AN ABSTRACT OF THE THESIS OF

Mark Scott Cranswick for the degree of Master of Science

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Title: THE STRATIGRAPHY, STRUCTURE AND PETROGRAPHY OF KEYES MOUNTAIN, TERTIARY UPPER CLARNO FORMATION, WHEELER COUNTY, OREGON

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Dr. Keith F. Oles

The Keyes Mountain area, located approximately six kilometers northeast of Mitchell, Oregon, consists of a volcanic pile of interstratified Clarno andesite flows and mudflows with very local tuff and vent agglomerate deposits. Intrusive andesites are also common.

The Upper Clarno Formation of the Keyes Mountain area unconformably overlies the Permian metasediments and the Cretaceous Gable Creek and Hudspeth Formations. It unconformably underlies the John Day and Columbia River Basalt Formations. The Clarno Group is radiometrically dated between 29.4 ± 0.6 and 48.9 ± 5.2 m.y.; from early Eocene to middle Oligocene time.

The andesite flows contain two to five phenocryst phases. These phenocrysts are plagioclase, clinopyroxene, hypersthene, hornblende and lamprobolite in order of decreasing abundance.

Intrusive andesites are very similar to andesite flows except that they commonly contain hornblende.

Indirect evidence indicates Keyes Mountain was a volcano and the source of some Upper Clarno strata in the Mitchell area. This conclusion is inferred from features that are characteristic of volcanic loci: quaquaversal dips, extremely large clasts within the mudflows, mudflow paleocurrent directions from the Keyes Mountain vicinity, the intracanyon nature of mudflows and andesite flows with respect to one another, the noncorrelative nature of sequences of andesite flows exposed in different ridges, and a possible vent agglomerate.

In post-Clarno time, Keyes Mountain stood as a paleotopographic high that was marginally onlapped by the John Day and Columbia River Basalt Formations.

The Stratigraphy, Structure, and Petrography of Keyes Mountain, Tertiary Upper Clarno Formation, Wheeler County, Oregon

by

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Foremost, I extend my gratitude forever to my father who has guided me with admirable knowledge and wisdom. To him I attribute my success in this project, in the pursuit of my profession, and in this world.

My mother, in her example of self-discipline and integrity of character, has unfailingly supported and helped me mold my future. To her I will always be deeply thankful and indebted.

Above all, I dedicate this work and all future endeavors to my wife, Barbara. For all her help, encouragement, confidence and inspiration I express my profound thankfulness.

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INTRODUCTION

Location

The study area is located in north-central Oregon, in the south-central part of Wheeler County (Fig. 1), east of Mitchell, and north of U.S. Highway 26. It encompasses approximately 28 square miles within T. 11 and 12 S., R. 22 and 23 E.

Geography and Climate

The study area lies within the Blue Mountains and is characterized by a dissected mature landscape composed of mountain ranges and plateaus (Thornbury, 1965) (Figs. 2 and 3). Keyes Mountain, at 1,739 meters elevation (5,704 feet), is the highest point. The lowest point is at 1,036 meters (3,400 feet) along U.S. Highway 26. The maximum topographic relief is 701 meters (2,300 feet).

The countryside around the town of Mitchell is characterized by extremes in climatic conditions. The average summer temperature is 21°C (70°F), reaching an average maximum of 29°C (85°F). The average winter temperature is -1°C (30°F), reaching an average minimum of -8°C (18°F). The average fluctuation in daily

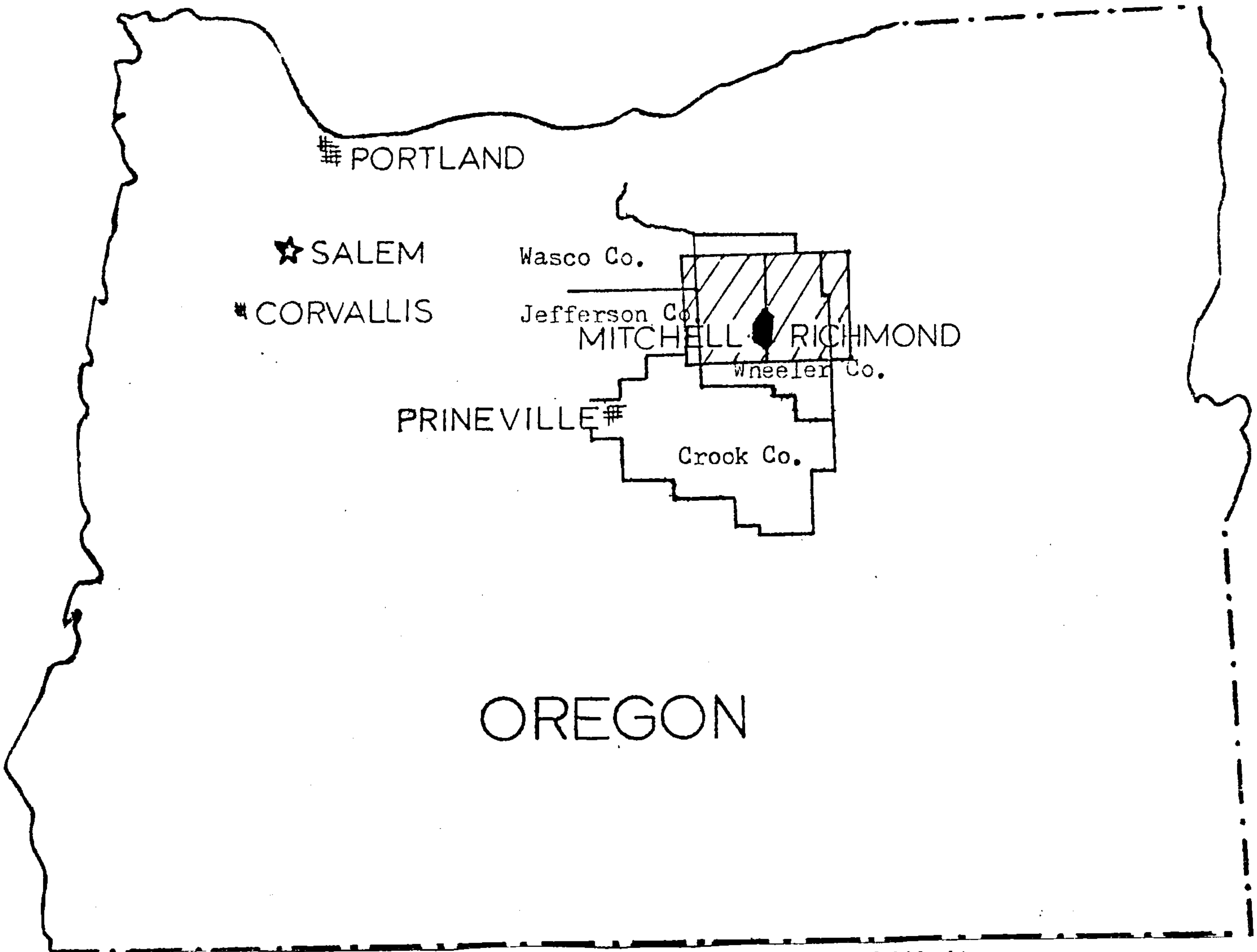

Figure 1. Index map of the Keyes Mountain study area (shown in solid black)

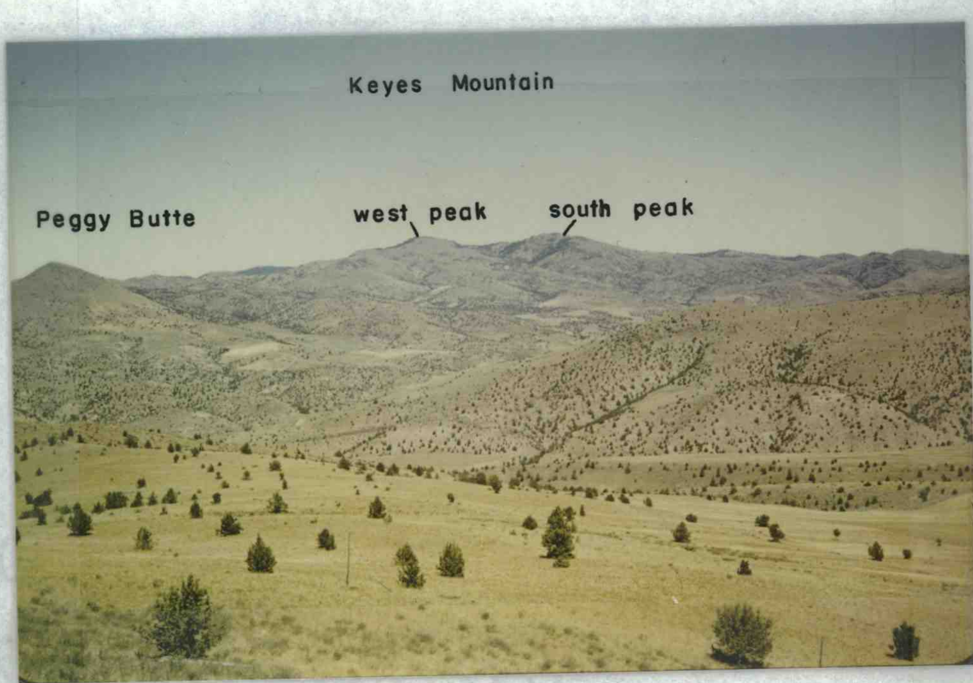

Figure 2. View of Keyes Mountain looking northeast.

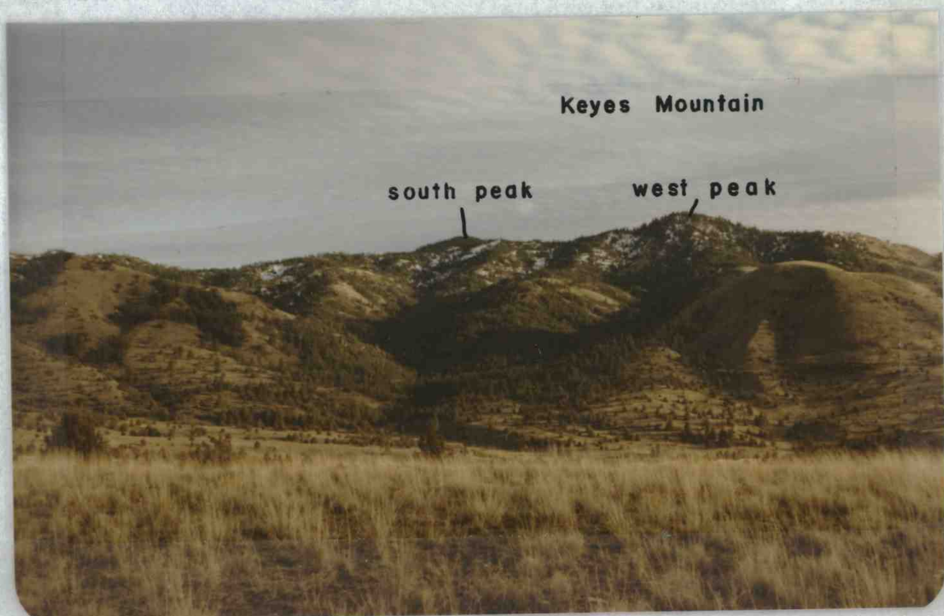

Figure 3. View to south of Monroe Roughs, located on the north side of the west and south peaks of Keyes Mountain, in sections 13, 14, 23, and 24, T. 11 S., R. 22 E.

temperatures is 10°C (22°F) in January and 17°C (35°F) in July. Sub-freezing temperatures (-7° to 0°C) average 60 days per year, and there are 140 days per year of frost. Approximately 90 days with precipitation occur annually. Total precipitation averages 18 to 26 cm (7-10 inches) per year, the majority occurring during the fall and winter seasons (Visher, 1954). Approximately 81 cm (32 inches) of snowfall accumulate per year (U. S. Geological Survey, 1970).

Accessibility and Exposure

U.S. Highway 26 is the only paved road within the study area. Light duty roads permit fair access into most of the area, and most locations can be reached by foot within two miles from one of these roads. The entire area is criss-crossed with jeep trails and abandoned logging roads that were utilized during logging operations in the 1940's and 1950's. Most of the roads, however, permit passage only by foot because of many obstructions, such as fallen trees and rock falls.

Significant limitations to vehicular access exist during the fall, winter, and spring seasons. Water saturation transforms the hard, sunbaked ground of summer months into an impassable slippery and soggy surface. Usually travel is limited to four-wheel-drive vehicles. Snow accumulates to great depths in some protected areas, such as Marshall Creek canyon, and renders passage impossible.

Furthermore, during Autumn all access is forbidden on account of hunting privileges extended only by corporations which own all property within the study area.

Exposures are limited to stream cuts, cliffs, ledges, and local outcroppings of bedrock (Fig. 4). Otherwise, soil and vegetative cover are ubiquitous, the only indication of underlying bedrock being rock float. Vegetative cover is dominantly composed of sagebrush, grasses, and juniper trees. Along streams and around springs, cottonwood and willow trees abound, while at the higher elevations ponderosa pine and Douglas fir forests are found. About one-third of the study area is covered by forest.

Purpose and Methods of Investigation

The primary objectives of this study were (1) to map geologically the Upper Clarno Formation in the Keyes Mountain vicinity, (2) to analyze petrographically the igneous rock types, (3) to determine whether or not Keyes Mountain is an exhumed volcano of Eocene age. The boundaries of the map area were determined by collecting enough information to establish item (3) above. Forty-five days were required to complete the field work.

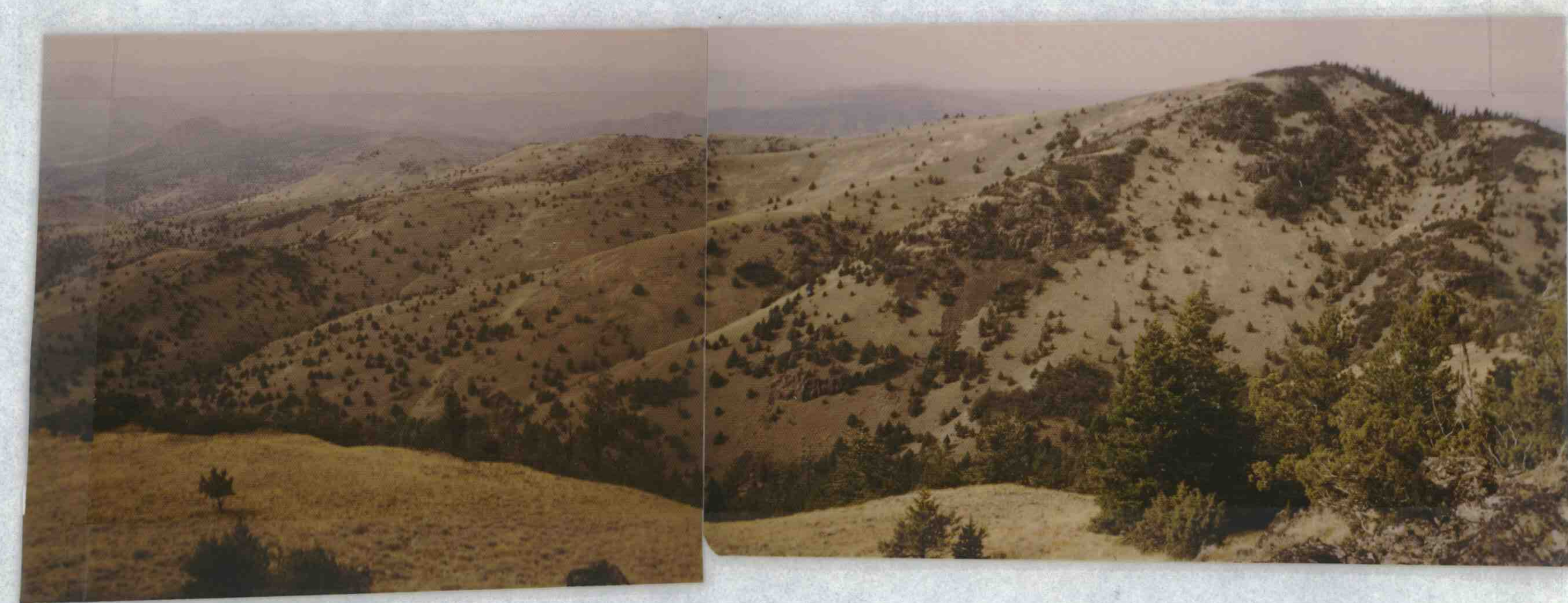

Figure 4. View west-southwest to west peak of Keyes Mountain. The ridge consists of andesite flows and mudflows. Cliffs are andesite. Andesite dipslopes extend along the length of the ridge.

Field mapping was on aerial photos of 1:36, 000 scale. High altitude aerial photos of 1:60, 000 scale also were utilized. The photo map was transferred to topographic base maps to the scale of 1:24, 000. The base map consists of a composite of three quadrangles which are the 7 1/2 minute Mitchell SE and NE quadrangles (U. S. G. S., 1966, unedited) and the west-central part of the 15 minute Richmond quadrangle (U. S. G. S., 1953) that was enlarged to a scale of 1:24, 000.

In the laboratory, detailed petrographic analyses were made on 14 andesite flows, 12 andesite intrusions, 5 flow breccias, 2 mudflows, and 3 volcanic agglomerates. Statistical point counts were made on four representative andesite flows and six representative andesite intrusions. Three hundred fifty to 400 points were counted to determine the relative abundance of constituent minerals. Three representative andesite flows were chemically analyzed for major element abundance. The chemical analyses (Appendix A) were incorporated to establish proper petrologic classification with respect to chemical composition. The analyses were made on the X-ray fluorescence machine belonging to the OSU Geology Department.

Geologic Setting

The Clarno Group in the study area unconformably overlies the Permian metasediments and Cretaceous Gable Creek and Hudspeth Formations. Unconformably overlying the Clarno Group are the John Day and Columbia River Basalt Formations (Fig. 5). The stratigraphic sequence records numerous episodes of orogeny since Jurassic time (Oles and Enlows, 1971).

Oles and Enlows (1971) have informally designated the Upper Clarno Formation as distinct from the underlying Lower Clarno Formation. This is based on the fact that the two units are dissimilar sequences of rock which are separated by an angular unconformity. Lithologically, however, they are genetically related and combined as the Clarno Group (Oles and Enlows, 1971).

The Upper Clarno strata on Keyes Mountain are a series of interstratified and cross-cutting andesite flows and mudflows. These rock units originated from a vent-cone complex, located in the vicinity of the south peak of Keyes Mountain and Flock Mountain. A vent agglomerate, situated at this locality, delineates the primary eruptive vent. Numerous andesite sills and dikes of Clarno age cut the sequence. Many dikes have been emplaced along prominent faults.

Keyes Mountain is situated along the southeast flank of the

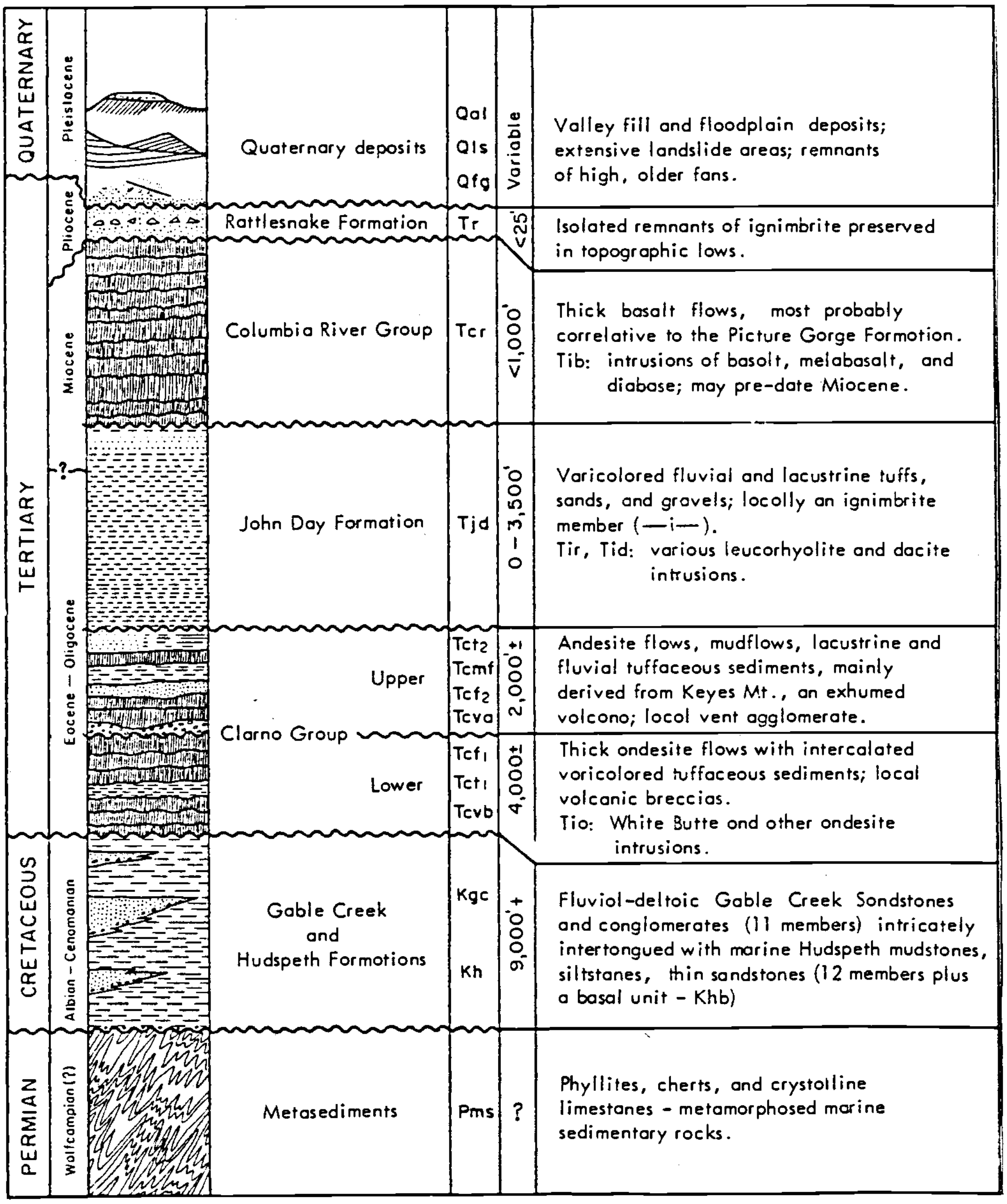

Figure 5. Stratigraphic sequence in the Mitchell quadrangle, (from Oles and Enlows, 1971)

Mitchell anticline. The Mitchell fault is known to exist immediately south of the study area (Oles and Enlows, 1971). The south side of the study area contains strike-slip faults which trend east-west and northeast-southwest. Separation along the latter faults is inferred to be right-lateral. Other faults within the study area trend approximately east-west and north-south and are normal in nature.

Previous Work

The first description of the geology of this area was by Merriam (1901a and 1901b) who described the geology of the John Day basin, including the definition and description of the Clarno Formation. Calkins (1902) described some Clarno andesites and other volcanic rocks. Hodge (1942) published a map at the scale of 1:250, 000 and a monograph on the geology of north-central Oregon. He further described the Clarno Formation and interpreted the geologic history of the area. Swanson (1969) published a geologic map of a number of counties in north-central Oregon, including Wheeler County. His map is at a 1:250, 000 scale and shows only the generalized locations of the boundaries of the Clarno Group. Oles and Enlows (1971) published a study on the bedrock geology of the Mitchell quadrangle. This is the main source of information for this study because it is the most thorough and comprehensive study to date on all the rock units and geologic history of the area. Most of the study area lies within this quadrangle. Enlows and Parker (1972) published the geochronology of the Clarno igneous activity (Fig. 6). They radiometrically dated the igneous rocks by K/Ar isotopes. Prior to this latest and most accurate geochronology by Enlows and Parker(1972), most of the age limits that were placed upon the Clarno Formation were from paleontologic and radiometric dates taken from various publications. Thses publications are cited in Enlows and Parker (1972).

Various Master of Science theses on the Upper Clarno Formation are as follows: (1) Bowers (1953) mapped the northwestern part of the study area and delineated the contact of the Clarno Formation with the older rock units; (2) McIntyre (1953) mapped into the southwestern part of the study area, including Keyes Mountain itself, and delineated the contacts between the Clarno Formation and older and younger rock units. He also included some structural interpretation of Keyes Mountain; (3) Irish (1954) mapped the contact of the Clarno with younger formations in the extreme southeast part of the study area; (4) Snook (1957) mapped the contacts with the Clarno and younger formations in the north-central part of the study area, immediately south and west of Baldy Mountain; (5) Wilson (1973) studied the petrology of many of the igneous rocks of the Clarno

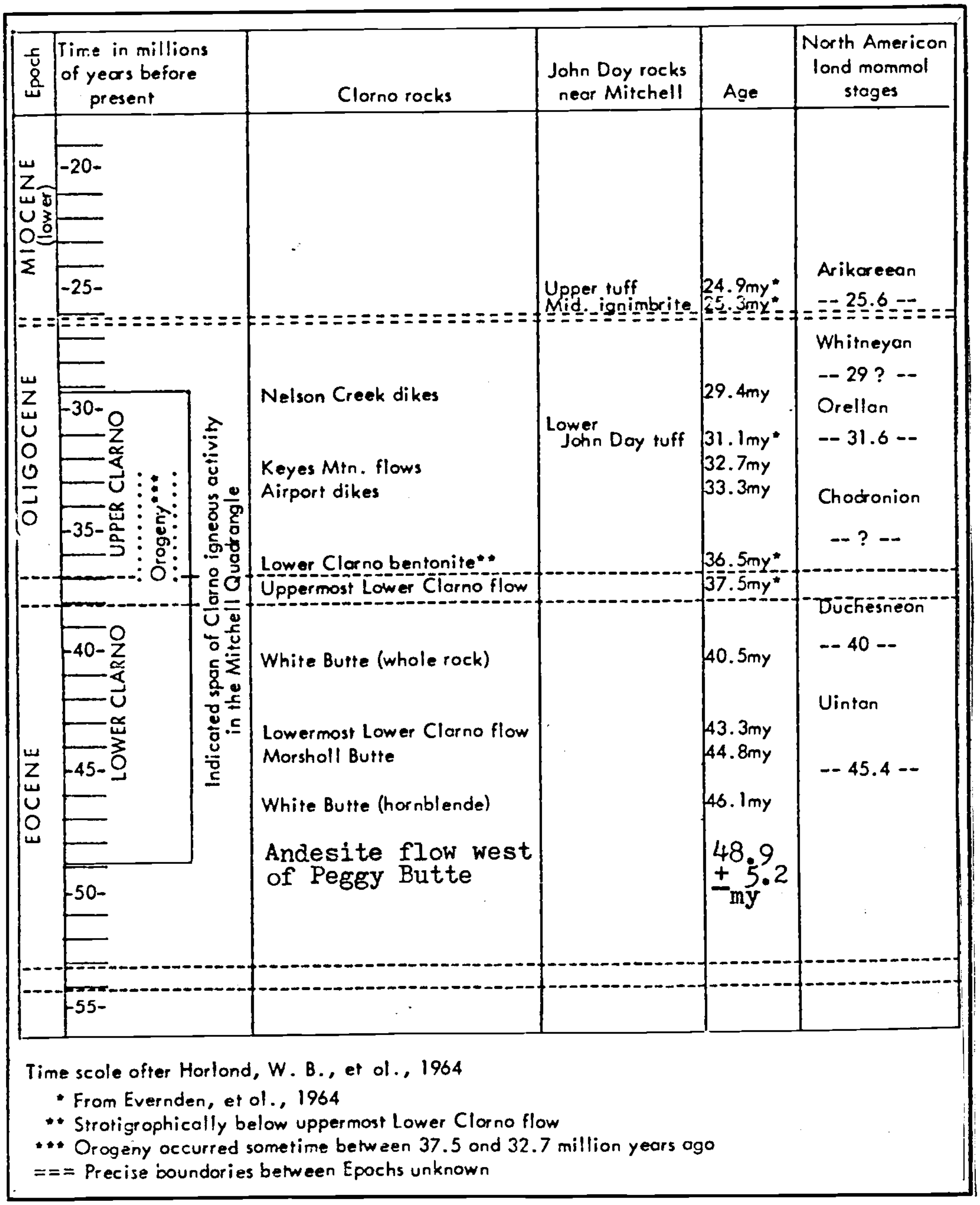

Figure 6. Geochronology of the Clarno rocks of the Mitchell quadrangle (modified after Enlows and Parker, 1972). The oldest age of the Clarno was increased from 46.1 to 48.9 ± 5.2 million years based on a K-Ar age from an andesite flow located west of Peggy Butte, in the N 1/4, section 28, T. 11 S., R. 22 E.

Group, a few of which were from the Upper Clarno Formation; (6) Novitsky-Evans (1974) chemically analyzed many of the igneous rock types, a few of which are Upper Clarno. She also interpreted the Clarno Group in light of plate tectonics.

Not within the study area but helpful to the author for information on Clarno stratigraphy are Taylor (1960), Owen (1977), Barnes (1978), Huggins (1978), and Stroh (1980).

STRATIGRAPHY

Permian Metasediments

General Characteristics

Southeast of Tony Butte, the Clarno strata unconformably overlie Permian metasedimentary rocks (Pl. 1). The Permian rocks encountered within the Mitchell quadrangle comprise phyllite, subordinate crystalline limestone, and chert. They were originally marine deposits, now intensely deformed by repeated orogenic episodes. Small-scale isoclinal and subisoclinal folds are displayed in the phyllites, their crestal parts frequently occupied by quartz boudins. Crystalline limestone occurs in pods or lenticular masses to 15 meters in length or as long stringers within the enclosing phyllite. Poorly preserved fusulinids within the limestone indicate a Permian age (Oles and Enlows, 1971).

In addition to the above mentioned rocks, the study area contains subordinate vuggy dolomites and schists, macroscopically identified as assemblages of tremolite-actinolite and chlorite-talc-wollastonite. In the center of the NE 1/4, section 1, T. 11 S., R. 22 E., a dark reddish brown, vertical dike-like feature proves to be a gossan capping serpentine and chlorite schist. The serpentine is estimated to be 30 meters in width.

A magnificent blue-colored schist with pearly lustre is found as float in the center of the extreme N 1/2, section 12, T. 11 S., R. 22 E. This schist is associated with float of other Permian metasedimentary and metamorphic rocks.

Cretaceous Gable Creek and Hudspeth Formations

General Characteristics

The Clarno strata unconformably overlie two intertonguing formations of Cretaceous age which in turn unconformably overlie the Permian rocks. The Cretaceous strata crop out along a northeast-southwest trend and border the study area on the west, northwest, northeast, and east.

One Cretaceous unit is the Gable Creek Formation. It is characterized by fluvial and deltaic conglomerates, sandstones, and minor siltstones and mudstones. The sandstones are immature lithic arenites (subgraywackes). The conglomerates are well indurated, display framework support, and predominantly comprise rounded to subrounded chert, quartzite, and granite.

The other Cretaceous rock unit is the Hudspeth Formation. It is characterized by quiet-water deposited, laminated and bedded marine mudstone interbedded with subordinate siltstone and sandstone (Wilkinson and Oles, 1968; Oles and Enlows, 1971).

Paleontologic ages on ammonites and pelecypods indicate deposition during late Albian to early Cenomanian time (Wilkinson and Oles, 1968).

The less resistant Hudspeth Formation is poorly exposed and forms pediments, narrow strike valleys, and swales. The more resistant Gable Creek Formation forms high cliffs and giant cuestas (Wilkinson and Oles, 1968; Oles and Enlows, 1971).

On Pl. 1 the Cretatcous Formations are undifferentiated with respect to their 11-12 tongue-like members. Because some Cretaceous sandstones bordering the study area were not identified as Gable Creek or Hudspeth, they were mapped as K_u-Cretaceous undifferentiated.

One peculiar rock unit, mapped as K_{al} on Pl. 1, merits description. This unit crops out along the Hudspeth logging road, in the S 1/2 of section 12, T. 11 S., R. 22 E. The outcrops are interpreted to be alluvial channels and are dominantly filled with rounded cobbles and boulders of Permian rocks. Subordinate Cretaceous Galbe Creek pebbles and cobbles also are found.

Clarno Formation

Introduction

The predominant rocks within the study area are mapped as the

Upper Clarno Formation by Oles and Enlows (1971). The Clarno strata were unconformably deposited on Permian and Cretaceous rocks that previously were highly dissected by erosion. This fact is revealed by the distribution and elevation of the Cretaceous rocks on the west and east sides of the study area. Oles and Enlows (1971) estimate that as much as 120 meters (400 feet) of paleorelief existed in the Mitchell area. The Clarno is unconformably overlain by the John Day and Columbia River Basalt Formations.

Although not directly measured, the maximum thickness of Clarno strata in the study area is 367 meters. Oles and Enlows (1971) estimate the thickness of the Upper Clarno Formation in the Mitchell quadrangle to be 600 meters.

The Clarno strata within the study area are composed of inter-stratified and cross-cutting andesite flows and mudflows and very local exposures of vent agglomerate and tuff.

Radiometric Ages of Claro Andesites

One K-Ar age date provided in this study alters the geo-chronology of the Clarno Group. Enlows and Parker (1972) obtained K-Ar radiometric ages on Clarno andesites, thereby bracketing the Clarno Group between 29.4 ± 0.6 and 46.1 ± 3.96 m.y.; from middle Eocene to middle Oligocene. However, the andesite flow[1] dated in this study extends the lower limit to 48.9 ± 5.2 m.y. (Fig. 6), the early Eocene. It should be noted, however, that the two oldest ages overlap within their experimental range of error.

However, uncertainty exists in the upper age limit of the andesites. Drs. Harold E. Enlows and Edward M. Taylor of Oregon State University have proof that the Nelson Creek and airport dikes (Fig. 6) are part of the John Day Formation and that the 32.7 m.y. age of the Keyes Mountain flows is incorrect (personal communication, 1979). Therefore, contrary to that illustrated in Fig. 6, the Clarno Group is probably strictly Eocene age. However the faunal stages established for the Clarno indicate middle Eocene to middle Oligocene age (Enlows and Parker, 1972).

Another problem resulting from the new age date is that the 48.9 ± 5.2 m.y. is earliest Lower Clarno, but the strata are considered Upper Clarno by Oles and Enlows (1971). Assuming that the age is correct, then the area contains Lower Clarno strata. In addition, the Lower Clarno in this area includes mudflows which is contrary to the interpretation of Oles and Enlows (1971). However, if the dated andesite is a sill, mistaken to be a flow, then there may

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[1] The age date was provided by Ted McKee of the U. S. Geological Survey. It was made on the fresh hornblende contained within the andesite flow located west of Peggy Butte, in the N 1/4, section 28, T. 11 S., R. 22 E.

be no Lower Clarno strata in the area that wer deposited subaerially.

I. Andesite Flows

Geomorphology

Andesite flows are topographically expressed as ridges, buttes, cuestas, cliffs, and dipslopes (Figs. 7, 8, and 9). Buttes and ridges are often comprised of poorly resistant mudflows capped by highly resistant andesites (Fig. 10).

Soil development on andesite flows ranges from thick to very thin and is typically medium dark gray (N4). Atop altered flows soils are dark yellowish orange (10 YR 6/6), grayish olive (10 Y 4/2), or dark greenish gray (5 GY 4/1).

Vegetative cover on dipslopes is usually restricted to grasses and sage. However, thicker soil is found on leeslopes of flows and flow breccias, commonly supporting dense growths of juniper, white and ponderosa pine, and brush.

General Characteristics

The most abundant rocks exposed in the study area are andesite flows. In Pl. 1 each flow is distinguished from another by a numbered or lettered symbol. The symbols refer to the sequence of stratigraphy for a particular area, not for the whole map area. Approximately 64 flows can be distinguished.

Three different types of andesites in the study area were chemically analyzed (Appendix A). Samples 25-1 and 27-1 are typical andesites. Sample 28-1 is a basaltic andesite which is atypical in the Upper Clarno Formation. When plotted on AFM and KCN diagrams (Fig. 11), the samples lie within the calc-alkaline field. Also displayed in Fig. 11 is the area of Kuno's hypersthenic series, and it can be seen that the rocks of this study plot within this field.

These findings support that of Stroh (1980) who augmented his chemical data on Clarno andesites with that of Huggins (1978) and Barnes (1978). The Clarno andesites illustrated in his study (Stroh, 1980) plot within the calc-alkaline field on the AFM and KCN diagrams. However, the same data on a Harker cross-plot diagram give a Peacock (1931) alkali-lime index of 62 which is within the calcic field.

The andesite flows are either stacked one upon another or interstratified with mudflow deposits. Both andesite flows and mudflows are locally intracanyon to each other.

Very few interflow contacts were observed in the study area because of the ubiquitous soil and vegetative cover. Visible contacts are indistinguishable because of the likeness of flow breccias above and below the contact.

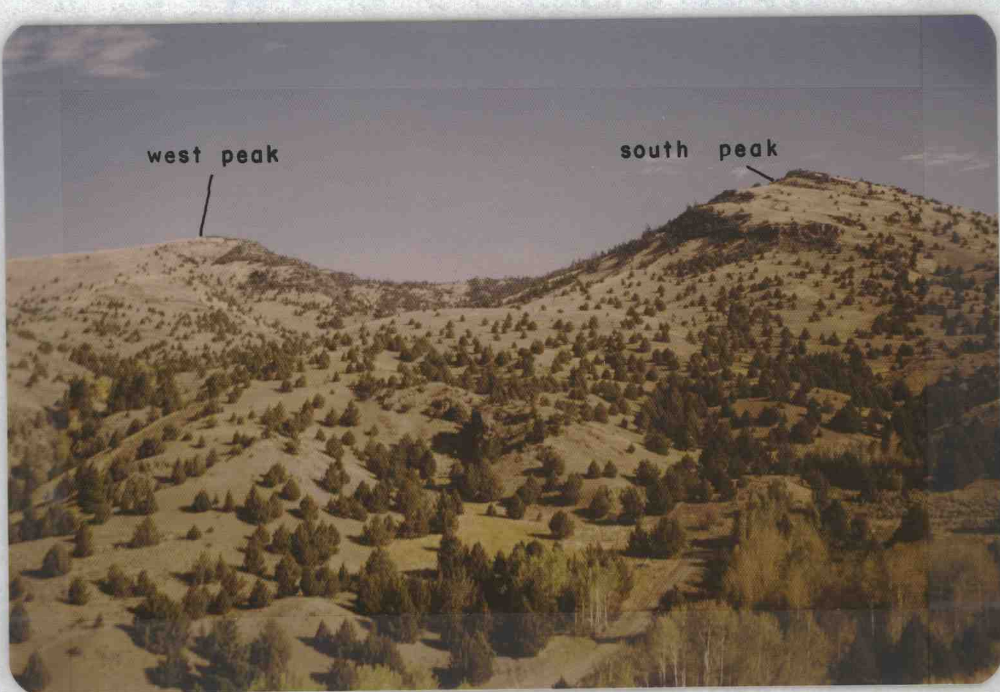

Figure 7. View north of west and south peaks of Keyes Mountain. Clarno andesite flows on the west peak dip to the southwest. Flows on the south peak dip to the southeast. Located in sections 23, 24, 25 and 26, T. 11 S., R. 22 E.

Figure 8. View north-northeast of Columbia River Basalts on Baldy Mountain with a ridge of Clarno andesite flows below. Mudflows are exposed at the base of the ridge. An angular discordance is located between the flows halfway up the ridge. Permian metasediments are in the foreground. Located north of Rattlesnake Creek, in the N 1/2, section 31, T. 10 S., R. 23 E.

Figure 9. View north of south slope of south peak of Keyes Mountain. A sequence of Clarno andesite flows can be seen dipping toward the camera. Located in the NW 1/4, section 25 and NE 1/4, section 26, T. 11 S., R. 22 E.

Figure 10. View northeast of a caprock of Clarno andesite flows over Cretaceous Hudspeth mudstone. Located at the intersection of sections 1, 2, 11, and 12, T. 11 S., R. 22 E.

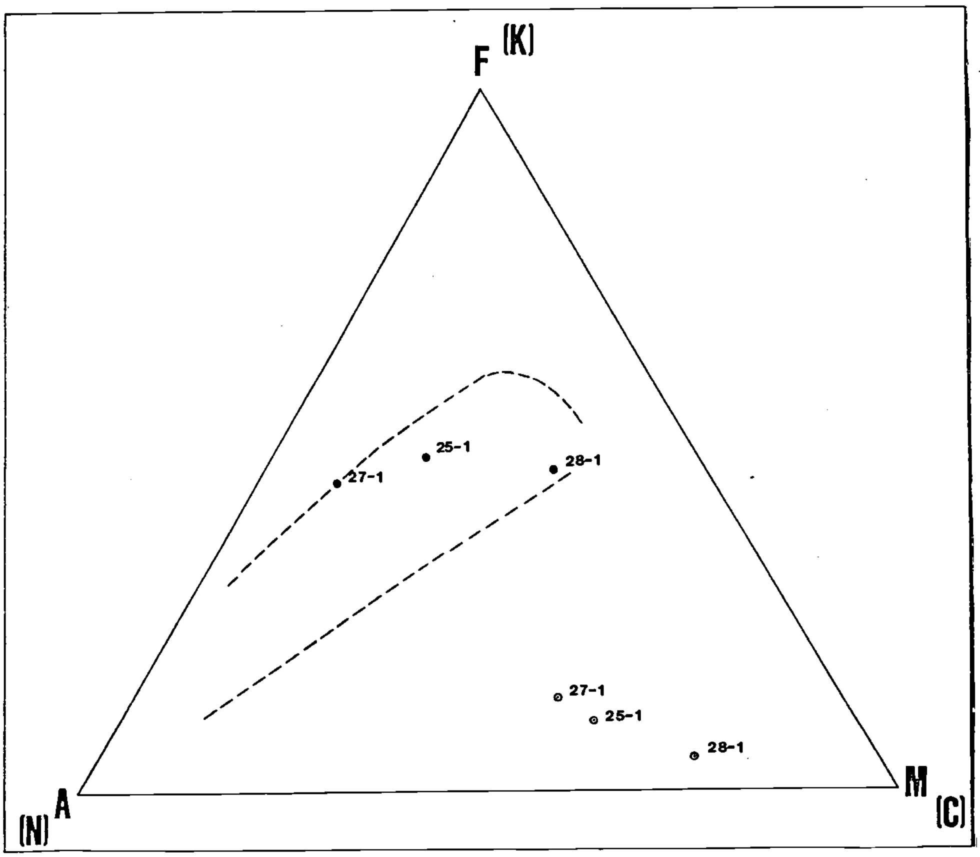

Figure 11. AFM diagram after Nockolds and Allen (1953) for Clarno andesite flows. Dashed lines show Kuno's hypersthenic series (1968). KCN plots are shown as circles.

Fresh andesite flows are medium gray (N 5) to light gray (N 7) with minor light brownish gray (5 YR 6/1). Altered flows are light olive gray (5 Y 4/1) to olive gray (5 Y 6/1), greenish gray (5 GY 4/1 to 6/1) to dark greenish gray (5 G 4/1 to 6/1), very light gray (N 8), medium dark gray (N 4) or dark gray (N 3). Staining resulting from surficial weathering colors the flows dusky red (5 R 3/4) or dark reddish brown (10 R 3/4). Streaks or parallel bands of hematite commonly stain both the rock and plagioclase phenocrysts.

All the andesite flows in the study area are aphanitic, porphyritic, and non-vesicular, except for extreme local examples of vesicularity.

Andesite flows range from two to sixteen meters thick. Locally, thinner flows coalesce to form a much thicker one. The thickest flows were exposed in cliff face and, although not directly measured, are estimated to be 30 meters thick.

Horizontal platy jointing is characteristic in the flows. The plates are typically two to several centimeters thick. The surfaces of the joints are curved, smooth, and oxidized to shades of reddish brown. However, exceptionally thick flows exhibit blocky jointing and, in a few cases, polygonal columnar jointing. The columns are a few to 20 cm in diameter.

Fault zones within the andesites exhibit alteration to shades of pale purple (5 P 6/2), bluish white (5 B 9/1), and pale red purple (5 RP 6/2). The andesite is poorly resistant, crumbly, and contains abundant veins and veinlets of calcite and stilbite, either in open-work or closed-work arrangement. Immediately adjacent to the fault zone, the andesite is very much altered to a dark greenish gray (5 GY 4/1). Other fault breccias were observed that did not display any discoloration of the andesite, but were cemented with white (N 9) chalcedony and local red jasper.

Mineralogy

All the flows within the study area are aphanitic, porphyritic, and locally glomeroporphyritic. The abundances of phenocrysts in hand specimen average 12 percent, but range from less than one to 40 percent of the rock. Phenocrysts discernible to the eye are plagioclase, clinopyroxene, hypersthene, hornblende, magnetite and magnetite pseudomorphs after hornblende. They generally are 2 mm long, but locally exist up to one centimeter. Locally glomerophenocrysts are found to one centimeter in diameter.

Some sequences of andesite flows exhibit vertical progressions in mineralogy. For instance, in the south peak of Keyes Mountain, in the NW 1/4, section 25, T. 11 S., R. 22 E., the
plagioclase and impoverishment of
andesite flows exhibit a progressive enrichment of pyroxene up

section. This phenomenon is likely the result of decreasing magmatic temperature; at lower temperatures the first phenocryst phase to develop would be plagioclase.

Flow Breccias

Flow breccias mantle the andesite flows (Fig. 12), and are commonly more resistant than the andesite flows. For this reason, flow breccias commonly crop out, whereas the accompanying andesite flows do not.

Examples of a flow breccia can be found on the north side of the microwave station road, in the extreme SW corner of section 25, T. 11 S., R. 22 E., and in the NW 1/4, SE 1/4, SW 1/4, section 25, T. 11 S., R. 22 E. Characteristically they are (1) pale red purple (5 RP 6/2) or pale red (5 R 6/2 to 10 R 6/2), (2) composed of non-vesicular andesite fragments in matrix-support, the matrix commonly comprising 70 percent of the rock, (3) commonly brittle and glass-like, sounding like porcelain when struck with a hammer, and (4) non-bedded. Local bottom-flow breccias display reverse size-grading: matrix-supported in the lowermost part, grading upwards into framework support, and finally into fragmented andesite without matrix. Rare vugs or vesicles exist in local exposures. These openings are locally coated with

Figure 12. Andesite flow breccia. Flow breccias typically crop out, whereas the accompanying andesite flows do not. Located in the SW 1/4, SW 1/4, SW 1/4, section 25, T. 11 S., R. 22 E.

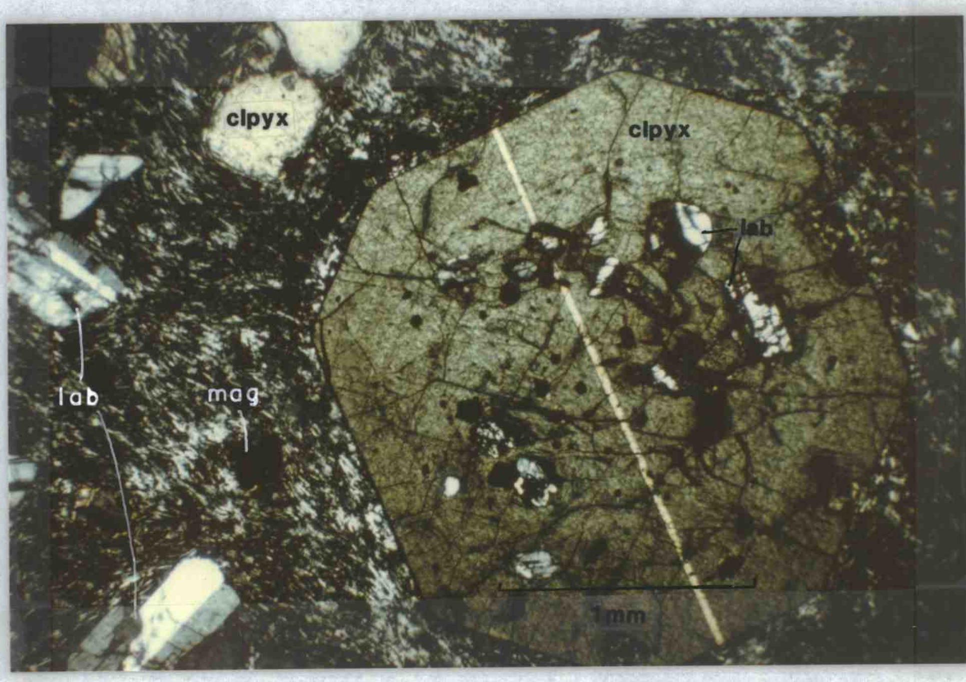

Figure 13. Photomicrograph of hornblende-bearing, hypersthene, clinopyroxene labradorite andesite (sample 6-7). Shows a twinned, euhedral clinopyroxene phenocryst with inclusions of labradorite and magnetite and stained with crystalline hematite and phenocrysts of twinned labradorite and magnetite. The groundmass is a subpilotaxitic arrangement of andesine microlites. Located in the SE 1/4, SE 1/4, section 25, T. 11 S., R. 22 E.

botryoidal deposits of silica, flattened, or stretched.

The andesite fragments within the flow breccias are (1) greater than 32 mm diameter, (2) monolithologic, (3) commonly pale red (5 R 6/2) to moderate red (5 R 5/4), or medium dark gray (N 4), with minor pale purple (5 P 6/2), light brown (5 YR 6/4), grayish brown (5 YR 3/2), and dark yellowish brown (10 YR 4/2), and (4) are dominantly subangular or subrounded, but ranging from angular to rounded. One lapilli-sized bomb was found.

The flow breccia matrix is indistinguishable from andesite, except for contrasting coloration. The matrix is medium gray (N 5), pale red (5 R 6/2), moderate red (5 R 5/4), or light bluish gray (5 B 7/1). Macdonald (1972) attributes this dense, andesite-like flow breccia to originate from breccias where the liquid lava filtered down between the rock fragments at the bottom of a flow, or the fragments settled down into the liquid at the top of the flow. Common variation exists in percentage, relative proportion, types, and size of phenocrysts between matrix and fragments. A few flow breccias were found which contain as high as 20 percent phenocrysts in the matrix.

Petrography

Fourteen mineralogically distinct andesite flows were petrographically analyzed. The following petrographic characteristics are common to all andesite flows. The andesites are (1) holocrystalline or hypohyaline, (2) microcrystalline, and (3) porphyritic. The phenocrysts comprise andesine, labradorite, clinopyroxene, hypersthene, magnetite, very minor hornblende or lamprobolite, and/or magnetite pseudomorphs after hornblende or lamprobolite. Glomerophenocrysts are common. The andesites average 24 percent phenocrysts, ranging from 2 to 40 percent. The phenocrysts average 70 percent plagioclase to 30 percent ferromagnesian minerals, ranging from 2 to 90 percent plagioclase. Table I illustrates the statistical evaluation of the relative percentages of constituents in four andesites.

Many flows exhibit a subparallel alignment of phenocrysts and microlites. Broken phenocrysts are also common. The alignment and fracturing of the minerals and platy jointing result from late stage flowage of a semi-solid lava.

Plagioclase phenocrysts are ubiquitous in all flows. Only samples 20-2 and 21-2 contain as little as two and ten percent plagioclase respectively. The plagioclase is found up to one centimeter in length and is anhedral to subhedral, rarely being euhedral. Table I illustrates that plagioclase phenocrysts comprise between 24 and 41 percent of the rocks that were statistically analyzed.

TABLE I. VOLUMETRIC MODES OF SELECTED CLARNO ANDESITE FLOWS

Sample	6-7	4-13	20-2	34-4
Phenocryst Phases				
Andesine	--	--	40*	--
Labradorite	24	41	--	41
Clinopyroxene*	10	10	12	15
Hypersthene	7	--	1	1
Unidentified pyroxene	Tr	--	--	--
Magnetite				
Pseudomorphs after hornblende	--	3	--	--
Groundmass Phases:				
Andesine microlites	24	2	--	6
Nondescript mineral mass	27	37	--	32
Smectite and nondescript mineral mass	--	--	43	--
Magnetite	8	4	4	1
Secondary quartz	Tr	3	--	4
Apatite	Tr.	--	--	--

*Phenocryst and groundmass phases were counted together on account of the extremely small size of the groundmass phase. Andesine phenocrysts and microlites were counted together.

6-7 Hornblende, hypersthene, clinopyroxene, labradorite andesite flow. Located on the SE slope of the south peak, Keyes Mountain, SE 1/4, SE 1/4, section 25, T. 11 S., R. 22 E.

4-13 Hornblende, clinopyroxene, labradorite andesite flow. Located on the SW slope of the south peak, Keyes Mountain, SE 1/4, NE 1/4, section 26, T. 11 S., R. 22 E.

20-2 Andesine, clinopyroxene, hypersthene andesite flow. Located in the west side of Monroe Roughs, in the NE 1/4, SE 1/4, section 14, T. 11 S., R. 22 E.

34-4 Hypersthene, clinopyroxene, labradorite andesite flow. Located north of Bearway Meadows, in the NW 1/4, SE 1/4, SW 1/4, section 8, T. 11 S., R. 23 E.

Compositionally the plagioclase phenocrysts range from An_{48} to An_{70}, averaging An_{60}. Nearly all phenocrysts exhibit albite and Carlsbad twinning (Figs. 13 and 14) with rare examples of pericline twinning. Zoning is common but is usually limited to only a small percentage of the phenocrysts in each rock. Common normal and oscillatory zoning along with abundant examples of reverse and patchy zoning are found in the plagioclase (Figs. 15 and 16). Resorption rims within some plagioclase phenocrysts are found in a few flows. Zoning in plagioclase phenocrysts are found in a few flows. Zoning in plagioclase is characteristic of extrusive and hypabyssal andesites (Nockolds et al., 1978; Taylor, 1960) and most likely manifests the relaxation of confining pressure on a magma chamber by intermittent eruptions (Taylor, 1960; Vance, 1965). However, the mixture of the non-zoned with the zoned phenocrysts in the samples studied is problematic. The mixing of magma in the subsurface could account for this phenomenon. This concurs with Taylor (1960) who found Clarno andesites with an odd association of phenocrysts of quartz and calcic plagioclase and a peculiar combination of stable and unstable plagioclase. Rare glass blebs found within the plagioclase are thought to be the result of very rapid extrusion of lava.

The groundmass plagioclase microlites are euhedral to

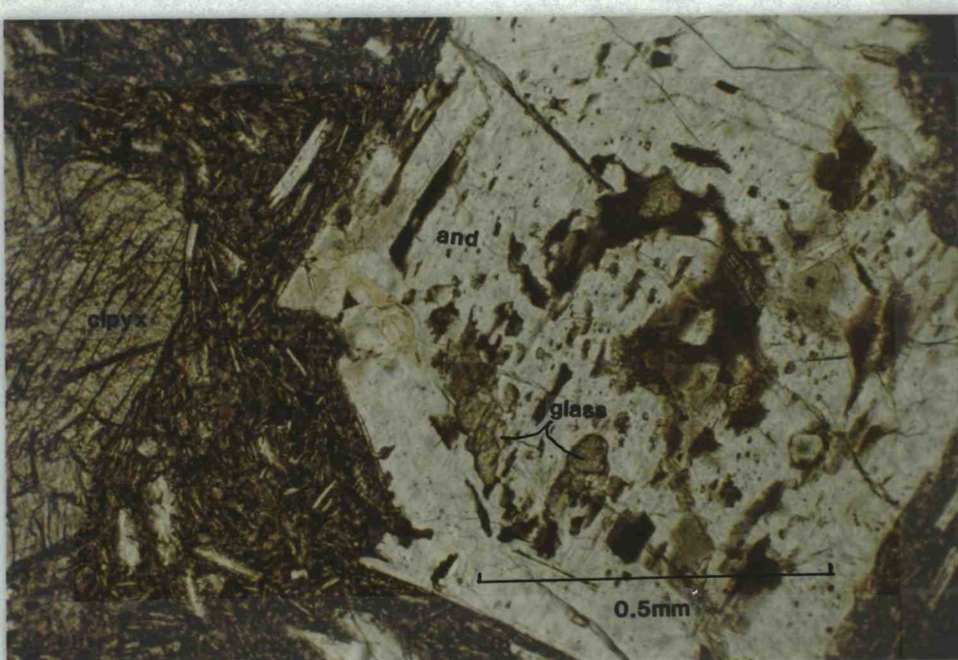

Figure 14a. Photomicrograph of hypersthene- and hornblende-bearing, clinopyroxene labradorite andesite (sample 4-13). Shows phenocrysts of euhedral magnetite pseudomorphs after hornblende, hypersthene, labradorite (An_{60}) and magnetite. Groundmass is an intersertal to felted arrangement of andesine microlites, a nondescript feebly birefringent mineral mass and minute euhedral clinopyroxene. Located in the center of the SE 1/4, NE 1/4, section 26, T. 11 S., R. 22 E.

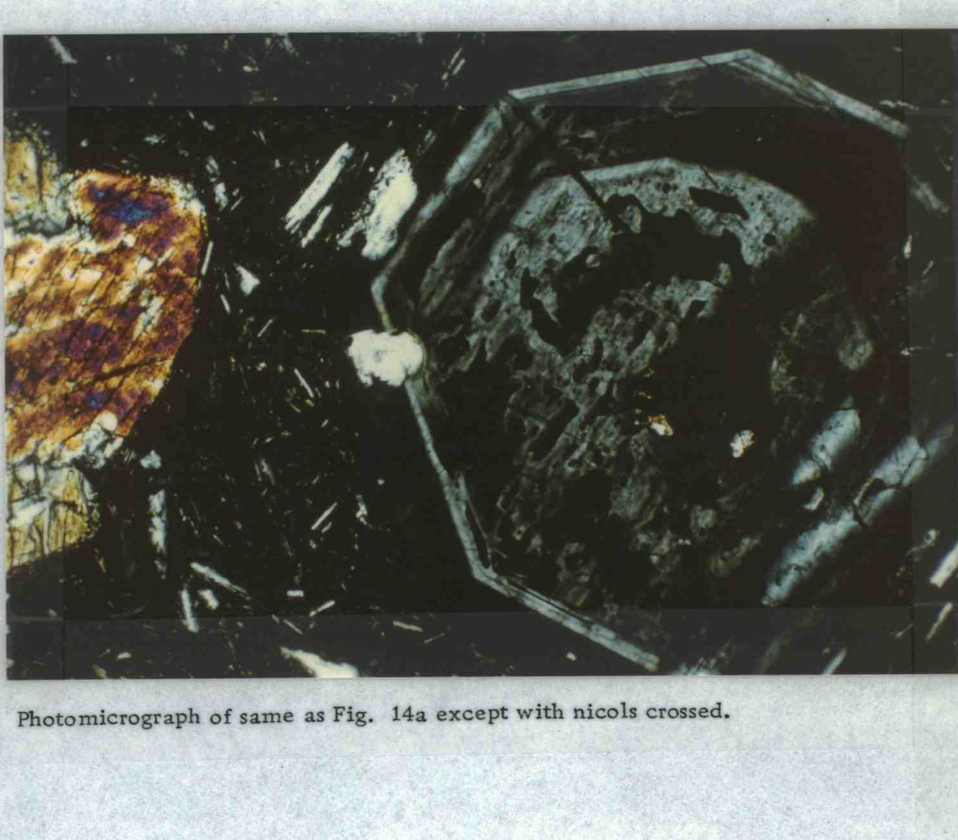

Figure 14b. Photomicrograph of same as Fig. 14a except with nicols crossed.

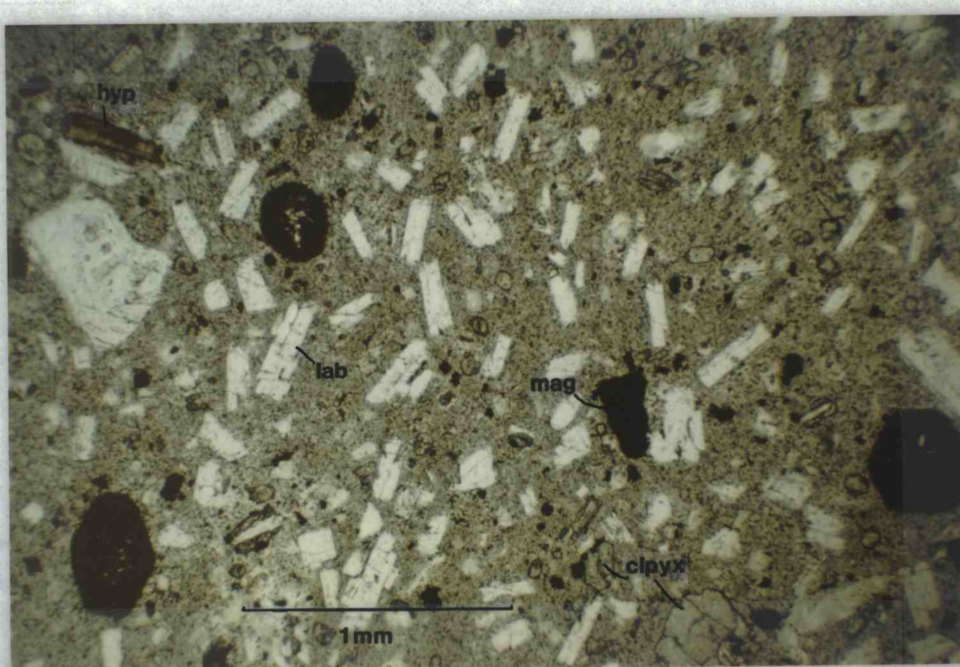

Figure 15a. Photomicrograph of hypersthene, clinopyroxene andesine andesite (sample 37-3). Shows phenocrysts of clinopyroxene and andesine (An_{48}) with oscillatory and reversed zoning and inclusions of pale green glass. The groundmass is a hyalopilitic arrangement of andesine (An_{41}) microlites, brown glass, minute granular pyroxene and apatite. Located in the center of the SE 1/4, NE 1/4, section 28, T. 11 S., R. 22 E.

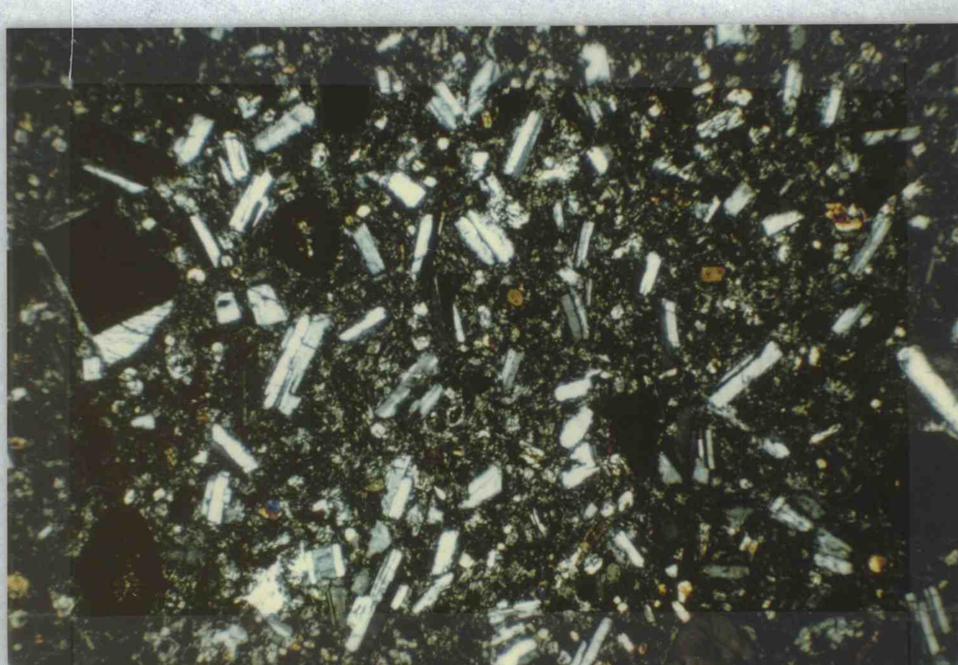

Figure 15b. Photomicrograph of the same as Fig. 15a except nicols crossed.

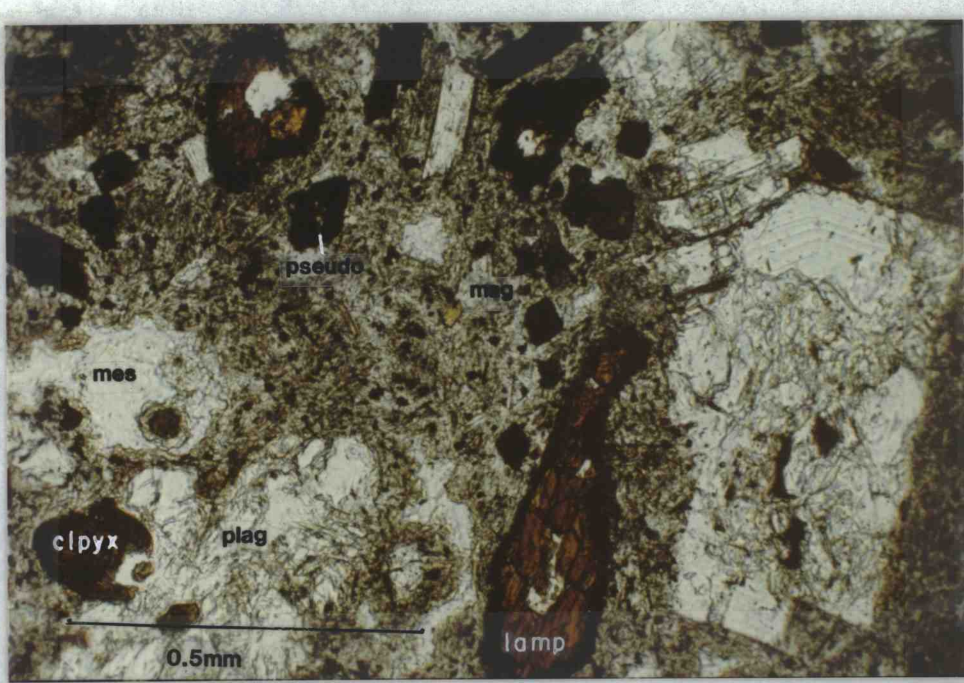

Figure 16a. Photomicrograph of lamprobolite-bearing, clinopyroxene plagioclase andesite (sample 3-7). Phenocrysts of plagioclase badly altered to zeolite, resorbed lamprobolite with magnetite rims, magnetite pseudomorphs after lamprobolite, olive green clinopyroxene, and magnetite. Groundmass is an intersertal arrangement of plagioclase microlites, a nondescript feebly birefringent mineral mass, hematitic clay, magnetite and mesolite. Located in the center of the S 1/2, SW 1/4, section 24, T. 11 S., R. 22 E.

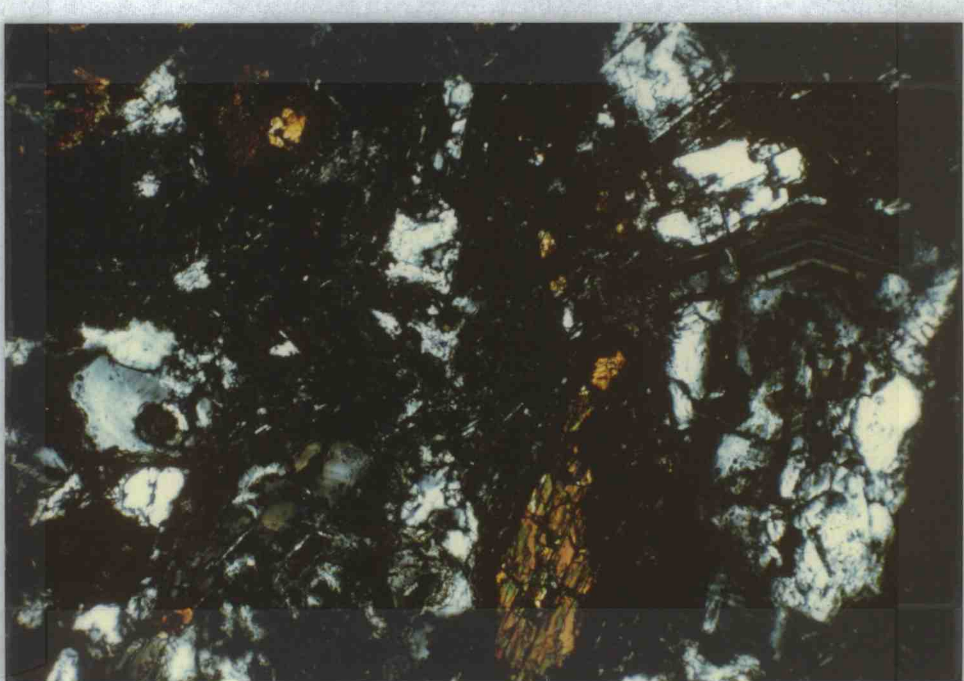

Figure 16b. Photomicrograph of same as Fig. 16a except with nicols crossed.

subhedral and compositionally range from An_{34} to An_{48}, averaging An_{40}. Table I illustrates that the volumetrically analyzed samples contain 2 to 24 percent groundmass andesine.

Plagioclase phenocrysts commonly are slightly altered to smectite and/or zeolite, most likely laumontite (Fig. 16a). Taylor (1960) reports that the plagioclase in Clarno andesite is commonly altered to heulandite, laumontite, and stilbite. Glass blebs within the phenocrysts commonly are partly to wholly altered to celadonite. Rare alteration products include calcite and sericite. Red plagioclase phenocrysts in hand sample reveal microfractures filled with hematite when observed in thin section. Green and brown plagioclase exhibited in hand specimens are celadonite alteration and limonite staining, respectively.

Pyroxene phenocrysts exist in all andesite flows whether or not they are observable in hand specimen. The relative percentages of clinopyroxene and hypersthene vary greatly from flow to flow, some flows having much more hypersthene than clinopyroxene and other flows displaying theopposite. In samples 3-5, 3-9, 4-8a, and 4-13 the hypersthene is altogether absent. Generally however, the hypersthene phenocrysts display a greater degree of crystal form, commonly being euhedral (Figs. 13-17), and are smaller than the clinopyroxene. Both clinopyroxene and hypersthene are locally found to be as much as six millimeters long. Normal zoning and simple twinning are common in clinopyroxene (Fig. 13) and uncommon in hypersthene. In sample 13-1 the clinopyroxene displays an anomalous pale brown to pale green pleochroism.

The pyroxenes are commonly partly to wholly altered to celadonite or some type of smectite clay (Fig. 16). Minor alteration products include chlorite, biotite, and hematite. In some samples, pseudomorphs of celadonite or magnetite after pyroxene exist. Rims of magnetite, smectite and celadonite are common. Sample 4-3 contains a trace of hornblende that displays pyroxene cores. Sample 13-1 contains unaltered subhedral to euhedral clinopyroxene, whereas the euhedral hypersthene is pseudomorphed by celadonite. This selective alteration is most likely the result of hydrothermal alteration. Sample 3-9 contains some clinopyroxene phenocrysts that display cores of biotite. Samples 3-7 and 3-9 contain clinopyroxene displaying dark brown perimeters (Fig. 16) which Owen (1977) determined to be pigeonite phenocrysts. Sample 3-2 contains hypersthene with granular clinopyroxene rims.

Some andesite flows contain lamprobolite or hornblende in amounts up to 25 percent. Table I illustrates that of the four

Figure 17. Photomicrograph of hypersthene, clinopyroxene labradorite andesite (sample 34-4). Shows phenocrysts of hypersthene and clinopyroxene pseudomorphs after hornblende. Green smectite alteration of clinopyroxene is visible. Located in the NW 1/4, SE 1/4, SW 1/4, section 8, T. 11 S., R. 23 E.

statistically analyzed samples, only one contains three percent magnetite pseudomorphs after hornblende. Both hornblende and lamprobolite are fresh or slightly to wholly replaced by magnetite (Figs. 14 to 16). Lamprobolite exists up to two millimeters in length and is anhedral to euhedral, slender prismatic, and usually displays various degrees of corrosion (Fig. 16). Hornblende is found up to four millimeters in diameter, either as slender prismatic or columnar crystals, and exhibits subhedral to euhedral form. Sample 3-7 contains approximately one percent unaltered, subhedral to anhedral lamprobolite to two millimeters long. Sample 3-9 contains a trace amount of subhedral lamprobolite to two millimeters in length which is partly to wholly replaced by magnetite. Sample 4-3 contains a trace amount of anhedral to subhedral pseudomorphs of hematite after magnetite after hornblende to three and one-half millimeters in length, some of which display cores of pyroxene. Sample 4-8a contains a minor amount of euhedral to subhedral lamprobolite to two tenths of a millimeter which is partly to wholly replaced by magnetite. Sample 4-13 contains one percent subhedral to euhedral magnetite pseudomorphs after hornblende to one-half millimeter in length (Fig. 14). Sample 6-7 contains a trace amount of subhedral hornblende to one quarter of a millimeter. Sample 34-4 contains 25 percent euhedral to subhedral clinopyroxene pseudomorphs after hornblende to four millimeters long (Fig. 17). Sample 37-3 contains a trace of subhedral lamprobolite to one quarter millimeter long which is partly to wholly replaced by magnetite.

The groundmass of the andesite flows is dominantly intersertal (Figs. 14 and 16) but includes minor felted, pilotaxitic (Fig. 13) and hyalopilitic (Fig. 15) textures. The intersertal texture is composed of minor amounts of minute, granular anhedral clinopyroxene, minor apatite, anhedral to euhedral magnetite to five percent, a large proportion of andesine microlites, and variously fresh or devitrified glass, smectite, or a nondescript, feebly birefringent mass of minerals, resembling a mixture of feldspar and quartz (Figs. 14 and 16). The andesine microlites range from An_{34} to An_{48}, averaging An_{40}. Secondary polycrystalline quartz exists in some flows. Table I statistically illustrates the groundmass composition of four flows. The samples consist of 27 to 43 percent of the nondescript, feebly birefringent mass of minerals, 2 to 24 percent andesine microlites, 1 ot 8 percent magnetite, 1 to 4 percent secondary quartz, and up to 1 percent apatite.

Alteration products commonly found in the groundmass are smectite clays, celadonite, zeolites--specifically mesolite (Fig. 16)--crystalline hematite, limonite, very minor calcite, and devitrified glass with a cryptocrystalline "salt-and-pepper"-type extinction. Rare vugs display fillings of mesolite or chalcedony.

II. Mudflow Breccias

Geomorphology

Mudflows are highly variable in topographic expression. Commonly they form suppressed landforms such as gentle slopes and valleys. Locally they form ridges, cliffs (Figs. 18 and 20), hoodoos, and steep hillslopes beneath andesite caprocks. In contrast to andesite flows, they are more eroded, forming an irregular gullied topography.

Soil development upon mudflows is also highly variable. Highly resistant mudflows are mantled by a thin veneer of granular soil, and poorly resistant types by a thick cover. The soil is characteristically streaked and mottled in colors of white (N 9), grayish orange pink (5 YR 7/2), dark yellowish orange (10 YR 6/6), pale red (10 R 6/2), and light olive gray (5 Y 6/1) to olive gray (5 Y 4/1). The prevailing color is pale yellowish brown (10 YR 6/2). Strewn upon the surface are pebbles, cobbles, and boulders of various types of andesite that have weathered out of a less resistant matrix; the clasts are subrounded to rounded, but locally

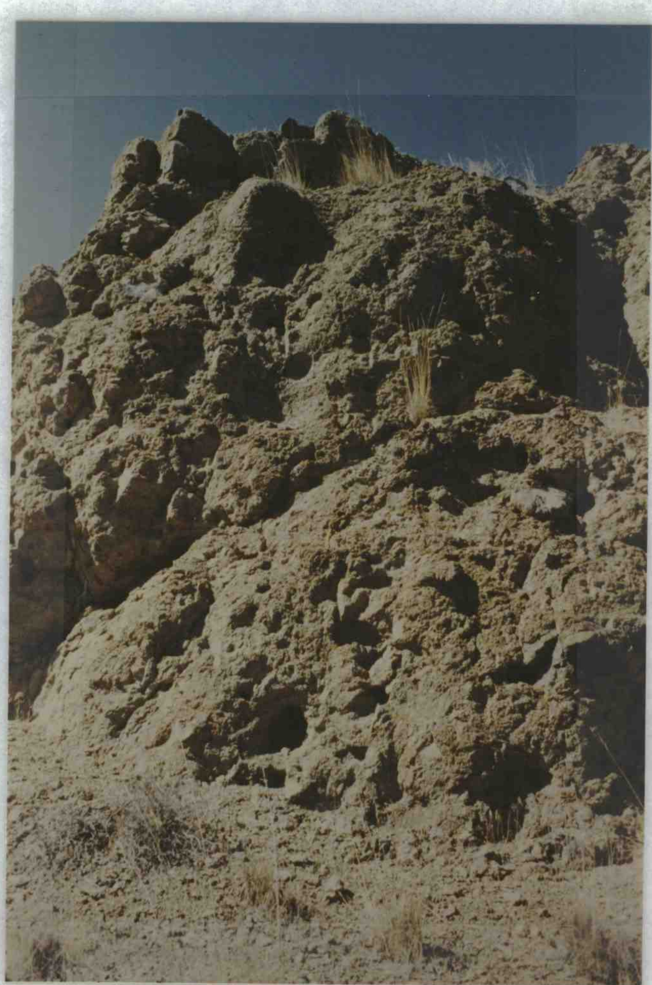

Figure 18. Typical outcrop expression of a Clarno mudflow. Note extreme poor sorting. Located in the SE 1/4, NW 1/4, NW 1/4, section 35, T. 11 S., R. 22 E.

subangular.

The most resistant mudflows crop out through the soil cover either as irregular knobs or local, irregular sliver-like joints with a very granular surface texture.

In contrast to highly resistant types, the less resistant mudflows seldom crop out through the soil. Exposures have a rough but even surface texture with irregular fractures. The soil forms discrete blocky masses from one-half to several centimeters in diameter. This texture nearly resembles the "popcorn" textured soil that develops on the John Day tuffs. This texture is the result of highly expandable clays that shrink and swell upon dehydration and hydration respectively.

The vegetative cover ranges from sparse grasses and juniper to thick forests of white and ponderosa pine and Douglas fir.

General Characteristics

Mudflow breccias are the second most abundant rock unit in the study area (Figs. 18 and 19). They are interstratified with the andesite flows, and few contacts were observed because of soil and vegetative cover. The few bottom contacts that were observed proved to be highly irregular. Most mudflows occupy channels where seen in cross-section.

Figure 19. Closeup of a Clarno mudflow breccia. Shows extreme poor sorting and range of angularity of the clasts.

Figure 20. A ridge composed entirely of Clarno mudflow, estimated to be approximately 230 meters thick. Located in section 36, T. 10 S., R. 22 E.

The mudflows range from less than two to 230 meters thick (Fig. 20), and are shoestring-like bodies deposited in Clarno age channels (Fig. 21).

Clasts within the mudflows range from pebble- to boulder-size. On the south peak of Keyes Mountain, mudflow clasts are found to five meters in diameter, but at a few localities they are as much as ten meters. Huge boulders of Cretaceous Gable Creek conglomerate are found within one mudflow channel situated on the west side of the study area (Fig. 22).

Fault zones within mudflows are characteristically silicified or extremely altered to a crumbly consistency and discolored to shades of green, orange, and red. In addition there are abundant veins and veinlets of stilbite and calcite which display laminated, open-work, and closed-work structures.

Lithology

Mudflows are characterized by the following: (1) extremely poor sorting; (2) a general lack of bedding; (3) matrix-support; and (4) flat tops and irregular bottoms.

Mudflows are dominantly very pale orange (10 YR 8/2), pinkish gray (5 YR 8/1), or grayish orange pink (10 R 8/2). Locally they are greenish gray (5 G 6/1) because of pervasive smectite

Figure 21. Shows a Clarno mudflow channel that flowed west from Keyes Mountain. This is also the locality where abundant mudflow sediments, tuffs, and petrified logs are located. Located in the W 1/2, section 22, T. 11 S., R. 22 E. (Photo by Dr. Keith F. Oles)

Figure 22. Extremely large boulders of Cretaceous Gable Creek conglomerate are found within the mudflows in Fig. 21. These boulders attest to the fact that the mudflows flowed over an ancient rugged terrain of Cretaceous rocks. (Photo by Dr. Keith F. Oles with Dr. W. D. Wilkinson for scale)

alteration. They are composed of pebble- to boulder-sized rock clasts supported in a sand-silt-clay matrix. The clasts are dominantly subrounded, ranging from angular to subrounded, and monolithologic or heterolithologic. The dominant clasts are composed of andesite, but local tuff, basalt, pebbles and cobbles and boulders of Cretaceous conglomerate, chert, and quartzite, and fragments of Permian phyllite, schist, and limestone exist. One mudflow is composed predominantly of tuff clasts with minor andesite clasts (Fig. 23).

The mudflow matrix consists of sand, silt, and clay. The sand-sized fraction is composed of subangular to subrounded andesite fragments and mineral detritus. The minerals dominantly are subhedral to euhedral clinopyroxene and plagioclase crystals up to five millimeters in length. Very local hornblende crystals are found, some to three centimeters in length. The crystals comprise four percent of the matrix, locally up to 15 percent. Minerals of the same species commonly display varying degrees of alteration.

Very few outcrops of bedded sedimentary strata within the mudflows were observed (Fig. 24). Existing exposures exhibit crude crossbedding within the mudflows, along with fine-grained strata of laminated to thin-bedded[2] sandstone, siltstone, and

[2]stratal thickness parameters fromMcKee and Weir (1953).

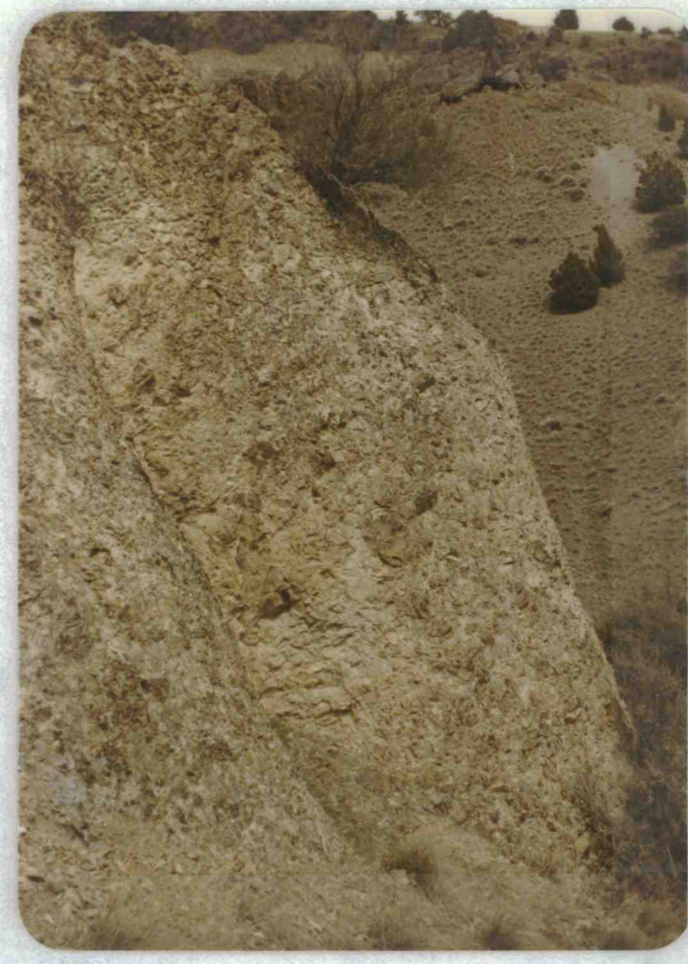

Figure 23. Clarno mudflow breccia composed predominantly of tuff clasts and minor porphyritic andesite. Located in Rattlesnake Creek, in the center of the N 1/2, SW 1/4, section 31, T. 10 S., R. 23 E.

claystone.[3] One example is found along the Hudspeth road, in the center of the S 1/2, S 1/2, section 12, T. 11 S., R. 22 E. Here a channel of sedimentary strata three meters long and one meter deep is exposed. The surrounding mudflow is classified as a sandy boulder conglomerate. The strata exhibit thin to very thin beds of pebbly sandstone that grade upward into a medium sandy siltstone, interbedded and interlaminated with conglomeratic medium to coarse sandstone. A subordinate amount of the pebbles, cobbles, and boulders consist of Cretaceous Gable Creek quartzite and Hudspeth mudstone. Some soft-sediment deformation was observed in this channel. The best exposure is situated along the Hudspeth road, in the NW 1/4, SW 1/4, NE 1/4, section 22, T. 11 S., R. 22 E. (Fig. 24). This exposure exhibits parallel laminations and festoon cross-laminations in silty fine to medium sandstone and silty fine sandstone. In addition, there are interstratified laminated to thin-bedded, pebbly, fine to coarse sandstone and fine to medium sandstone, with minor thick interbeds of bouldery, pebble-cobble conglomerate. Normal and reverse grading are displayed within this outcrop, indicating turbulent flow and torrential deposition.

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[3] textural classification of sedimentary rocks from Miller and Scholten (1966).

Cross-bedding in this exposure indicates a paleocurrent flow direction to the west. The other exposures are located on the steep hillside, in the NW 1/4, SE 1/4, section 22, T. 11 S., R. 22 E., and exhibit similar features to that along the Hudspeth road. This locality contains abundant petrified logs to 25 cm in diameter either in original growth position or aligned in horizontal subparallel fashion. Abundant carbonaceous remains and imprints of woody debris are found. Within this locality abundant examples of parallel lamination, festoon and planar cross-lamination, and normal and reverse grading are found. The southwest paleocurrent direction from these outcrops was averaged from the azimuths taken from cross-bedding and subaligned, horizontal petrified logs.

The westward current directions of the mudflows indicate the mudflows were derived from a nearby volcanic highland to the east, and that same volcanic highland must have been Keyes Mountain because east of Keyes Mountain the Clarno rocks are deeply buried beneath John Day tuffs and Columbia River basalts, existing at much lower elevations.

Petrography

Three samples of mudflows were examined petrographically. These samples were 5-3, 5-4, and 35-1. The matrix is composed

Figure 24. Outcrop of bedded sedimentary strata within a Clarno mudflow. Chalk marks show cross bedding that indicates a paleocurrent flow direction to the west. Description in text. Located in the NW 1/4, SW 1/4, NE 1/4, section 22, T. 11 S., R. 22 E. (Photo by Dr. Keith F. Oles)

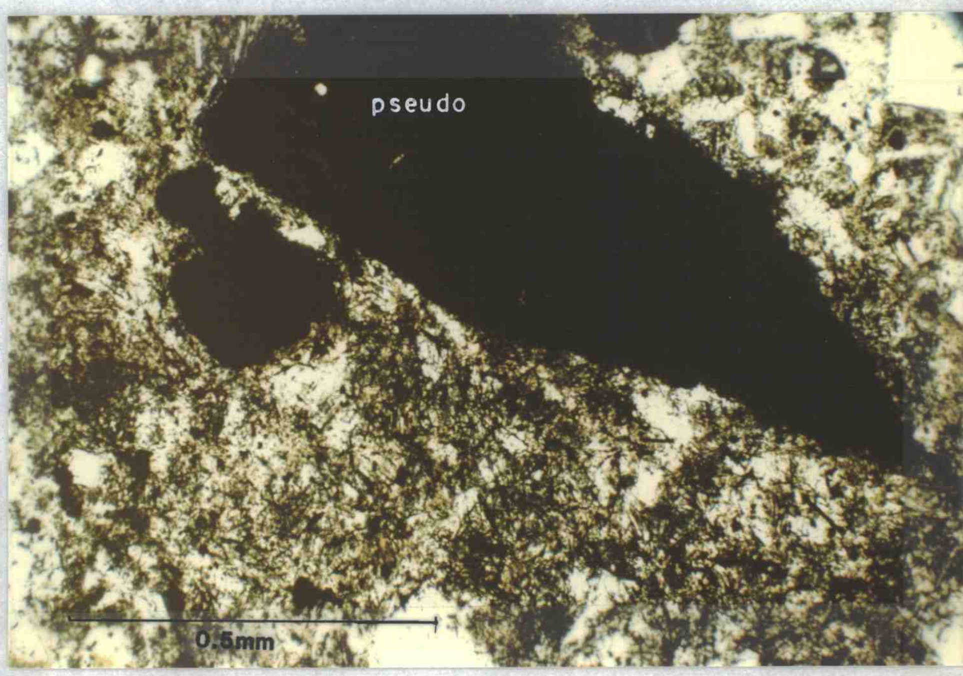

Figure 25. Photomicrograph of a Clarno mudflow. Shows a magnetite pseudomorph after lamprobolite with some lamprobolite visible within the phenocryst. Matrix composed of much opaque clay and fragments of plagioclase phenocrysts. Located in the center of section 2, T. 11 S., R. 22 E.

of unidentifiable silt, opaque clay, and green glass (Fig. 25) along with whole and fragmented crystals of labroadorite, andesine, clinopyroxene, magnetite, hornblende, magnetite pseudomorphs after hornblende, lamprobolite, sanidine, and plagioclase microlites. Some plagioclase crystals contain glass blebs and exhibit resorption rims. Sample 5-4 contains minute clasts of holohyaline basalt and silicic rock fragments resembling opal, flow banded rhyolite, or rhyodacite.[4]

Each mineral species displays variable degrees of alteration. Plagioclase has been altered to zeolite and smectite, clinopyroxene to celadonite, and magnetite to hematite. The groundmass glass and glass shards are either devitrified or altered to smectite. Taylor (1960) reports that heulandite, laumontite, and stilbite are common in Clarno mudflows.

III. Volcanic Agglomerate

Geomorphology

The Clarno volcanic agglomerate is moderately to poorly resistant. It forms the eroded floor and sideslopes at the head of Marshall Creek. Springs are abundant.

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[4]these fragments are identical to rhyolite and rhyodacite documented in Barnes (1978).

The soil developed upon this unit is thick and pale yellowish brown (10 YR 6/2). It is granular to blocky with discrete masses ranging from 0.5 to 15 mm in diameter. However, this blocky nature is not as well developed as in the mudflow soil.

Rock fragments weathered out of the less resistant matrix are scattered about the surface. These fragments differ from those of the mudflows in that they are quite heterolithologic and contain amygdaloidal to vesicular andesite and tuff. Also, the fragments are dominantly subangular, ranging from angular to subrounded. It is observed that surficial exposure and weathering produce a higher degree of roundness than those fragments still embedded within the agglomerate.

The vegetative cover developed on this unit is characterized by thick growths of pine, juniper, and thickets of brush and grasses.

General Characteristics

There are two separate outcrops of volcanic agglomerate within the study area. The largest exposure crops out in the basin-like canyon at the head of Marshall Creek, situated in the SE 1/4, section 24, and the NE 1/4, NE 1/4, section 25, T. 11 S., R. 22 E. These exposures are found along the microwave station road and in isolated exposures within the heavily forested basin. The other volcanic agglomerate crops out at a small quarry on the east side of Harrison Creek, situated in the center of the W 1/2, NE 1/2, NE 1/2, section 6, T. 12 S., R. 23 E. The Marshall Creek and Harrison Creek agglomerates are dissimilar and will be separately described.

The Marshall Creek agglomerate (Fig. 26) crops out only locally within the heavily forested basin. Because of the lack of exposure, no contacts were observed, and all contacts were approximated along topographic breaks in slope, normally coinciding with topographically higher andesite flows. The contacts between the Harrison Creek agglomerate and andesite wall rocks are readily observed within the quarry. Above the quarry the agglomerate can be traced for a very short distance of about eight meters, establishing its very limited dimensions.

According to Oles and Enlows (1971), an agglomerate is a pyroclastic deposit within and immediately adjacent to the vent of a volcano. It is a breccia consisting of a poorly sorted arrangement of porphyritic andesite fragments and matrix. The andesite fragments are angular to subrounded and range from boulder- to small pebble-sized. The matrix consists of a medium- to coarse sand-sized mixture of plagioclase laths, lithic fragments and much smectite clay (Oles and Enlows, 1971). Other criteria for

Figure 26. Outcrop of volcanic agglomerate at the head of Marshall Creek. Located in the NW 1/4, SE 1/4, section 24, T. 11 S., R. 22 E.

Figure 27. Harrison Creek parasitic-vent agglomerate. Outcrop in a quarry shows wallrock of platy andesite with fragments partially assimilated into the vent breccia. Located between sections 19 and 30, T. 11 S., R. 23 E.

recognition of an agglomerate according to Parsons (1969) are (1) the extreme size range of the fragments and extreme poor sorting, (2) lack of bedding, (3) thick localized deposit geometry, and (4) included lenses of andesite. Likewise, the basinal landform occupied by the agglomerate at Marshall Creek is quite suggestive of an eroded, central vent complex of poorly resistant and rubbly pyroclastic debris, brecciated rock, and minor andesite flows.

There exists a high degree of similarity between the Marshall Creek agglomerate and some of the highly resistant mudflows within the study area. These mudflows occur in the center of section 14, T. 11 S., R. 22 E. and in the NW 1/4, NW 1/4, section 35, T. 11 S., R. 22 E. The distinction between the mudflows and the agglomerate is mentioned below in detail. The likeness between the two breccias may be attributable to an agglomerate source rock for the mudflows.

Discussion. The literature is confusing and vague as to what constitutes agglomeratic and mudflow breccias and what characteristics differentiate the two. Often identical breccias may be produced by entirely different modes of origin.

This author concludes, after study of the literature and work in the field, that lithology alone will not reveal the mode of origin of a volcanic breccia. That is, mudflow and laharic breccias, agglomerates, flow breccias, and breccia dikes and plugs may all be lithologically alike. Therefore, the definitive criteria as to the mode of origin of a rock unit, specifically a breccia, is in the structural and stratigraphic relationships such as bedding, deposit geometry, cross-cutting relationships, and superposition. Parsons (1969) states that,

> vent-filling volcanic breccias can be recognized and distinguished only if the material is seen in place in an eroded and exposed vent structure where their structural relationships can be studied and their origin can therefore be worked out.

Lithology

The Marshal Creek agglomerate (Fig. 26) is an overall pale yellowish brown (10 YR 6/2) to a pale brown (5 YR 5/2) breccia characterized by matrix support and a rubbly texture in outcrop. The rock fragments are more heterolithologic than those in the mudflows and consist of various types of andesite along with minor fragments of tuff and basalt. The agglomerate can be differentiated from other breccias by the following characteristics: (1) the lithic fragments are angular to subrounded, dominantly subangular; (2) included are about 20 percent rounded andesite fragments that are very light gray (N 8) or light greenish gray (5 GY 8/1) and amygdaloidal to vesicular; and (3) there is a large range in the degree of alteration of matrix phenocrysts and rock fragments.

The matrix has a patchy coloration varying between light brown (5 YR 6/4), yellowish gray (5 Y 7/2), and greenish gray (5 GY 6/1). Matrix phenocrysts include plagioclase, augite, hornblende, hypersthene, and magnetite. Phenocrysts of the same species range from anhedral to euhedral, from fresh to highly altered, and from broken to whole.

The Harrison Creek agglomerate (Fig. 27) is unlike that of Marshall Creek and is more aptly described as an agglomerate belonging to a parasitic-vent breccia-pipe (Oles, personal communication, 1979). It is more like what one would expect an agglomerate to look like; all sizes of vesicular andesite fragments resting in framework support (Fig. 28). The overall rock is light gray (N 7) and the andesite fragments range from medium gray (N 5) to pale red (10 R 6/2), from 5 mm to 1.5 meters in diameter, and from angular to subrounded, typically subangular. In addition, there are minor fragments of scoria. The fragments grade into the matrix.

The matrix (Fig. 29) is light bluish gray (5 B 7/1) and consists of either a moderately-resistant andesitic-appearing rock or dust composed of pulverized andesite along with crystals of subhedral plagioclase and pyroxene to 3 mm diameter. Throughout this agglomerate are irregular veins and veinlets from 2 mm to 10 cm thick of red chalcedony and boxwork- or honeycomb-like mixtures

Figure 28. Closeup of the same agglomerate as in Fig. 27. Shows block- and lapilli-sized fragments of porphyritic andesite in framework support.

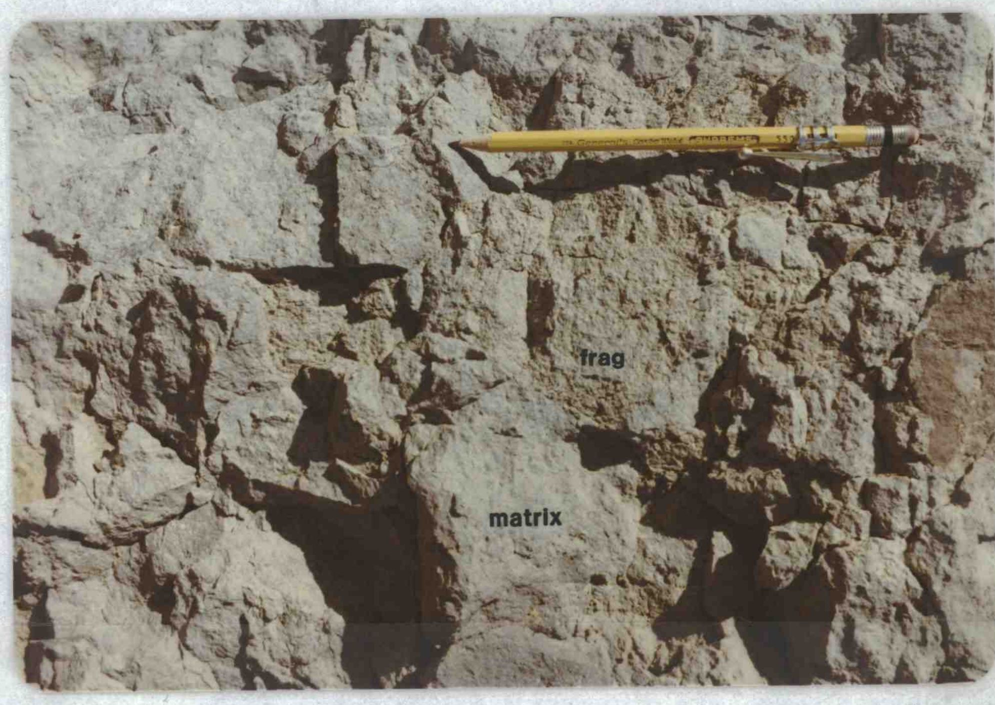

Figure 29. Closeup of the same agglomerate as in Fig. 27. Shows the contrast between the matrix and the less resistant fragments. The matrix is a light bluish gray breccia with lapilli-sized fragments.

of hematite and/or limonite.

The andesite wall rock of the breccia pipe exhibits fragments that are partially or completely ripped off and assimilated into the breccia (Fig. 27).

Petrography

Two samples were analyzed from the agglomerate in Marshall Creek. The lithic fragments consist of a diverse assortment of subrounded to angular, holocrystalline to holohyaline porphyritic andesite. Minor fragments of basalt, tuff, tachylite (that possibly represent obsidian), pumice, and scoria (Fig. 30) were found.

The matrix of the agglomerate consists primarily of clay- and silt-sized fragments of nondescript minerals along with fragments of phenocrysts consisting of andesine (An_{44}), clinopyroxene, very minor green hornblende, and magnetite. Glass and crystalline hematite are also found.

Pervasive alteration of the agglomerate is evident both in hand sample and in thin section. All minerals and rock fragments exhibit varying degrees of alteration. Andesites are partly altered to clay, basalts are highly oxidized and altered to hematitic clay, and pumice and tuff are partly devitrified. The clinopyroxenes are partly to wholly altered to chlorite, the plagioclase slightly altered

Figure 30. Photomicrograph of the volcanic agglomerate of Marshall Creek (sample 45-1). Shows a scoria fragment with isotropic glass bubble walls with included clinopyroxene phenocryst. The matrix is a haphazard arrangement of plagioclase and pyroxene fragments, magnetite, opaque clay, brown glass and chlorite. Located at the same locality as Fig. 26.

to zeolite and celadonite, and the matrix glass is partly devitrified and partly altered to smectite.

IV. Tuffs

Geomorphology

The Clarno tuffs within the study area are so minor that they are not topographically expressed. They are moderately resistant and spall apart into thin plates and chips.

The soil developed on this unit is characteristically thin and mottled and streaked with colors of pale red purple (5 RP 6/2), very pale orange (10 YR 8/2), light olive gray (5 Y 5/2), yellowish gray (5 Y 7/2), and light gray (N 7). The soil contains thin chips and plates of tuff along with angular fragments of disintegrated sandstone and siltstone.

The vegetative cover upon this unit is sparse and consists of patches of grass and juniper.

General Characteristics

The only tuff outcrop within the study area is located north of Peggy Butte, inthe NW 1/4, SW 1/4, section 22 T. 11 S., R. 22 E. (Fig. 21). Very local tuff float exists at two other localities, but no outcrops were observed. One such locality is on the north side of

Monroe Roughs, in the center of section 13, T. 11 S., R. 22 E. The second is north of Flock Mountain in the extreme NW corner of section 19, T. 11 S., R. 22 E.

The tuffs are extremely limited in extent and mostly covered with soil so that no contacts were exposed. They are interstratified with mudflows and sandstone/siltstone equivalents of mudflows. There is a broad outcrop north of Peggy Butte.

Lithology

The multicolored nature of the tuffs is like that mentioned in the geomorphology section. Tuffs are composed of tuffaceous fine-sandy siltstone and claystone. They are waterlaid deposits as indicated by parallel laminations, cross-laminations, and thin-bedding. Parting along laminations and bedding planes produces thin plates to a few millimeters thick. The plates locally contain carbonaceous remains and imprints of leaves, evergreen needles, and roots to eight millimeters in diameter. Petrified logs to 30 cm diameter are found in vertical growth position.

V. Intrusive Andesites

Geomorphology

The andesite sills and dikes are topographically expressed as prominent ridges, walls (Fig. 31), cliffs, and one plug. Moderately altered intrusives are poorly resistant and without topographic expression with respect to the country rock. Commonly, the dikes abruptly swell and pinch out along fault zones.

The cover developed upon these rocks is a dark yellowish orange (10 YR 6/6) to a dark greenish gray (5 GY 4/1) thin veneer of disintegrated granular rock rather than soil. Locally a thin soil of like color covers parts of these intrusives and supports patches of grasses and brush.

General Characteristics

Andesite sills and dikes are distributed irregularly throughout the study area. Each intrusive is labelled on Pl. 1 for the sake of correlation.

Intrusives are lithologically indistinguishable from andesite flows. Their form, habit, and structure must be observed in order to accurately identify them as intrusions. Many intrusions contain either hornblende phenocrysts or magnetite pseudomorphs after

Figure 31. Four meter high dike of biotite clinopyroxene labradorite andesite (sample 42-3) of Clarno age. Located in the NE corner of section 7, T. 11 S., R. 23 E.

Figure 32. Same dike as in Fig. 31, showing rhombohedral jointing.

hornblende or both. When hornblende is seen in outcrop, it invokes immediate suspicion as to the intrusive nature of the andesite.

The thickest sill is approximately 120 meters thick. It is exposed in a nearly vertical hillslope in the NW 1/4, SW 1/4, section 6, T. 11 S., R. 22 E. The most prominent dike in the study area is 18 to 30 meters thick and lies in Monroe Roughs, in sections 13 and 24, T. 11 S., R. 22 E. (Fig. 33).

Jointing in sills and dikes is variable. Sills most commonly display blocky, irregular, vertical polygonal columns or well developed, horizontal platy jointing, the plates dominantly two to five centimeters thick. Very locally they display vertical octagonal columns. Dikes display vertical platy jointing trending along strike. The platy jointing is either best developed along the margins of the dikes and poorly developed in the central part or best developed in the central part of the dikes, the plates bending outward to meet the margins in perpendicular fashion. Individual plates in the dikes range from 2 to about 30 cm thick. Very local dikes display vertical, irregular polygonal columns or rhombohedral jointing (Fig. 32).

Very few intrusives exposed well enough to reveal contact relationships. Margins of sills in the northern part of the study area commonly contain hornfelsic fragments of tuff and Permian

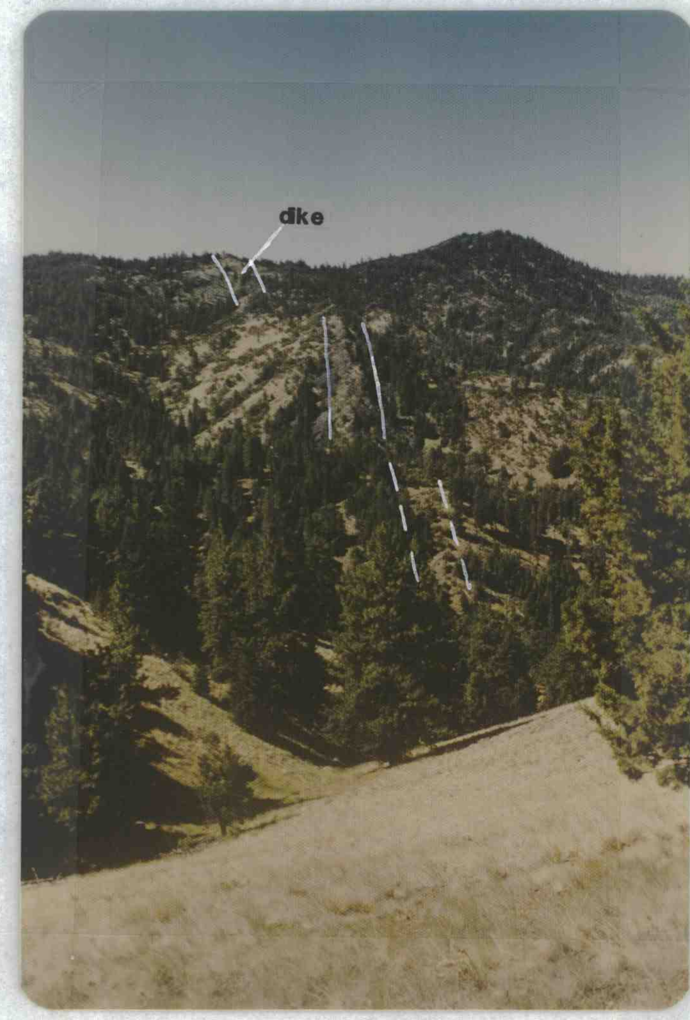

Figure 33. Large Clarno dike of plagioclase, clinopyroxene, hornblende andesite. Located in Monroe Roughs, sections 13 and 24, T. 11 S., R. 22 E.

metamorphic rocks. A hornfels is commonly found throughout the study area where sills or dikes intrude Cretaceous Hudspeth mudstone. This hornfels is very similar to dacite in that it is black, shatters like glass when struck by a hammer, locally contains pseudo-flow banding, and exhibits conchoidal fracture. The hornfels has squeezed through some sills so that it forms dike-like structures as in the center of the SW 1/4, section 8, T. 11 S., R. 23 E.

Some dikes (Fig. 34) are bordered by intrusion breccias. The example in Fig. 35 exhibits a matrix-supported breccia that is composed of dike fragments. The breccia contains angular to subangular andesite fragments altered to varying degrees and is an overall light bluish gray (5 B 7/1) with a bluish white (5 B 9/1), moderately to well-indurated matrix composed of pulverized andesite. Another intrusion breccia is found in the southwest corner of the study area in the NW 1/4, section 34, T. 11 S., R. 22 E. This breccia pinches and swells along with the dike, locally up to two meters thick.

One location containing numerous dikes and sills deserves description. Southwest of the Baldy Mountain summit, in the NW 1/4, section 8, T. 11 S., R. 23 E., a steep, almost cone-like hill composed of mudflows and andesite flows contains many crisscrossing andesite dikes and sills. "Dike hill," a term coined by

Figure 34. Four meter wide dike of hornblende, pyroxene andesine andesite (sample 44-2) of Clarno age. The dike is almost vertical and shows very thick platy jointing parallel to the wallrock. Located in the NW 1/4, SW 1/4, SW 1/4, section 31, T. 10 S., R. 23 E.

Figure 35. Intrusion breccia accompanying the same dike as in Fig. 34. Note sorting and angularity of constituent fragments.

the author, contains many excellent examples of dike mineralogy and structures. Fig. 31 illustrates one of the numerous wall-like dikes on this hill.

Lithology

Andesite dikes and sills are greenish gray (5 GY 6/1; 5 G 6/1), very dark greenish gray (5 GY 4/1, light olive gray (5 Y 6/1), dark gray (N 4), and medium light gray (N 6) to light gray (N 7). In general, all intrusives are holocrystalline and porphyritic. Hand specimens exhibit 3 to 40 percent phenocrysts, averaging 18 percent.

In general, there are two mineralogical types of intrusives. The most abundant type contains approximately 30 percent phenocrysts, approximately half of which is subhedral plagioclase, commonly less than one millimeter in length. The other half is anhedral to subhedral columnar pyroxene less than one millimeter long. Locally, this first type contains traces of slender prismatic hornblende to eight millimeters in length. The hornblende is either fresh or pseudomorphosed by magnetite. The second type of intrusive is aphanitic and platy with approximately five percent phenocrysts. The phenocrysts comprise one of the following: subhedral columnar pyroxene to one millimeter in length; subhedral plagioclase to two millimeters; or euhedral to subhedral, slender prismatic or columnar hornblende or magnetite pseudomorphs after hornblende to eight millimeters along with very minor plagioclase.

Petrography

Twelve intrusive andesites were examined petrographically, six of which were volumetrically analyzed for their mineralogical composition (Table II). Andesite intrusives are holocrystalline or hypohyaline, microcrystalline, and porphyritic. The groundmass textures are felted, subpilotaxitic, intersertal, or hyalopilitic. Visual estimates reveal phenocrysts totalling from 3 to 40 percent of the rock, averaging 24 percent. The plagioclase:ferromagnesian ratio of phenocrysts ranges from 60:40 to 90:10, averaging 70:30. The phenocrysts comprise labradorite, andesine, clinopyroxene, hypersthene, hornblende, magnetite pseudomorphs after hornblende, biotite, and magnetite. Groundmass minerals comprise andesine microlites, glass, a nondescript feebly birefringent mineral mass, magnetite, biotite, smectite clay, calcite, apatite, secondary quartz and chalcedony.

Plagioclase phenocrysts range in composition from An_{41} to An_{62}, averaging An_{49}. Groundmass plagioclase microlites range from An_{32} to An_{48}, averaging An_{39}. Six volumetrically analyzed samples reveal the following: (1) labradorite phenocrysts comprise from 14 to 33 percent of the entire rock, averaging 25 percent; (2) andesine microlites comprise 21 to 62 percent, averaging 44 percent; and (3) one sample contains 42 percent andesine in both phenocryst and groundmass phases (Table II). Plagioclase phenocrysts are dominantly subhedral, with only minor examples of broken or euhedral phenocrysts varieties. Groundmass andesine microlites are subhedral, slender, and not greater than one tenth of a millimeter long. Most plagioclase phenocrysts display albite and Carlsbad twinning (Figs. 36 and 38) with very minor examples of pericline twinning. A few phenocrysts display minor or poorly developed twinning which may be attributable to the thin section being cut parallel to the 010 twin plane. This concurs with Taylor (1960). Some plagioclase phenocrysts display corrosion (Fig. 37) which can be attributed to resorption of the crystal into the melt by the release of pressure on the magma chamber during surficial eruptions (Taylor, 1960; Vance, 1965). Also common are normal, reverse, and oscillatory zoning and inclusions of glass blebs (Fig. 37). These phenomena also indicate eruptive episodes that caused changes in crystal chemistry and thermodynamic phase relationships (Taylor, 1960; Vance, 1965).

The plagioclase commonly alters to smectite and/or

TABLE II. VOLUMETRIC MODES IN PERCENT OF SELECTED CLARNO ANDESITE INTRUSIONS

Sample	4-10	15-1	21-5	29-1	34-2	42-3
Phenocryst Phase:						
Andesine	--	--	--	--	42*	--
Labradorite	33	14	26	21	--	29
Clinopyroxene*	12	--	6	4	--	3
Hypersthene	5	--	2	--	--	--
Hornblende	--	4	--	6	11	--
Magnetite pseudomorphs after hornblende	--	--	Tr	2	--	--
Biotite	--	--	--	--	--	9
Groundmass Phase:						
Andesine	21	62	47	51	--	37
Glass	25	--	--	--	--	--
Nondescript mineral mass	--	--	16	--	--	19
Clay or Glass + nondescript mineral mass	--	--	--	8	44	--
Magnetite*	4	2	3	3	3	3
Unidentified	--	--	--	5	--	--
Chalcedony	--	18	--	--	--	--

*Phenocryst and groundmass phases were counted together because of the extremely minute size of the groundmass phase. Andesine phenocrysts and microlites were counted together.

4-10 Clinopyroxene, hypersthene, labradorite andesite dike. Located on the south slope of the south peak of Keyes Mountain, SW 1/4, NW 1/4, section 25, T. 11 S., R. 22 E.

15-1 Hornblende, labradorite andesite plug. Located on the east slope of the Marshall Creek headwaters, NW 1/4, NW 1/4 NW 1/4, section 30, T. 11 S., R. 22 E.

21-5 Hornblende, hypersthene, clinopyroxene, labradorite andesite dike. Located in Monroe Roughs, SW 1/4, NE 1/4, NW 1/4, section 24, T. 11 S., R. 22 E.

29-1 Hornblende, clinopyroxene, labradorite andesite dike. Located in the center of the SE 1/4, SE 1/4, section 31, T. 11 S., R. 23 E.

TABLE II. (Continued)

34-2	Clinopyroxene, hornblende, andesine andesite sill. Located in the north end of Bearway Meadows, in the SW 1/4, SE 1/4, SE 1/4, section 7, T. 11 S., R. 23 E.
42-3	Biotite, clinopyroxene, labradorite andesite dike. Located at the headwaters of Shoofly Creek, in the extreme NE corner of section 7, T. 11 S., R. 23 E.

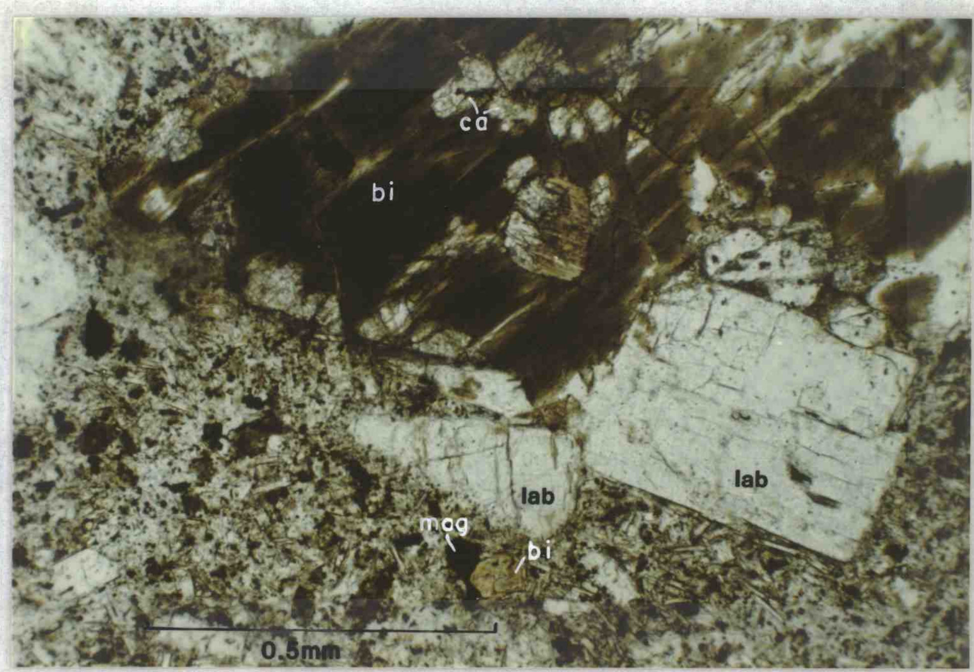

Figure 36a. Photomicrograph of biotite- and clinopyroxene-bearing labradorite andesite (sample 42-3). Shows phenocrysts of biotite partially altered to calcite, labradorite (An_{51}) and magnetite. The groundmass consists of an intersertal arrangement of andesine (An_{37}) microlites, pale green glass, biotite and minute magnetite. Located in the NE corner of section 7, T. 11 S., R. 23 E.

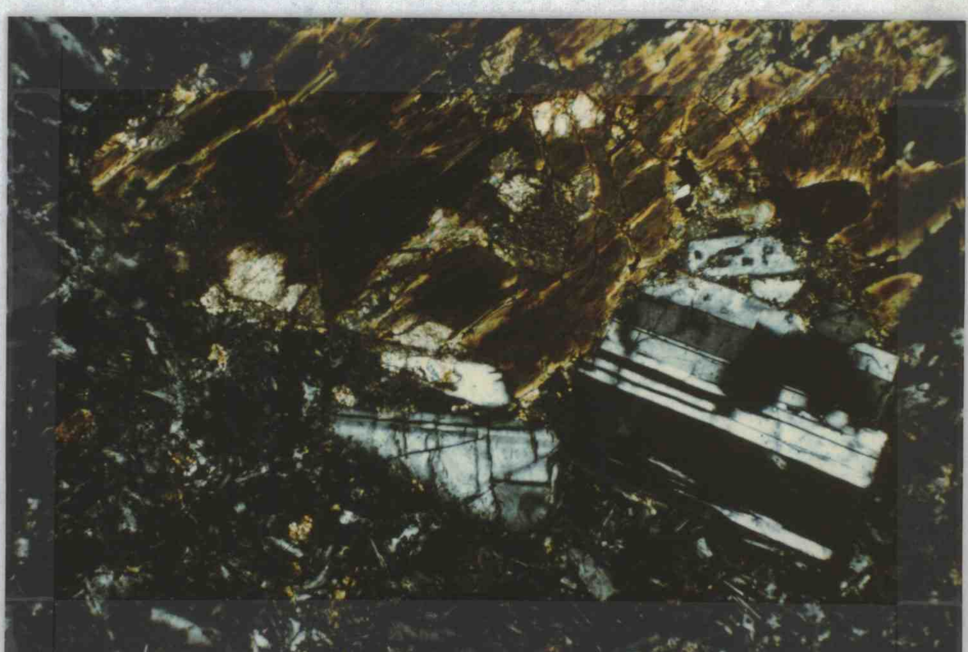

Figure 36b. Photomicrograph of the same as Fig. 36a except with crossed nicols.

Figure 37. Photomicrograph of hypersthene- and hornblende-bearing, clinopyroxene andesine-labradorite andesite (sample 21-5). Shows phenocrysts of andesine-labradorite (An_{50}), the largest displaying an internal resorption rim and oscillatory and reverse zoning, euhedral clinopyroxene, a magnetite pseudomorph after hornblende, and magnetite. The groundmass consists of a subpilotaxitic to intersertal arrangement of andesine (An_{48}) microlites, a feebly-birefringent, nondescript mineral mass, and minute magnetite. Located in the SW 1/4, NE 1/4, NW 1/4, section 24, T. 11 S., R. 22 E.

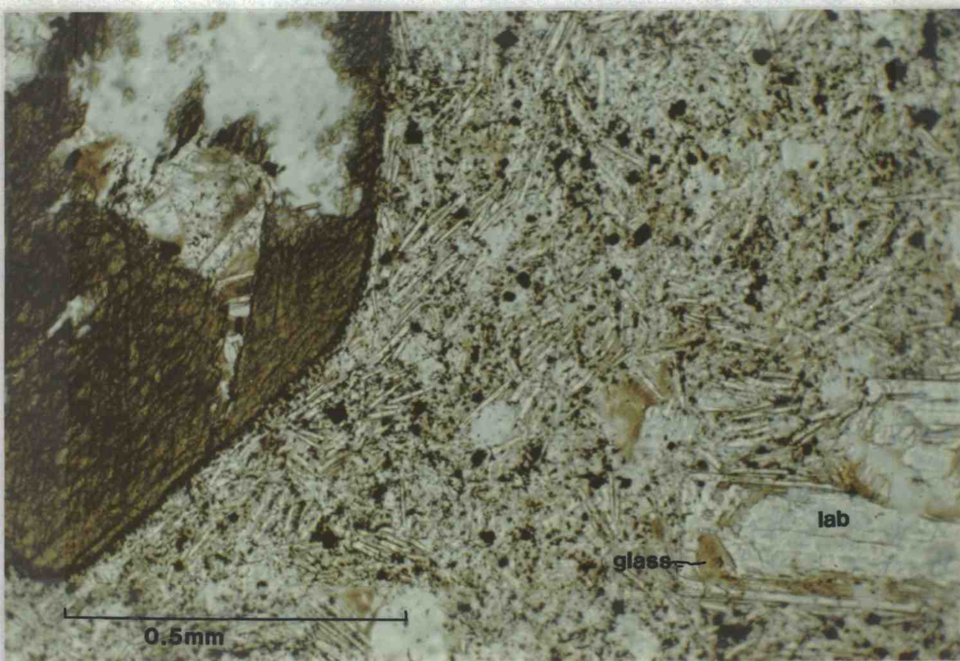

Figure 38a. Photomicrograph of a hornblende labradorite andesite from a plug (sample 15-1). Shows phenocrysts of euhedral hornblende and twinned labradorite (An_{60}) displaying an internal resorption rim filled with brown glass. The groundmass consists of a subpilotaxitic arrangement of andesine (An_{40}) microlites, magnetite and chalcedony. Located in the NW 1/4, NW 1/4, NW 1/4, section 30, T. 11 S., R. 23 E.

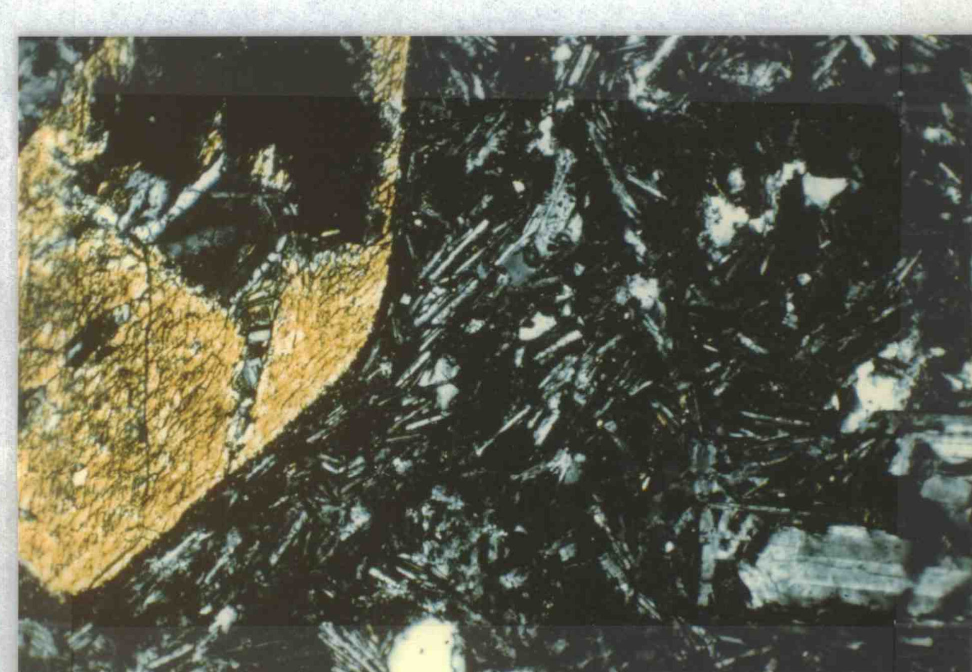

Figure 38b. Photomicrograph of the same as Fig. 38a except with crossed nicols.

celadonite with minor examples of calcite, sericite, and zeolite. Hematite staining in microfractures is also common.

Pyroxene phenocrysts are present in all samples except 15-1 and 39-4. Four out of six samples volumetrically analyzed (Table II) contain clinopyroxene ranging from three to 12 percent of the total rock, and two samples contain hypersthene fromtwo to five percent. Visual estimates reveal two to 12 percent of all phenocrysts are hypersthene and a trace to 25 percent of all phenocrysts are clinopyroxene. A few samples contain only hypersthene, the clinopyroxene being absent. In general, all pyroxenes are characteristically (1) anhedral to euhedral (Fig. 37 and 40), dominantly subhedral, (2) dominantly columnar with minor, short stubby varieties, and (3) up to three millimeters in length. Some clinopyroxene displays simple twinning (Fig. 40). Clinopyroxene in sample 12-1 is found to exhibit similar pleochroism to hypersthene; very pale bluish gray to very pale pink. However, the very pale pink is exhibited in the north-south crystallographic direction for clinopyroxene, in contrast to the east-west direction for hypersthene. Sample 29-1 exhibits some schiller structure within the clinopyroxene.

Pyroxene alteration products consist of celadonite and smectite. A few examples of magnetite replacement exist In sample

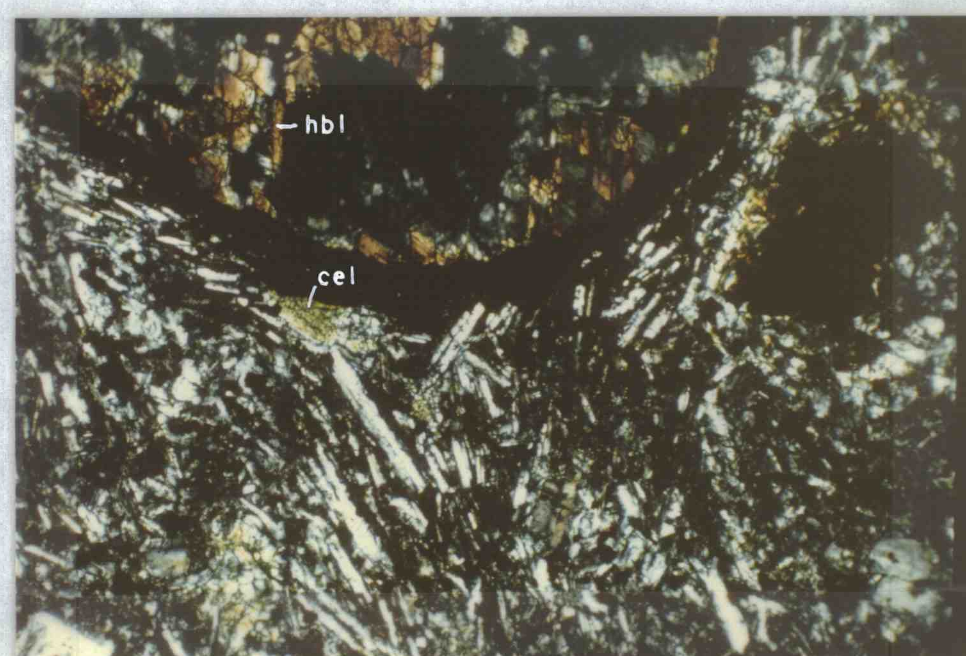

Figure 39. Photomicrograph of a hornblende-bearing, clinopyroxene andesine andesite (sample 43-1). Shows phenocrysts of hornblende with a magnetite rim and andesine (An_{43}). The groundmass consists of a felted to subpilotaxitic arrangement of andesine (An_{40}) microlites partially altered to celadonite. Located in the center of the W 1/2, SE 1/4, NW 1/4, section 34, T. 11 S., R. 22 E.

Figure 40. Photomicrograph of andesine-, clinopyroxene- and hornblende-bearing andesite (sample 44-1). Shows phenocrysts of corroded hornblende with magnetite rims, twinned clinopyroxene, and andesine. The groundmass consists of a hyalopilitic arrangement of andesine (An_{41}) microlites, glass, minute magnetite and incipient calcite alteration. Located in the SE 1/4, SE 1/4, SW 1/4, section 31, T. 10 S., R. 23 E.

21-5, some pyroxene appears to be altered to actinolite that displays cockscomb habit.

Green hornblende is common in intrusive andesites. Four out of six samples volumetrically analyzed (Table II) contain hornblende from a traceamount to 11 percent of the total sample. Visual estimates of all 12 samples reveal hornblende comprising from five to 60 percent of the constituent phenocrysts (Figs. 38-40). The hornblende is characteristically (1) anhedral to euhedral, (2) unaltered to wholly replaced by magnetite (Figs. 37 and 40), (3) columnar or slender prismatic, and (4) up to four millimeters in diameter. Many samples display rims of magnetite around hornblende (Fig. 39 and 40) and a few display corrosion (Fig. 40). One example of simple twinning was found in sample 34-2.

Hornblende alteration consists of celadonite and calcite with minor examples of chlorite. Often microfractures are filled with crystalline hematite.

Sample 42-3 contains subhedral biotite from a minute groundmass phase to a phenocryst phase up to one and one-half millimeters long (Fig. 36). The biotite comprises nine percent of the total rock (Table II) in this sample and is partially altered to calcite.

Magnetite is ubiquitous in all samples. Volumetric analyses of six samples (Table II) reveal magnetite comprising from two to four percent of the total rock. Visual estimates of other samples show up to five percent magnetite. Anhedral to euhedral varieties exist. All size grades exist from a minute groundmass phase to a one-half millimeter diameter phenocryst phase. Magnetite is commonly altered to hematite.

The percentage and composition of the groundmass in intrusive andesites is similar to andesite flows (Table II). Some samples display felted and pilotaxitic texture (Figs. 37-39). Others display intersertal or hyalopilitic texture (Figs. 36 and 40). The interstices of the andesine microlites are filled with (1) brown glass, (2) a nondescript, feebly-birefringent mineral mass, (3) smectite clay, (4) and mixture of items (1), (2), and (3) above, (5) magnetite, (6) unidentified minerals, and (7) chalcedony.

Groundmass alteration includes smectite (Fig. 39) with minor examples of sericite, calcite (Fig. 40), and an opaque non-birefringent clay resembling kaolinite.

John Day Formation

General Characteristics

The middle Oligocene to early Miocene John Day Formation unconformably overlies the Clarno Group in the eastern and southeastern parts of the study area. It unconformably underlies the Picture Gorge Basalt.

The John Day strata encountered in this study consist of a lower, dark reddish brown pebbly claystone and a very local, upper, highly-altered white tuff. The dark reddish brown claystone is readily distinguishable in the field and on aerial photos. In the Mitchell quadrangle, Oles and Enlows (1971) report that the John Day consists of varicolored fluvial and lacustrine tuffaceous claystones and siltstones and subordinate sands and gravels. Locally, but not within the study area, an ignimbrite and intrusions of leucorhyolite and dacite exist. The tuffs consist of two members: a thin lower member that is moderate to dark reddish brown and a thicker upper member that is very light gray to very pale orange. In outcrop the colors are banded, accentuating the well-bedded nature of the strata. The contact between the John Day and Clarno rocks is distinguishable by a dark red paleosol (Oles and Enlows, 1971).

The tuffs in the study area appear to be very thin, approximately two meters or less. Within the Mitchell quadrangle Oles and Enlows (1971) report the John Day Formation to be a minimum of 1050 meters thick.

The John Day Formation is poorly resistant and forms rounded hills, gently dipping slopes, pediments, and valleys (Merriam, 1901; Oles and Enlows, 1971).

Columbia River Basalt

General Characteristics

The John Day Formation in the southeastern part of the study area is unconformably overlain by Miocene age Columbia River Basalt (Hodge, 1942; Oles and Enlows, 1971) which is mapped as Picture Gorge Basalt by Brown and Thayer (1966). Outside of the study area, the Rattlesnake Formation overlies the Columbia River Basalts with angular discordance (Oles and Enlows, 1971).

The study area contains one Picture Gorge Basalt flow that is less than four meters thick and irregularly distributed. It is dark gray (N 3) to grayish black (N 2), holocrystalline, non-porphyritic, and aphanitic. The magnetite is commonly weathered to hematite.

The flow is in near horizontal position, lapping onto Clarno strata of Keyes Mountain.

Within the Mitchell quadrangle, Columbia River basalt flows have accumulated to as thick as 300 meters. They form cliffs, steep-walled box canyons, dipslopes, mesas, buttes, and giant narrow benches that are arranged in staircase-like fashion (Oles and Enlows, 1971).

One peculiar rock unit, labelled $T_{cr_{al}}$ on Pl. 1, is underlying a Picture Gorge Basalt flow in the southeastern part of the study area. It appears to be float belonging to Picture Gorge Basalt age alluvium. The alluvium comprises well-rounded cobbles and boulders of dense, vesicular, and scoriaceous basalt. Also found in minor quantity are clasts of petrified wood and white, densely welded ignimbrite exhibiting well-developed eutaxitic texture.

STRUCTURE

The Clarno Group in the study area is bordered both above and below by unconformities. Before Clarno time, these rock units developed substantial erosional relief which is best observed near Tony Butte. The unconformity between the Cretaceous and Clarno strata is observed in the north part of the area where southward dipping Cretaceous strata are overlain by horizontal or slightly northward dipping Clarno andesites. In the Mitchell quadrangle, an intra-Clarno unconformity between the Lower and Upper Clarno Formations is documented by Oles and Enlows (1971). However, no unconformity was observed in the study area. The Clarno strata are unconformably overlain by John Day and Columbia River Basalt Formations. The John Day tuffs that are located in Frog Hollow, immediately east of the study area, are approximately 200 meters thick. However, in the study area, only several meters of these tuffs exist which indicates the presence of an unconformity. The overlying Picture Gorge Basalt, also much thicker immediately to the east, rests horizontally upon tilted Clarno andesites and John Day tuff.

The northeasterly trending Mitchell Anticline is situated to the northwest of the study area. The south flank of the anticline extends into the study area, manifested by the southward dipping

Cretaceous strata. The anticlinal limb is also reflected in the quaquaversal arrangement of the Clarno andesites; those on the north side of Keyes Mountain are horizontal or dip slightly northward, and those on the south side dip southward and at greater angles than the northern flows.

Approximately east-west trending faults are located in the central and southern parts of the study area. Displacement along these faults is inferred to be strike-slip in nature. Where visible, these fault zones are several meters wide at the most and display both horizontal and vertical slickensides. Some faults are intruded by andesite dikes. The most prominent of such faults trends up Keyes Creek on the south side of the south peak of Keyes Mountain. A strong photo lineament continues this trend through the eastern part of the study area. The amount of displacement along the Keyes Creek fault is unknown and could not be determined by matching andesite flows across the fault. However, separation is measurable on a fault that is subparallel to the Keyes Creek fault. This fault begins at Harrison Creek and trends east-northeast through the southeast part of the study area. This fault displays 96 meters of right-lateral horizontal separation in a Picture Gorge Basalt flow.

Normal faults in the study area generally trend approximately east-west. The faults in the north part of the study area generally are downthrown to the north. Those in the central part are downthrown to the south.

Many lineaments on aerial photos are illustrated on Pl. 1. They may represent faults, joints, or dikes. However, no definite evidence of any of these features was found in the field.

A cuesta block capped by Picture Gorge Basalt is found in the center of section 32, T. 11 S., R. 23 E. This indicates deformation occurred at least as late as Picture Gorge Basalt time.

CONCLUSIONS

Indirect evidence suggests that Keyes Mountain is most likely an Eocene age volcano. It was probably thesource of some of the Clarno strata in the Mitchell area. Supporting evidence is as follows: (1) the andesite flows dip in quaquaversal fashion in the Keyes Mountain vicinity; (2) the drainage is radial, directed away from Keyes Mountain; (3) there is present what is interpreted to be a central vent agglomerate; (4) the varied paleocurrent directional indicators in the mudflows that show their source to be from the Keyes Mountain vicinity; and (5) mudflow clasts up to ten meters in diameter on Keyes Mountain indicative of a proximal source. In addition, between eruptive episodes a highly rugged antecedent topography must have developed on theflanks of the volcano. Supporting evidence is as follows: (1) noncorrelatable sequences of andesite flows exposed in different ridges; (2) andesite flows and mudflows that are intracanyon to each other; (3) the geometry of some andesite flows suggesting that they blanketed the slopes of the volcano; (4) the andesite flows that are narrow, winding shoestring-like bodies or wide sheet-like stacks suggesting that they were confined to either narrow winding canyons or fairly broad valleys with flat bottoms; (5) the short lateral extent of all flows, less than three kilometers; and (6) individual flows that characteristically pinch, swell, and abruptly terminate.

The Keyes Mountain volcano, however, has not been exhumed, as postulated by Oles and Enlows (1971). Since post-Clarno time, Keyes Mountain has stood above the surrounding topography as a paleotopographic high or inselberg. Conclusive evidence lies in the southeast part of the study area. The John Day tuffs and Picture Gorge Basalt, which are less than several meters thick, rest in horizontal position upon tilted Clarno strata. Both units obviously lapped onto Keyes Mountain because both units thicken extensively within three kilometers to the east and south.

GEOLOGIC HISTORY

Within Permian time the sea covered the area and an assemblage of bedded clay and local accumulations of calcareous and siliceous sediments were deposited below wave base. These sediments were subducted at a convergent margin. Metamorphism transformed the clay to phyllite, the calcareous sediment to beds of recrystallized limestone and dolomite, and the siliceous sediments to bedded chert and local pods of chert. Subduction is inferred because of the local assemblages of serpentine, talc-chlorite- and amphibolite schists. Subsequent orogenic uplift tightly folded the rocks into isoclinal and subisoclinal folds, the axes of which are often occupied by quartz boudins. The orogenic stress was oriented in a northwest-southeast direction and terminated in Early Jurassic time (Oles and Enlows, 1971).

Following uplift of the Permian metasediments, probable subaerial erosion occurred until the Early Cretaceous, Albian age. Beginning at this time, downwarping occurred and a shallow sea transgressed over the area. Oles and Enlows (1971) and Wilkinson and Oles (1968) report that the sea must have been a shallow marine embayment. Major rivers, originating from a strongly rising source area to the north and east, poured huge volumes of sediments into the sea. These sediments consisted of quiet water marine silt and clay (Hudspeth Formation) intertonguing with very high energy fluvial and deltaic gravels and sands (Gable Creek Formation). The deposition of the two strikingly different rock sequences represents a cyclic pattern of diastrophism. The Cretaceous sediments were then buried deeply enough to become well indurated (Oles and Enlows, 1971; Wilkinson and Oles, 1968).

The area was then subjected to epirogenic uplift and orogeny sometime during the Paleocene. Compressive stress was again oriented in the northwest-southeast direction. In the study area the Cretaceous strata acquired a southward dip along the south limb of the Mitchell Anticline, documented by Oles and Enlows (1971). During this orogenic episode the Cretaceous and Permian rocks were subjected to subaerial erosion until the beginning of Clarno time. High relief promoted dissection by high gradient streams and active mechanical erosion, thus inhibiting the development of a thick regolith reported to have developed elsewhere in the Mitchell quadrangle.

In early Eocene time subaerial volcanism occurred in the area, unconformably depositing Clarno andesite flows and mudflows upon the eroded Cretaceous and Permian rocks. Originating from a central vent (or possibly multiple vents) located in the vicinity of the Marshall Creek canyon, andesite and mudflows poured out over the terrain. Most were channelized down canyons, radiating off the slopes of the volcano. The mudflows probably originated as lahars resulting from violent stream-blast eruptions on the volcano, accompanied by copious amounts of juvenile and meteoric water. They were torrentially deposited as thick slurries of mud, sand and rock clasts of all sizes. They ponded in one channel that was occupied by a dense growth of trees, some to 0.75 meters in diameter. The trees were buried, petrified, and preserved in original growth position. The ponded mudflows were subsequently sedimented by fine-grained alluvium. In this same locality a small lake was formed and filled with epiclastic volcanic ash originating from eruptions nearby. Hardwood and evergreen trees proliferated around the lake. Enough time elapsed between eruptive episodes in order for erosion to dissect the area. Canyons transecting andesites and mudflows were subsequently filled with the same, some deposits accumulating to great thicknesses. Andesites that flowed over Hudspeth mudstone metamorphosed the mudstone to a rigid hornfels that locally squeezed up into the overlying flows. Some flows flowed down steep hillslopes and covered extensive areas. Other flows poured over tectonically disturbed flows or escarpments, plausibly formed by contemporaneous faulting.

Concurrent with the building of the Keyes Mountain volcano, intrusive andesites were emplaced throughout the area. Many of the dikes were emplaced late in the development of the volcano, localizing along prominent fault zones.

Faulting occurred cogenetically with deposition of Clarno strata. The approximate east-west-trending faults in the north part of the area are multiple distributive in nature (Lahee, 1969) and display downthrow to the north. This displacement may represent volcanic swelling during the upbuilding of Keyes Mountain. The other faults in the central and southern parts of the area form a conjugate set displaying strike-slip separation. Probable northwest-southeast compressive stresses that produced these faults began during Clarno time and continued until at least post-Miocene time. During mid-Clarno time, this same stress pattern produced the Mitchell Anticline and the angular unconformity between the Lower and Upper Clarno Formations. Continued northwest-southeast compression since mid-Clarno time has progressively tilted the Keyes Mountain volcano to the south and produced a few normal faults displaying downthrow to the south.

Since the end of Clarno time, the Keyes Mountain volcano has projected above the surrounding terrain as an inselberg, or island moi ntain, until the present day.

Middle Oligocene to early Miocene time witnessed volcanism and deposition of tuffs of the John Day Formation. Very minor John Day tuff accumulated in the study area because Keyes Mountain did not trap the epiclastic air-fall debris. During this time erosion continued along with displacement along the Keyes Creek and associated strike-slip faults.

In the early Miocene a high energy stream flowed through the southeast part of the study area. Subsequently one Picture Gorge basalt flow lapped onto the southeast fringe of Keyes Mountain.

Tectonism and erosion have continued from post-Columbia River Basalt time until the present. No younger rock units are recorded in the area. One basalt flow was faulted by a right-lateral strike-slip fault, and local areas were deformed and eroded to produce cuestas capped by basalt. Latest movement along the conjugate set of faults has been both horizontally and vertically. The vertical offset may be a manifestation of Pliocene uplift of the Ochoco Mountains to the south. Quaternary geologic activity includes erosion and alluviation, the formation of fans and/or pediments, and landsliding. In the Pleistocene, erosion has produced reversed topography. The east part of the area was inundated by a flood or high energy river which deposited coarse gravels.

REGIONAL TECTONIC HISTORY AND THE CLARNO FORMATION

Generation of Calc-Alkaline Magma

Various authors have established the Clarno volcanics to be calc-alkaline (Rogers and Novitsky-Evans, 1977; Taylor, 1977; Huggins, 1978; Barnes 1978; Stroh, 1980). There are four major hypotheses that account for the generation of calc-alkaline igneous rocks. They are the processes of subduction, anatexis of the lower continental crust, differentiation of basic magma, and contamination of basic magma. Each is separately discussed below.

The first and most probable hypothesis is that of calc-alkaline volcanism being generated by subduction. Subduction is a type of crustal plate interaction resulting from spreading oceanic crust which is pushed beneath adjoining continental or oceanic crust (Stearn et al., 1979). Boettcher (1973) explains that the oceanic crust at depth is thought to be a metamorphosed peridotite or eclogite or amphibolite and that in the presence of water anatexis will produce andesitic magma. Pelagic sediments are presumed to be subducted also, a conclusion which is substantiated by lead-isotope ratios. The source of water also could be apparently from the pelagic sediments. This process would occur at depths of approximately 60 km where the pressure is about 20 kb. There are various lines of evidence to support this conclusion. One is the experimental melting of systems that represent these rock types. These systems included excess water and were brought to pressures up to 30 kb. Because of the high water-vapor pressure a quartz-normative liquid was produced. A dry system does not produce a silica-rich system. This silica-rich melt may coexist with solid peridotite without melting the latter and altering the chemistry of the melt (Boettcher, 1973). Fyfe and McBirney (1975) cite trace-element and isotopic data which indicate that the andesite was partly generated from the mantle. However, their hypothesis differs slightly in that there are two zones of dehydration within the subduction zone. During shallow subduction compression within the descending slab forces the pore water to react with the overlying mantle peridotite and basalt to produce hydrous minerals such as amphibole, talc, serpentine, mica, and chlorite (Fyfe and McBirney, 1975). Boettcher's (1973) experiments show that amphibole in water-rich basalt would not survive depths greater than 90 km (greater than 28 kb). In the first zone amphibole breaks down at these pressures and temperatures to release water, causing heating, expansion of the overlying country rock, and surficial uplift (Fyfe and McBirney, 1975). The solutions liberated in this reaction form an alkali-rich melt with Na_2O remaining in the melt and the K_2O reincorporated into micas. Consequently, the initial melting between 60 and 90 km produces magma characterized by a high Na_2O/K_2O ratio (Boettcher, 1973). At depths of about 100 km (approximately 30 kb pressure and 600°C) the muscovite breaks down to produce a solution rich in silica, alkali and water. These recombine with the serpentine and peridotite in the hanging block to produce phlogopite-bearing pyroxenites. The final generation of andesitic magma occurs at depths where the phologopite breaks down to release solutions rich in water, silica and alkalis (extra high in potassium) (Fyfe and McBirney, 1975). Boettcher (1973) estimates this depth extends down to about 175 km because the interior of the slab is cooler and characterized by a lower geothermal gradient. This reaction raises the water-vapor pressure and melts the overlying rocks to produce a calc-alkaline magma (Fyge and McBirney, 1975). In support of this idea the plutonic rocks of the western Cordillera exhibit an eastward increase in K_2O content. This trend is thought to be proportional to the depth of the underlying Benioff zone (Boettcher, 1973; Dickinson, 1975). In support of the magmatic-arc origin of andesite, Boettcher (1973) cites two other hypotheses that are based on experimental evidence. One is that as the oceanic basalt spreads out laterally from the spreading ridge it subducts as the result of cooling, contraction and increased density. With depth it reverts to quartz ecologite. At about 100 to 150 km deep (approximately 27 to 36 kb pressure) high-alumina basalt partially melts to produce a silica-rich solution of andesitic composition and a residuum of garnet-clinopyroxene. The other hypothesis is that of amphibole fractionation. Silica-poor amphiboles (less than 44% SiO_2) are likely to be differentially melted from a hydrous basalt to produce andesitic magma at pressures of 12-20 kb (approximately 40-65 km deep) because in the experiments this mineral lies within 60°C of the liquidus. The additional temperature for melting could be provided by the frictional heating. A modern example is the eruptive sequence of basalt-andesite-dacite of Santorini (Boettcher, 1973).

Another hypothesis for the origin of calc-alkaline volcanics is that of the antexis of the lower crust. This is essentially the same as the subduction hypothesis except that the mechanism to reproduce the melting is not provided. Isotopic and trace element geochemistry do not support this hypothesis. In addition, unrealistic temperatures (greater than 1000°C) are required for anatexis (Boettcher, 1973).

Another hypothesis for the production of calc-alkaline magma is that of contamination of basaltic magma by acidic crustal material.

This also is not supported by isotopic and trace element geochemistry. Besides, andesite commonly occurs in island arcs, where no acidic, subsurface continental crust exists, such as the Tonga and Mariana Islands (Boettcher, 1973). On the contrary, Eichelberger (1974) indicates the likely possibility of the mingling of diverse magmatic types underneath arc suites.

The final hypothesis cited by Boettcher (1973) by which calc-alkaline magma could be generated is that of differentiation of basaltic or other basic magmas. This is supported by strontium and oxygen isotopic ratios that show a similarity between andesite and basalt. Even though this is known to occur at some localities, as in Iceland, it is doubtful that it occurs to such an extent and regularity as that required to produce such voluminous andesitic magma in orogenic zones. However in support of this hypothesis it is interesting to note that experimental evidence on liquid systems of basic composition, with a high partial pressure of oxygen, show that magnetite, the first mineral to crystallize out, has a large stability field on the liquidus. It crystallizes out instead of the usual olivine and pyroxene which leaves a residual calc-alkaline melt. The oxygen isotope abundance in andesites supports this idea and the possible source of oxygen could be a wet crust through which the magma rises. Boettcher (1973), however, raises valid arguments to this hypothesis, plus his own experimental evidence, that show oxygen-buffered systems do not react in this way upon cooling.

Hypotheses on the Tectonic Regime of Early Tertiary North-Central Oregon

Introduction

The following section presents various proposals for the genesis of Cenozoic volcanism in the Pacific Northwest. In light of these hypotheses, this writer believes that the Clarno originated from extensional tectonism, not as the direct result of magmatism over a subduction zone. However, concomitant microplate tectonics probably played a subordinate role in the generation of Tertiary volcanism in this area.

A clear understanding of the origin of the Clarno volcanics is difficult. The gradual development of our understanding of regional geology and tectonic mechanisms has induced various tectonic models for its origin. Among the varying hypotheses are models of subduction/magmatic arc complexes, back-arc spreading, and volcanism over provinces experiencing extension. These models will be separately discussed below.

The bend in the western Cordillera through the Pacific

Northwest may hold the key to the origin of the Clarno. The rocks of the Cordillera are comprised of Mesozoic age batholitic rocks, ophiolites, blueschists, and serpentines to mention a few (Hamilton, 1969). The bend includes the northern Cascades of Washington, western Idaho, the Blue Mountains of Oregon, and the Klamath Mountains. On a map this pattern forms a backward "S" and has been called the Columbia Arc (Taubeneck, 1970). It may be an undeformed, subduction/magmatic-arc complex (Holz et al., 1977), an orocline (Carey, 1958), or formed as the result of megashear (Wise, 1963).

Whether or not the Columbia Arc is a deformational feature or a subduction/magmatic-arc complex is not determinable until it is known what underlies the Tertiary volcanic cover of the Oregon Cascade Mountains and Blue Mountains and central Oregon (Hamilton and Meyers, 1966; Dickinson, 1975b).

Any hypothesis on the origin of the Clarno volcanics must be consistent with the structure within the Clarno outcrop area (Taylor, 1977). The andesite dikes, sills, and irregular intrusive bodies are elongated and trend in a northeast-southwest direction. Taylor (1977) states that this andesite belt formed during an episode of northwest-southeast compression that reached its maximum intensity during Clarno time.

Plate Tectonics

Volcanic rocks produced over active Benioff zones in modern island arcs and continental margins are most typically calc-alkaline (Hamilton, 1969; Jakes and White, 1972; Lipman et al., 1972; Miyashiro, 1974). On this basis Lipman et al. (1972) state that the early to middle Cenozoic volcanism in the western United States is related to subduction tectonics. Previously mentioned studies have established the calc-alkaline nature of the Clarno. It is noteworthy that Stroh (1980) augmented his chemical analyses of the Clarno volcanics with those of Barnes (1978) and Huggins (1978) to show that the Clarno falls within the calcic field on a Peacock diagram. However, he aptly pointed out that when evaluated by other parameters, such as the AMF ternary diagram, the Clarno shows distinct calc-alkaline affinitites. A Harker variation diagram of K_2O vs. SiO_2 shows the Clarno exists well within the continental andesites (Stroh, 1980).

Probably the eastward trending oceanic ridge that separated the hypothetical Kula from the Farallon plates migrated northward across the Oregon/Washington area in the early Cenozoic, changing the oceanic/continental plate boundary from right-lateral strike-slip to that of subduction (Atwater, 1970; Stearn et al., 1979; Vance, 1979). Therefore, during the early Cenozoic a subduction zone is postulated to have operated in about the present-day location of the western continental margin of North America (Atwater, 1970; Lipman et al., 1972; Stearn et al., 1979). Concurrent with this convergent plate motion, the Absaroka intermediate volcanism in the Eocene, the San Juan intermediate volcanism of the Oligocene (Lipman et al., 1972), the Basin and Range volcanism (Stearn et al., 1979), and the basaltic volcanism of the ancient Cascades (Wilson, 1973) were occurring. Based on geochemistry of igneous rocks, Lipman et al. (1972) postulate two eastward-dipping subduction zones coexisting during early and middle Cenozoic time. Both trended north-south, one located at the present continental margin and the other within the interior of the present-day continent along the Wasatch Front. Alternatively, Rogers and Novitsky-Evans (1977) proposed that this mid- to late Eocene trench lay in about the present position of the western Cascades. This concurs with the conclusions of Snavely and MacLeod (1977). They calculated that the Clarno was generated on a thin continental margin, more specifically, perhaps that of back-arc basin volcanism. They also calculated the paleodepth of the subduction zone to be 120 km, varying with the thickness of the crust. The depth to subduction zones is calculated by a K-h graph from Dickinson (1975a). Barnes (1978) analyzed the chemistry of the Clarno strata in the Mitchell area and calculated the paleodepth to be 170 km. Stroh (1979) did the same and obtained a paleodepth of about 145 km. However, little confidence can be put in these data because of the finding of Condie and Potts (1969) and Nielson and Stroiber (1973). The former determined that the potassium content in volcanic rocks varies directly with the thickness of intruded crust. The latter studied modern examples of subduction/magmatic-arc complexes and concluded that the potassium content is significantly affected by the original content of potassium in the magma, irrespective of the thickness of crustal rock traversed by the ascending magma.

The early Cenozoic subduction zone has also been postulated to have been parallel to the trend of the Columbia Arc (Hamilton, 1969). That is, the oceanic crust was embayed into the North American continent occupying much of present day Oregon and Washington, and a subduction zone trended northeastward diagonally through present-day Oregon. Hamilton (1969) noted the association between subduction zones, batholiths and suture zones composed of serpentine, blueschists, and ophiolites. This concurs with Hess (1937) who found these suture zones to be exposed in orogenic belts and connected with ancestral continental margins. The nature and occurrence of batholiths with their spatial variation in potassium, alkali, and silica content were noted by Moore (1959). He discovered a "quartz diorite boundary line" within the lineation of batholiths along the western Cordilleran Orogen. It marks the boundary between intermediate (quartz diorite) rocks on the west side and more acidic rocks (granodiorite, quartz monzonite) on the east side and displays a consistent zonation within the length of the cordillera. Following Hamilton's (1969) hypothesis of a northeasterly trending subduction zone, Burchfiel and Davis (1972) and McWilliams (1978) expanded on the same idea. Burchfiel and Davis (1972) envision a paleosubduction zone trending northeast-southwest through the present western U.S.A. from the late Precambrian to the Early Triassic. In Early Triassic time the continental margin and subduction zone jumped to about the present-day location of the coastline of California and persisted to the middle Cenozoic. However, the position of the trench did not change through present-day Oregon, rather, it retained its northeastward trend. Upon subduction and consequent orogeny, the convergent plate boundary became the Columbia Arc (Burchfiel and Davis, 1972). In accord with this idea first Lipman et al. (1972) and subsequently Wilson (1973) found that the Eocene volcanics of the Pacific Northwest are progressively enriched in K_2O from the Coast Range to Yellowstone Park. However, the K_2O values for the Clarno are too low for the calculated dip of the subduction zone. In order to account for this discrepancy they proposed an easterly trending shoreline and trench axis during Eocene time. Snavely and MacLeod (1977) and McWilliams (1978), however, conclude that concurrently with the northeast-trending subduction zone another trench formed in the late Eocene (early Refugian). The new trench was located approximately in the present location of the continental shelf margin. These two subduction zones persisted together between 40 and 20 million years b. p.

Cenozoic Tectonic Rotation of the Columbia Arc

Beck (1976) proposed that paleomagnetic rotations of crustal blocks could be produced by a style of deformation called "ball-bearing" tectonics, first introduced by Wise (1963). This phenomenon would be produced over a broad diffuse zone of parallel strike-slip shears. Hamilton and Meyers (1966) cite paleomagnetic studies that show the early Cenozoic formations of the Pacific Northwest to be rotated clockwise. Northeastern Oregon has been rotated by 45°, southwestern Idaho by 25°, and post-Miocene southeastern Washington by 15° (Hamilton and Meyers, 1966). However, no paleomagnetic rotation has occurred for the Clarno volcanics[5] as shown by Whitney (1974) nor for the Upper

[5] Dr. Robert Lawrence (personal communication, 1979) cites personal communication from M. E. Beck, Jr., that 7° ± 14° of paleomagnetic rotation exists in the Clarno.

Yakima Basalts of the Columbia River Basalt Group as shown by Rietman (1966). Taubeneck (personal communication, 1979) supports these findings by recent unpublished evidence. Therefore, the Clarno volcanics and Yakima basalts must post-date the rotational movement. Taubeneck (1966) also discounts Hamilton and Meyers' (1966) idea on the basis of his structural analysis of the dike systems in the area of the eastern part of the Columbia Arc. The stress relationships that produced the dikes do not fit the oroclinal hypothesis for the Columbia Arc. He also showed that Hamilton and Meyers (1966) used many dikes in their study that were pre-Miocene, and many were not basalts, but lamprophyres. Cox and Simpson (1976) proposed a slightly different scheme than that of Hamilton and Meyers (1966). They proposed two models for the plate interactions of post-late Eocene time. Both models are based on earlier findings that the Eocene Coast Range basalts and overlying sediments have been rotated 70° in a clockwise fashion. This concurs with Cox and Magill (1977) and Plumley and Beck (1979). These basalts are the Siletz River Volcanics and overlying sedimentary Tyee and Flournoy Formations. Their first and least viable hypothesis is that the Siletz River Volcanics were an intra-oceanic island chain with a paleostrike of about N. 70°W. The chain was rafted into a subduction zone that trended approximately north-south in the location of western Oregon and Washington. The southern end of the chain hinged on and pivoted off of the Klamath Mountains and rotated to its present position as it was carried down into the trench (Cox and Simpson, 1976). This concept concurs with Lovell (1969) who determined the provenance of the Tyee Formation to be from the Klamath Mountains. He determined the paleoshoreline trended northeastward, the dispersal pattern was northward, and the water depth graded from shallow in the south to deep marine in the north. Cox and Simpson's (1976) second hypothesis envisions a northwest-southeast-trending subduction zone in the early to middle Eocene. This concurs with Vance (1979). The Siletz River Volcanics were an island chain trending parallel to the trench and later rafted down into it. The basaltic islands may have been generated by a hot spot that has since migrated underneath the continent to its present-day position under Yellowstone National Park. The northwest-southeast-trending subduction process produced a linament of andesitic volcanics through Washington, northern Idaho, and western Montana (Cox and Simpson, 1976). Vance (1979) calls this volcanic pattern the Challis arc and mentioned that the Clarno volcanics may be genetically related to it. In the late Eocene the islands clogged the subduction process and the trench switched position to the southwest side of the chain. The newer trench paralleled the older and trended through the present day location of southwest Oregon into the Pacific Ocean. Also in the late Eocene the rotation of the Siletz River Volcanics began to occur about a pivotal point at the north end of the islands, located about at the southern terminus of the present Olympic Mountains. Armentrout (1979) lends further credit to the second model of Cox and Simpson (1976) by citing unpublished studies by M. E. Beck, Jr., and others. He stated that only about 10° of paleomagnetic rotation of the Goble and Black Hills Volcanics of the Willapa Hills has occurred. This helps support the idea that the island chain rotated about a pivotal point located about at the present southern terminus of the Olympic Mountains of Washington. Discrepancies in the amount and direction of rotation suggest the existence of two or more miniplates (Armentrout, 1979). Burr and Beck (1979) recently discovered a 32° clockwise rotation of the Goble volcanics in southwestern Washington. They also suspect a northward translation of the same volcanics, highly suggestive of micro-plate movements. This possibility was also mentioned by Cox and Simpson (1976). Rotation was caused by right-lateral strike-slip faulting, the same mechanism that emplaced the Klamath Mountains to their present day location from the southeast (Cox and Simpson, 1976). Hamilton (1969) and Wright (1976) attribute the cause of this faulting to the westward migration of the Sierra Nevada, Lawrence (1976) to the upward and westward bulging of the Basin and Range Province, and Cox and Simpson (1976) to back-arc spreading behind the late Eocene trench. Extensional tectonics in eastern Oregon and Washington during this interval of time may be the cause of the origin of the Clarno volcanics (Cox and Simpson, 1976).

Lawrence (1976) has analyzed the timing of deformation on faulting patterns in the northern Basin and Range Province in southern Oregon. He believes that not only were the Klamath Mountains emplaced from the southeast by right-lateral strike-slip faulting, but the northernmost fault zones, such as the Brothers and Eugene-Denio zones, are younger than the southern ones and are currently active. The juvenile activity of these faults is clearly demonstrated by the marked right-lateral offset of the Pliocene/Pleistocene Cascade Range seen across the Eugene-Denio fault zone (Lawrence, 1976; Wright, 1976).

Other Hypotheses of Origin

Not all workers believe that the Clarno volcanics are subduction related. Robyn (1977a, 1977b) states that the Clarno is non-subduction related. He points out that the late Miocene calc-alkaline volcanic groups in northeastern Oregon trend in a direction that is structurally transverse to the trend of calc-alkaline volcanics in the same area. Also, the late Miocene volcanics occur between two geologic provinces, the tholeiitic basalt Columbia River Plateau and the olivine-tholeiite basalt of the northern Basin and Range. This calc-alkaline volcanism occurred contemporaneously with that of the baslatic volcanism of the two flanking provinces, but not all of these volcanics are related chemically. Therefore, their compositional differences cannot be the result of magma fractionation, magma contamination or partial melting of the same source rock, but must represent the transition between major lithospheric segments (Robyn, 1977a, 1977b).

Rogers and Novitsky-Evans (1977) noted the characteristics of the Clarno volcanics that diverge from the modern analogues of plate tectonics. For one, the andesites are pyroxene-bearing in the Clarno rather than hornblende-bearing as in island-arcs and continental margins.[6] Secondly, the Clarno plots on the SiO_2-FeO/MgO diagram bridging the cutoff between calc-alkaline and tholeiitic fields. Thirdly, the strontium content is too low. And lastly, unlike subduction/magmatic arc volcanism that has less than 10 percent of all rock types with silica percentages greater than 63

[6] This is not the case as noted in Oles and Enlows (1971) and Brown and Thayer (1966).

percent and only rare rocks with less than 56 percent SiO_2, the Clarno volcanics have 23 percent of all rock types with greater than 63 percent SiO_2 and 23 percent with less than 56 percent SiO_2.

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APPENDIX

APPENDIX A. CHEMICAL ANALYSES OF CLARNO ANDESITE FLOWS

SAMPLE	25-1	27-1	28-1
FeO	6.8	5.8	9.2
TiO_2	1.05	1.05	1.10
CaO	6.5	6.4	10.0
K_2O	1.10	1.7	0.6
SiO_2	61.9	61.5	54.2
Al_2O_3	16.3	18.4	15.8
Na_2O	3.6	4.3	3.0
MgO	2.6	1.3	6.9
TOTAL	99.85%	100.45%	100.8%