continuation of the Doolittle Flat Anticline. The other anticline, the axial trace of which trends north-northeast down the valley of the West Branch Creek south of the study area, has a width, between equal elevations of the Gable Creek Tongue 3, of about 4.8 km, an amount equal to the curvature of the Mitchell Anticline of Oles and Enlows (1971) north of the Mitchell Fault in the Mitchell Quadrangle. This fold is considered for this reason to be the contribution of the Mitchell Anticline. The axial trace of this large-scale anticline within the study area would trend north-northeast from the south border at approximately the mid-point of Section 3, T. 12 S., R. 20 E., to the eastern side of the

Cougar Gulch intrusion. The fading of the folds nearer the fault zone into this larger fold indicates that the Mitchell Anticline was crumpled by the movements on the Mitchell Fault.

Faults

The primary fault structure of the study area is the Mitchell Fault. The other faults in the area are all considered to be secondary in their genesis to the Mitchell Fault, with the exception of the block slumps and the two faults on the east side of the Doolittle Flat Anticline. Faults are difficult to trace in the lava units; the possibility exists that the Stephenson Mountain Member contains some faults. Those boundaries of this unit which could be traced with confidence showed no faulting.

Mitchell Fault

The Mitchell Fault transects the project area from east to west in a northward convex curve. The curve is not even; most of the curvature is confined to a five kilometer section centered at Lawson Mountain. The fault slip-surface appears vertical where valleys have been cut across it, but there is a slight correspondence between topography and the deviations from linearity of the slip-surface, which indicates that the slip-surface probably dips to the south a few degrees from vertical within the study area. This tilt makes the bend of the fault appear slightly tighter; the bend was present in the fault before the tilting and was probably the result of an inhomogeneity in the stress field which formed the fault.

The fault is inconspicuous for most of its length in the area. It cuts ridges and valleys without scarps or line scarps to betray its location. In places the fault forms a shatter zone up to 50 m wide (Figure 39); these zones are often oxidized to a dark reddish brown (approximately 10R-4/2). On the south side of Stephenson Mountain, the fault zone is mineralized with cinnabar, which was mined in the 1930's (Brooks, 1963).

The fault is traced by the changes in the orientation of the strata and the change of stratigraphic units across it. From the east border of the study area to the ridges west of Ross Flat, the lithologies on the opposite sides of the fault are dissimilar and differently oriented; the fault separates the folds in the Cretaceous Formations and the Ross Flat Member from the sediments and lavas in the West Branch Monocline and the southeast limb of the Sutton Mountain Syncline. From the ridges west of Ross Flat to the west limb of the Dodds Creek Anticline, the divergence in the orientation remains, though the lithologies on either side of the fault are the same. To the west of the Dodds Creek Anticline, the orientation of the flows on either side of the fault is similar; the flows on the south side of the fault strike more northerly.

Figure 39. Shatter zone in the Mitchell Fault zone. The flows in the middle-distance ridge are cut by the Mitchell Fault in the left center. The movements on the fault have shattered the rock of the flow in an area about 50 m wide, which is here altered to a grayish color. The two buttes are the Spring Gulch rhyolite flows. The sediments of the Ross Flat Member crop out in the foreground.

If the Lawson Mountain mudflow of the Ross Flat Member is used as a piercing point through the fault zone, the Mitchell Fault has a right lateral displacement with a horizontal component of 6360 m and a vertical component of 140 m, south side up. The mudflow is a narrow unit which flowed in a fairly straight line in a northwesterly direction. Because the stratigraphic succession of the Ross Flat Member is nearly identical on either side of the fault, the two pieces of the mudflow are correlated with some confidence. The mudflow cannot be traced within 200 m of the fault zone on the north side and 100 m on the south side; the maximum amount of error in the components of the net slip is probably within 100 m horizontally and 30 m vertically.

This slip determination is reinforced by the matchup of units and structures which it provides. The nearly identical Mitchell Anticline intrusions on either side of the fault fit together; the axis of the Mitchell Anticline joins fairly closely. The boundaries of the Ross Flat and Stephenson Mountain Members of the Clarno Formation fit approximately, but the differences in orientation preclude an exact match. The Lawson Mountain sill becomes more proximate to a chemically similar plug near Sargent Butte (analyses EMT-73 and EMT-59, appendices). The folds between Black Butte and Dodds Creek on the south side of the fault do not have correlative folds on the north side, nor does the West Branch Monocline have a continuation of the south side; these missing structures are consistent with the hypothesis that these folds were fault produced. The major missing correlative unit is the Bear Creek Member flows which should occur on the north side of the fault; this body of flows must have been eroded away, or it is possible that these flows were not discerned from the similar Stephenson Mountain Member flows.

Secondary Faults of the Mitchell Fault System

There are two groups of faults which formed from adjustments to stresses created by the movements of the Mitchell Fault. Both groups diverge about 30° from the trend of the Mitchell Fault in their vicinity.

One group of faults, located on the ridge west of Spring Gulch, is composed of three eastward-trending faults, each of which has brought Gable Creek material to the surface. None of these faults can be traced to the Mitchell Fault zone, nor can they be traced to the east of Spring Gulch; the amount of displacement diminishes to the west and probably also lessens to the east from the crest of the Spring Gulch Anticline. The northern fault has been intruded by a basalt dike. The maximum amount of displacement on these faults, from north to south respectively, is approximately 30 m, 35 m, and 15 m, north side up. The components of these displacements are impossible to determine, because nothing usable as a piercing point crosses the faults; however, the crest line of the Spring Gulch Anticline is offset between five and ten meters right laterally by each of the two southern faults. The anticline cannot be traced north of the northern fault.

The other group of faults occurs on the north side of the Mitchell Fault, in the area of the southwest corner of Section 25, T. 11 S., R. 20 E. Two blocks of Cretaceous sediment have been faulted to the surface; the Ross Flat Member sediments to the south of these faults are oriented at an angle inconsistent with the West Branch Monocline. The disorientation of the rock units gives the appearance of a group of jumbled blocks. The displacements of the faults involved could not be determined because it is impossible to determine from where the blocks were torn.

Tectonic Regime

In general, the hinge line of a fold is considered to be the intermediate stress axis; the horizontal perpendicular to the hinge line, the maximum stress axis; and vertical, the minimum stress axis in a horizontal, compressive fold system. The folds in the study area fit into such a system because they are regional, which indicates non-local causes for the deformation, and they are long and narrow along their axes, which indicates that horizontal stress predominates (Hills, 1963).

The intermediate stress axes of the major folds of the study area, the Sutton Mountain Syncline and the Mitchell Anticline, are considered here to have been horizontal or nearly horizontal at the time of the formation of the folds. The present plunges of the folds are the result of the effects of the faulting, the initial dips of the units, and the overprinting of two fold systems.

There are two separate fold systems in the Mitchell region. Oles and Enlows (1971) point out that the Sutton Mountain Syncline, which trends approximately east-northeast in the Mitchell Quadrangle, is paralleled by another syncline in the southeast corner of the quadrangle, which they named the Thorn Hollow Syncline. The Mitchell Anticline, as they show it, does not parallel this fold system; the axial trace trends approximately north-northeast, as it does in the area to the south of the study area. Amidst the initial dips, faults, and other folds, the east-northeast-trending anticline is very difficult to find; in the study area this fold is completely camouflaged. Indicators of its presence are a nearly linear group of silicic intrusions which extends 35 km to the east-northeast from Stephenson Mountain, the tilting of the slip-surface of the Mitchell Fault, and the more northerly dips of the Bear Creek Member in the study area than those of the earlier members. In the Mitchell Quadrangle the anomalous tilt of the Keyes Mountain lavas mentioned by Oles and

Enlows (1971) and the presence of exposures of the metamorphic basement of the region along the same trend line as the silicic intrusions are other indicators of this folding. The axial trace of this anticline runs approximately from the southern side of Tony Butte west-southwest to the intersection of the Mitchell Fault with the east border of the study area; the axis crosses the south boundary of the study area near Doolittle Flat. To the east of the Mitchell Quadrangle this anticline is called the Richmond Anticline in the Picture Gorge Formation basalts (Fisher, 1967). The positioning of the axis of this anticline in the Cretaceous formations and the Clarno Formation is very tentative; the amount of error is probably less than one kilometer.

The stress fields involved in the formation of these fold systems went from a maximum stress axis oriented west-northwest in the Mitchell Anticline to a maximum stress axis oriented north-northwest in the Sutton Mountain Syncline - Richmond Anticline - Thorn Hollow Syncline fold system. The Mitchell Anticline appears to be the older of the systems, because its fold trend is not traceable in the younger units and the Sutton Mountain system can be approximately located in the older units.

In strike slip faulting, the maximum and minimum stress axes are horizontal, and the stress on the systems increases faster than the system can accommodate by slow yielding. A situation such as this does not occur, on the scale of a six kilometer displacement, unless large pieces of the crust of the earth are in motion relative to one another; motion of this sort causes a stress couple in which the minimum stress may even be tensional. The direction of slippage, right or left lateral, is determined by the inhomogeneities within the stress field; the fault slip-surfaces from at 30° to 45° to the maximum compressive stress axis. In the case of the Mitchell Fault, the requirements for strike slip faulting are satisfied by a maximum stress axis oriented northwest.

Timing of the Deformations

Unconformities can only be evaluated as to their significance in an area when the time hiatus contained by them and the stratigraphic and structural shifts involved are discerned. In a volcanic terrane it is possible for lavas to have large angular divergences of little temporal significance: the paraconformity (Dunbar and Rodgers, 1957) is an example of the opposite extreme. The Tertiary rocks of the Mitchell region suffer a problem of time collapse; in units which were deposited, eroded, and recovered over a ten million year interval, it is very easy to over-discriminate the minor episodes into a welter of rock units and to forget the broad patterns of rock deposition. This is the problem of the Clarno Formation and, to some extent, the John Day Formation. The Clarno Formation is best conceived as a group of lava lenses; the spaces amidst the lenses are filled with mudflows and tuffaceous sediments. There are many unconformities within the Clarno Formation. In this sense the separation of the Clarno Group into two formations by Oles and Enlows (1971), which separates two nearly identical groups of andesite flows, does not seem justifiable.

The Mitchell Anticline started to form prior to the deposition of the Clarno Formation. The angular discordance between the Clarno Formation and the Cretaceous sediments is slight; deformation had not been prominent in the history of the Cretaceous sediments. The Clarno Formation was laid across a bevel of the Cretaceous sediments. Deformation along the Mitchell Anticline continued through the deposition of the Stephenson Mountain Member. The folding of the Mitchell Anticline tightened to approximately the dips found on it today.

After the deposition of the Stephenson Mountain Member, in a period of erosion, the direction of compressive stress changed and the Sutton Mountain - Richmond - Thorn Hollow fold system started to form. This deformation continued until a pulse of increased stress apparently occurred, which caused the formation of the Mitchell Fault. The Mitchell Fault occurred in another period of non-deposition, one which separates the rock units termed herein the Clarno Formation from the John Day Formation. After the cessation of movements on the Mitchell Fault, the deformation on the Sutton Mountain - Richmond - Thorn Hollow fold system restarted and continued through the Miocene.

From the viewpoint of erosional unconformities, there are three important unconformities in the study area: the Cretaceous - Ross Flat Member, the Stephenson Mountain Member - Bear Creek Member, and the Bear Creek Member - John Day Formation. From the viewpoint of time hiati, the Stephenson Mountain Member - Bear Creek Member unconformity has little significance, and the Bear Creek Member - John Day Formation unconformity may not be very important. From the viewpoint of lithology the Stephenson Mountain Member - Bear Creek Member unconformity has no significance. In the final analysis the division of these rock units is dependent upon the criteria used; for the purposes of this thesis, the importance of the Bear Creek Member unconformity is not enough to warrant the reclassification of the Clarno Formation into a Group, because the rocks of the member are similar to those of the rest of the formation, and the unit is too patchy and scattered to be mappable on a small scale.

Landslides

The study area has a wide assortment of landslide types, ranging from tongues of talus which extend down the slides of Stephenson Mountain, to earthflows on the northeast side of Black Butte, and to block slumps, in which large pieces of lava or conglomerate have slid as a unit over the units below them. In general all these landslide deposits formed where a durable unit was underlain by a more easily eroded unit and was undercut in the course of erosion. The block slumps show the features of faults, but the faulting exhibited is usually incompatible with the structure of the area.

The largest block slump comprises most of Section 26, T. 11 S., R. 20 E. This block of Stephenson Mountain Member lavas, about three square kilometers in area, has slid across the lower part of the Ross Flat Member, both of which emerge from the sides of the slide little deformed. The block has split in half; the southern part dips 35° to the northwest, and the northern part dips about 25° to the northeast. The Stephenson Mountain Member and the Ross Flat Member are steeply dipping, 35° northwest to vertical, in this area.

Another block slide, spectacularly displayed in a Highway 26 road cut, occurs at the south edge of Doolittle Flat, in Section 4, T. 12 S., R. 20 E. A 0.2 km^2 block of Gable Creek conglomerate has slide over the Hudspeth mudstones; the slip zone is a 1.5 m band of structureless claystone. The slip zone dips to the southwest in contrast to the southeast dip of the Hudspeth Formation; the dip of the Gable Creek conglomerates is approximately parallel to the dip of the slip zone.

VI. GEOLOGIC HISTORY

The oldest rocks in the study area are the Cretaceous Hudspeth and Gable Creek Formations, whose sediments reflect a period of marine deposition near the edge of a high-energy delta, as described by Wilkinson and Oles (1968). These sediments were uplifted with little deformation locally between the Late Cretaceous and the Late Eocene. Erosion stripped the slightly folded sediments into a cuesta surface; the Mitchell Anticline was breeched to the level of the Main Mudstone Member of the Hudspeth Formation, a removal of at least 1000 m of sediment.

In the Late Eocene, about 45 million years ago, the sediments, lavas and mudflows of the Ross Flat Member of the Clarno Formation began to be deposited. The Ross Flat Member, composed of volcaniclastic sediments primarily, shows that the region sloped downward to the northwest by its sedimentary structures; presumably the lavas and mudflows found in the member in the study area and in the Mitchell Quadrangle arrived from the southeast. Eventually, at least 200 m of sediment was deposited in the basin of Ross Flat Member deposition.

The Ross Flat Member was deposited in a basin lying to the west of the Mitchell Anticline for the earlier part of its depositional time frame. The boundary sediments, transitional to the erosional areas, bear the structures of a beach or bar; this body of sediment, dubbed the Spring Bulch sandstone, parallels the axis of the Mitchell Anticline. This beach/bar was subjected to a high input of sediment, which caused much slumping off its deeper edge in the form of mudflows, grain flows (?), and turbidity currents, and a high-energy wave system, which winnowed the sediment on the beach/bar of its finer sized material. This finer material was deposited in the deeper water of the lake, to the west of the beach/bar, amidst the slump deposits. Beds of nearly pure ash indicate the tranquilty of the deeper waters of the lake. The water level of the lake was variable over long periods of time; tree stumps are found in places which should be the lakeward edge of the beach/bar.

Later the basin of Ross Flat Member deposition enlarged so that the Ross Flat sediments were deposited farther to the east. In the study area this part of the Ross Flat Member is represented by interbedded siltstones, slumps, and graded sandstones similar to those found further to the west in the lower part of the member.

The close of the Ross Flat depositional time frame is shown by the West Branch ignimbrite, which was deposited on dry ground. The reason for the disappearance of the lake is not apparent from the sediments of the study area; one possibility is the renewal of folding on the Mitchell Anticline system which occurred in some part of this time.

This folding tilted the Ross Flat sediments to a low angle; but not enough of an angle that much erosion took place before the eruption of the ignimbrite. The ignimbrite appears as a sheet throughout the area in which it is exposed, but the unit has local thickenings which are probably the result of the prior topography. Some local vitrophyres occur where the ignimbrite was deposited on wet ground.

After the eruption of the ignimbrite, but before much erosion of that unit, andesite volcanism started in the axial area of the Mitchell Anticline. White Butte and the Cougar Gulch intrusion were probably major conduits for these eruptions; possibly the Black Butte plug was also involved in these eruptions. The early eruptions of this episode produced much tephra, which is preserved in the lower part of the Stephenson Mountain Member as mudflows and tuffs interbedded with the lavas. Higher in the member ash beds are very minor; possibly the eruptive style of the vents changed to a less explosive mode. Before this period of volcanism ended, large mountains had been built; possibly 1600 m of lava was deposited, although the lateral distance included in this measurement makes this an approximate amount.

The region of the Ross Flat Member and the Stephenson Mountain Member deposition by its structure and its petrology was approximately analogous to the Cascade province today. The east-west compression was the result of a convergent plate margin; the andesite volcanism was the result of magma generation over a Benioff zone. Climatically the area was also comparable, because the present Cascade Range was not yet built, and the Pacific Ocean storms dumped their moisture on the John Day River basin (Williams, 1942).

During a lull in volcanic activity which occurred between the deposition of the Stephenson Mountain Member and the Bear Creek Member, the direction of compressive stress changed to a north-northwest direction. There was much erosion during this lull of activity; most of the Stephenson Mountain Member lavas were removed from the east side of the Mitchell Anticline. The valleys which can be traced in the upper surface of the Stephenson Mountain Member trend to the north as do the flows of the Bear Creek Member. This more northerly compressive direction began the formation of the Sutton Moutain - Richmond - Thorn Hollow - fold system. Hypothetically, this compression could have been caused by the beginning of the rifting in the Basin and Range Province.

The beginning of the Bear Creek Member volcanic activity was marked in the Stephenson Mountain area by the eruption of a large amount of rhyolitic lavas at some center to the southwest of the study area. These flows moved down the axis of the Sutton Mountain Syncline and also form the crest of the Ochoco Mountains to the southwest of the study area (Lukanuski, 1963). To the southwest of Sheep Mountain, another rhyolite flow was extruded, and possibly some of the Sheep Mountain rhyolite flows were erupted at this time. Andesitic vents formed in the junction area of Bear Creek after the rhyolitic episode; other vents formed to the south of the study area, on Tracy Mountain to the northwest of the study area 0.2 km, and in the Stephenson Creek Valley area. Possibly the Keyes Mountain lavas of Oles and Enlows (1971) belong to this episode. The andesitic vents built many large cones of lava. At the close of the Bear Creek Member volcanic activity, silicic eruptions again occurred, which produced the Sheep Mountain domes, the Stephenson Mountain intrusions, and probably the Lawson Mountain sill. Minor basaltic eruptions may also have occurred at this time.

The end of the depositional time period of the Clarno Formation is makred by the formation of the Mitchell Fault. The regional changes which caused the formation of this fault are conjectural; possibly the combination of the stress from the convergent margin and the stress from the south-southeast (Basin and Range?) diverged enough that a transform-type fault zone formed between them. The southern half of the study area was displaced 6360 m to the west relative to the northern half. The secondary stresses formed by this movement crumpled the crest of the Mitchell Anticline on the south side of the fault; possibly the West

Branch Monocline formed on the north side. The Mitchell Fault movements marked the end of andesitic volcanism in the study area, but silicic volcanism may have continued longer.

Another erosional time period occurred between the depositional periods of the Clarno Formation and the John Day Formation. In the study area this erosional period shows itself not by the formation of valleys in the Clarno surface, but by a soil formed on the Clarno surface and by the thick red claystone which forms the base of the John Day Formation in this area. Minor deformation along the Sutton Mountain fold system may have occurred during this time.

The John Day Formation as well as the Picture Gorge Formation and maybe other central Oregon rock units probably covered much of the study area; all traces of these units have been removed by erosion from the area. All the deformations which have occurred since the beginning of the deposition of the John Day Formation have been along the Sutton Mountain fold system. The latest period of erosion has given the area a youthful to mature topography, which is portrayed on the base map of the area. In the present arid climate the Hudspeth Formation is the key eroding unit, because by undercutting and slumping it causes the rapid erosion of the harder units.

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APPENDICES

Appendix I. Tables of Chemical Analyses of Rocks from Units in and Near the Lawson Mountain - Stephenson Mountain Area.

Table I-1. Chemical analyses of the Stephenson Mountain Member lavas.

Sample	TF-2	VB-SW	S-MF	JT-13
SiO_2	60.2	62.0	64.3	61.2
Al_2O_3	16.3	15.5	16.4	16.1
FeO	8.1	7.9	6.6	8.4
CaO	6.3	6.1	4.3	6.1
MgO	-	2.8	1.9	2.5
Na_2O	3.5	3.9	3.5	3.6
K_2O	1.05	0.80	1.40	1.00
TiO_2	1.00	1.10	1.00	1.10
Total	96.45	100.10	99.40	100.00
FeO/FeO+MgO	1.0	0.74	0.78	0.77

TF-2 Porphyritic hornblende-bearing andesite: elevation 4000, SW¼ of NE¼, Sec. 34, T. 11 S., R. 19 E.

VB-SW Porphyritic hornblende-bearing andesite: elevation 3240, SW¼ of NW¼, Sec. 31, T. 11 S., R. 20 E.

S-MF Vesicular andesite: elevation 3340, NE¼ of SW¼, Sec. 31, T. 11 S., R. 20 E.

JT-13 Andesite: elevation 3920, SW¼ of SW¼, Sec. 25, T. 11 S., R. 19 E.

Appendix I (continued)

Table I-2. Chemical analyses of the Bear Creek Member lavas.

Sample	DR-1	UBC-1	BCB-1	STM-4
SiO_2	63.8	61.9	59.2	64.8
Al_2O_3	15.5	16.8	17.8	16.4
FeO	7.0	5.8	6.9	6.0
CaO	4.8	6.0	6.7	4.7
MgO	2.0	3.0	3.1	1.3
Na_2O	3.9	3.7	3.8	4.0
K_2O	1.70	1.45	1.30	1.80
TiO_2	1.05	0.95	1.10	1.05
Total	99.75	99.60	99.90	100.05
FeO/FeO+MgO	0.78	0.66	0.69	0.82

DR-1 Hornblende-bearing andesite: hill 4165, SW¼ of NW¼, Sec. 24, T. 11 S., R. 19 E.

UBC-1 Porphyritic hornblende-bearing andesite: elevation 3440, SW¼ of NW¼, Sec. 2, T. 12 S., R. 19 E.

BCB-1 Porphyritic andesite: elevation 2640, NW¼ of NE¼, Sec. 30, T. 11 S., R. 20 E.

STM-4 Porphyritic hornblende-bearing andesite: elevation 5600, SW¼ of SE¼, Sec. 28, T. 11 S., R. 19 E.

Appendix I (continued)

Table I-2 (continued)

Sample	R-2	STM-1	STM-2	STM-3
SiO_2	55.7	75.5	75.5	71.6
Al_2O_3	18.2	13.7	13.3	16.1
FeO	5.1	1.9	1.8	2.5
CaO	9.1	0.6	1.0	0.8
MgO	5.7	-	-	-
Na_2O	3.1	3.5	3.2	3.8
K_2O	0.65	4.30	4.70	4.35
TiO_2	1.10	0.15	0.15	0.15
Total	98.65	99.65	99.65	99.30
FeO/FeO+MgO	0.47	1.00	1.00	1.00

R-2 Porphyritic two-pyroxene basaltic andesite: hill 4226, NW¼ of SW¼, Sec. 6, T. 12 S., R. 20 E.

STM-1 Flow-banded rhyolite: elevation 5080, NE¼ of NE¼, Sec. 33, T. 11 S., R. 19 E.

STM-2 Vitrophyre: elevation 5160, NE¼ of NE¼, Sec. 33, T. 11 S., R. 19 E.

STM-3 Porphyritic rhyolite: elevation 5250, NE¼ of NE¼, Sec. 33, T. 11 S., R. 19 E.

Appendix I (continued)

Table I-3. Chemical analyses of the Sheep Mountain domes and flows, and the Spring Gulch extrusion.

Sample	SH-2	SH-NS	SH-LF	RFR-5	VB-V
SiO_2	77.3	65.2	68.3	68.3	71.2
Al_2O_3	12.4	18.1	17.5	17.0	14.6
FeO	2.6	4.6	4.8	4.1	2.5
CaO	2.1	4.0	4.0	2.9	1.2
MgO	-	0.9	0.2	0.1	-
Na_2O	3.1	4.3	5.3	4.0	4.6
K_2O	2.05	1.40	1.90	2.45	3.35
TiO_2	0.25	0.60	0.75	0.55	0.15
Total	99.80	99.10	102.75	99.40	98.95
FeO/FeO+MgO	1.00	0.84	0.96	0.98	1.00

SH-2 Hornblende-bearing rhyolite: elevation 3800, boundary of Sec. 21 and Sec. 28, T. 11 S., R. 20 E.

SH-NS Porphyritic hornblende-bearing dacite: elevation 3800, NE¼ of SW¼, Sec. 21, T. 11 S., R. 20 E.

SH-LF Dacite: elevation 3180, NE¼ of SW¼, Sec. 22, T. 11 S., R. 20 E.

RFR-5 Vesicular dacite: hill 3112, NE¼ of SW¼, Sec. 20, T. 11 S., R. 20 E.

VB-V Vitrophyre: elevation 3640, NW¼ of NE¼, Sec. 31, T. 11 S., R. 20 E.

Appendix I (continued)

Table I-4. Chemical analyses of basaltic intrusions.

Sample	USG-1	CG-DI
SiO_2	48.2	51.3
Al_2O_3	16.4	16.1
FeO	7.6	9.1
CaO	14.8	10.6
MgO	3.7	8.8
Na_2O	2.6	2.3
K_2O	0.66	0.35
TiO_2	0.95	0.90
Total	94.91	99.45
FeO/FeO+MgO	0.67	0.58

USG-1 Porphyritic basalt dike: elevation 3600, SW¼ of SE¼, Sec. 32, T. 11 S., R. 20 E.

CG-DI Porphyritic olivine-bearing basalt dike; elevation 3760, NW¼ of NE¼, Sec. 34, T. 11 S., R. 20 E.

Appendix I (continued)

Table I-5. Chemical analyses of the Mitchell Anticline intrusions.

Sample	EMT-52	EMT-62	EMT-68
SiO_2	65.9	65.6	44.5
Al_2O_3	17.9	20.2	10.8
FeO	4.9	8.0	10.4
CaO	4.9	4.9	12.2
MgO	0.8	0.8	7.7
Na_2O	4.3	0.2	2.1
K_2O	1.50	0.08	1.90
TiO_2	0.55	1.08	3.75
Total	100.75	100.86	93.35
FeO/FeO+MgO	0.86	0.91	0.58

EMT-52 Altered porphyritic hornblende andesite sill: summit of Black Butte, SW¼ of NE¼, Sec. 1, T. 12 S., R. 20 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-62 Altered porphyritic hornblende andesite dike: Gilchrist Butte, NW¼ of SW¼, Sec. 11, T. 12 S., R. 20 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-68 Altered biotite-bearing hornfels: elevation 3840, Sec. 1, T. 12 S., R. 20 E. Collected and analyzed by Dr. E. M. Taylor.

Appendix I (continued)

Table I-6. Chemical analyses of the basaltic andesite and andesite intrusions.

Sample	HWB-1	HWY-2	RFI-1
SiO_2	59.0	56.6	59.2
Al_2O_3	17.8	17.2	16.5
FeO	7.0	7.9	7.6
CaO	5.7	8.1	7.0
MgO	3.7	5.2	5.0
Na_2O	4.1	3.3	3.6
K_2O	1.45	0.70	0.80
TiO_2	1.25	0.90	1.05
Total	100.00	99.90	100.75
FeO/FeO+MgO	0.65	0.60	0.60

HWB-1 Porphyritic andesite plug: butte, elevation 2760, NW¼ of NE¼, Sec. 25, T. 11 S., R. 20 E.

HWY-2 Porphyritic basaltic andesite plug: butte, NE¼ of NE¼, Sec. 25, T. 11 S., R. 20 E.

RFI-1 Porphyritic hornblende andesite plug: butte, elevation 3880, SE¼ of NW¼, Sec. 33, T. 11 S., R. 20 E.

Appendix I (continued)

Table I-6 (continued)

Sample	VB-I	JT-4	BUR-3	DR-2
SiO_2	62.0	59.8	62.0	62.9
Al_2O_3	17.1	17.7	17.4	17.8
FeO	7.4	7.7	6.9	7.0
CaO	4.1	7.4	5.5	5.2
MgO	1.0	3.5	1.7	1.5
Na_2O	4.5	3.5	4.2	3.5
K_2O	1.90	1.35	1.35	1.55
TiO_2	1.10	1.10	1.05	1.10
Total	99.10	102.05	100.10	100.55
FeO/FeO+MgO	0.88	0.69	0.80	0.82

VB-I Porphyritic hornblende-bearing andesite plug: butte, elevation 3400, SE¼ of SW¼, Sec. 30, T. 11 S., R. 20 E.

JT-4 Porphyritic hornblende-bearing andesite plug: butte, elevation 3160, NE¼ of NE¼, Sec. 36, T. 11 S., R. 19 E.

BUR-3 Porphyritic hornblende-bearing andesite plug: butte, elevation 4520, SW¼ of NW¼, Sec. 36, T. 11 S., R. 19 E.

DR-2 Altered hornblende-bearing andesite plug: elevation 3960, SW¼ of NW¼, Sec. 24, T. 11 S., R. 19 E.

Appendix I (continued)

Table I-7. Chemical analyses of the silicic intrusions.

Sample	EMT-73	B-2	B-3	JT-6
SiO_2	68.8	80.5	71.8	74.1
Al_2O_3	16.0	11.4	14.2	11.8
FeO	4.1	1.9	2.6	3.5
CaO	3.7	0.4	0.7	0.7
MgO	1.0	-	0.3	-
Na_2O	3.9	2.4	3.1	3.0
K_2O	1.95	1.45	6.70	3.80
TiO_2	0.43	0.10	0.25	0.10
Total	99.88	98.15	99.65	97.00
FeO/FeO+MgO	0.80	1.00	0.90	1.00

EMT-73 Porphyritic hornblende-bearing dacite sill: summit of Lawson Mountain, NE¼ of NE¼, Sec. 33, T. 11 S., R. 20 E. Collected and analyzed by Dr. E.M. Taylor.

B-2 Altered rhyolite dike: elevation 3580, NW¼ of SE¼, Sec. 25, T. 11 S., R. 19 E.

B-3 Porphyritic, fresh zone of B-2 dike: same location.

JT-6 Rhyolite plug: elevation 3140, NW¼ of SE¼, Sec. 36, T. 11 S., R. 19 E.

Appendix II. Tables of Chemical Analyses of Rocks from Units in the Mitchell Quadrangle which Show Some Comparison with those of the Lawson Mountain - Stephenson Mountain Area.

Table II-1. Chemical analyses of basaltic rocks.

Sample	EMT-43	EMT-3	EMT-23	EMT-11
SiO_2	49.0	44.8	51.9	53.2
Al_2O_3	12.8	11.6	15.0	14.5
FeO	8.9	10.0	12.2	12.9
CaO	10.6	14.6	9.7	8.6
MgO	14.2	11.6	2.4	4.2
Na_2O	2.0	3.8	4.7	3.1
K_2O	2.15	1.05	0.38	0.98
TiO_2	0.93	1.23	3.05	2.85
Total	100.58	98.68	99.33	100.33
FeO/FeO+MgO	0.39	0.46	0.84	0.75

EMT-43 Basalt plug: boundary Sec. 19 and Sec. 20, T. 11 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-3 Porphyritic melabasalt: Marshall Butte, Sec. 29, T. 11 S., R. 22 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-23 Basalt dike: NE¼ of NW¼, Sec. 27, T. 11 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-11 Basalt dike: TV Hill 71, Sec. 1, T. 12 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

Appendix II (continued)

Table II-2. Chemical analyses of andesitic rocks.

Sample	EMT-8	EMT-39	EMT-28
SiO_2	58.7	70.1	63.4
Al_2O_3	17.8	17.3	19.8
FeO	7.8	2.4	4.9
CaO	7.8	3.2	2.2
MgO	2.0	0.2	1.0
Na_2O	3.4	5.0	6.8
K_2O	0.80	1.95	1.60
TiO_2	1.02	0.21	0.51
Total	99.32	100.36	100.21
FeO/FeO+MgO	0.76	0.92	0.83

EMT-8 Andesite sill: TV Hill, NW¼ of NW¼, Sec. 12, T. 12 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-39 Altered porphyritic hornblende andesite plug: White Butte, NW¼ of NW¼, Sec. 20, T. 12 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-28 Altered hornblende andesite sill: Mitchell Rock, SW¼ of NW¼, Sec. 35, T. 11 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

Appendix II (continued)

Table II-3. Chemical analyses of silicic rocks.

Sample	EMT-59	EMT-56	EMT-24
SiO_2	68.9	79.3	72.5
Al_2O_3	17.1	14.4	15.7
FeO	4.0	1.4	2.6
CaO	1.3	0.2	2.2
MgO	0.2	-	0.1
Na_2O	6.5	0.7	4.5
K_2O	2.00	3.95	1.39
TiO_2	0.48	0.06	0.07
Total	100.48	100.01	99.06
FeO/FeO+MgO	0.95	1.00	0.96

EMT-59 Porphyritic dacite plug: butte, elevation 2960, NW¼ of NW¼, Sec. 28, T. 11 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-56 Leucorhyolite plug: summit of Sargent Butte, elevation 3315, SE¼ of SE¼, Sec. 17, T. 11 S., R. 21 E. Collected and analyzed by Dr. E. M. Taylor.

EMT-24 Porphyritic rhyolite plug: southeast side of Tony Butte, NE¼ of SW¼, T. 10 S., R. 22 E. Collected and analyzed by Dr. E. M. Taylor.