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Geology of the Breitenbush Hot Springs area, Cascade Range, Oregon

Clifford Michael Clayton
Portland State University

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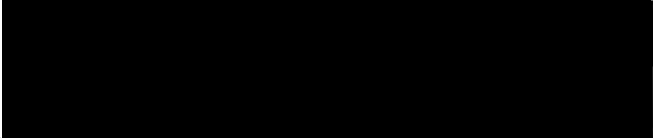
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AN ABSTRACT OF THE THESIS OF Clifford Michael Clayton for
the Master of Science in Geology presented February 27, 1976.

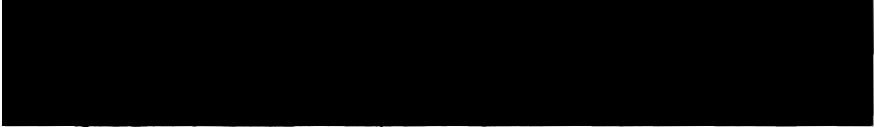
Title: Geology of the Breitenbush Hot Springs Area,
Cascade Range, Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:


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The Breitenbush Hot Springs area lies on the boundary
of folded middle to late Tertiary Western Cascade rocks
and younger High Cascade rocks. Within the mapped area

the Western Cascade rocks are represented by four formations. The Detroit Beds, a sequence of interstratified tuffaceous sandstone, mudflow breccia, and tuff, is overlain unconformably by the Breitenbush Tuff. The Breitenbush Tuff consists of three units of welded pumice-rich, crystal-vitric ash-flow tuffs interbedded with tuffaceous sedimentary rocks. The Outerson Formation unconformably overlies the Breitenbush Tuff and consists primarily of basaltic lava and breccia.

The Outerson Formation includes three localized members: a basal, glassy, aphanitic basalt, the Lake Leone Sediments, and the Outerson Tuff. The Outerson Formation is cut by a number of feeder dikes and plugs and is unconformably overlain by the Cheat Creek Sediments, composed of volcanic sedimentary rocks and a distinctive basaltic tuff. The Western Cascade formations total more than 1660 m (5500 ft) of strata and range from Oligocene to Pliocene in age.

The High Cascade rocks are represented by two formations: the Triangulation Peak Volcanics of basalt and andesite lava and breccia, lying unconformably atop the Cheat Creek Sediments; and unconformably beneath the Collowash Volcanics, a series of thin basaltic lava flows and breccias. The Western and High Cascade rocks are covered extensively by surficial deposits, primarily glacial drift. The High Cascade formations are at least

840 m (2800 ft) thick, ranging in age from Pliocene to Pliestocene.

The Western Cascade rocks have been folded and faulted in the Breitenbush Hot Springs area, and form the eastern limb of the north-trending Breitenbush Anticline. The folded rocks and the erosional unconformities between the rock units probably represent two local episodes of orogeny: one in early to middle Miocene and another in late Pliocene to Pleistocene time. The Outerson Formation represents a depositional sequence between the periods of uplift and deformation. Faulting accompanied the orogenic sequences.

The primary volcanic landforms in the area have been destroyed by erosion but skeletal remains of High Cascade volcanoes are recognized. Stream erosion and glaciation are responsible for the present landforms.

Breitenbush Hot Springs occurs, in part, along basaltic dikes which channel the water through impermeable Breitenbush Tuff. The dikes are believed to be associated with the Outerson basalts. The Hot Springs discharge upwards at 3400 l/min. (900 gpm) of water at temperatures up to 92°C (198°F).

GEOLOGY OF THE BREITENBUSH HOT SPRINGS AREA,
CASCADE RANGE, OREGON

by

CLIFFORD MICHAEL CLAYTON

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

MASTER OF SCIENCE
in
GEOLOGY

Portland State University
1975

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Breitenbush Hot Springs Area, Cascade
Range, Oregon In Pocket

INTRODUCTION

Purpose

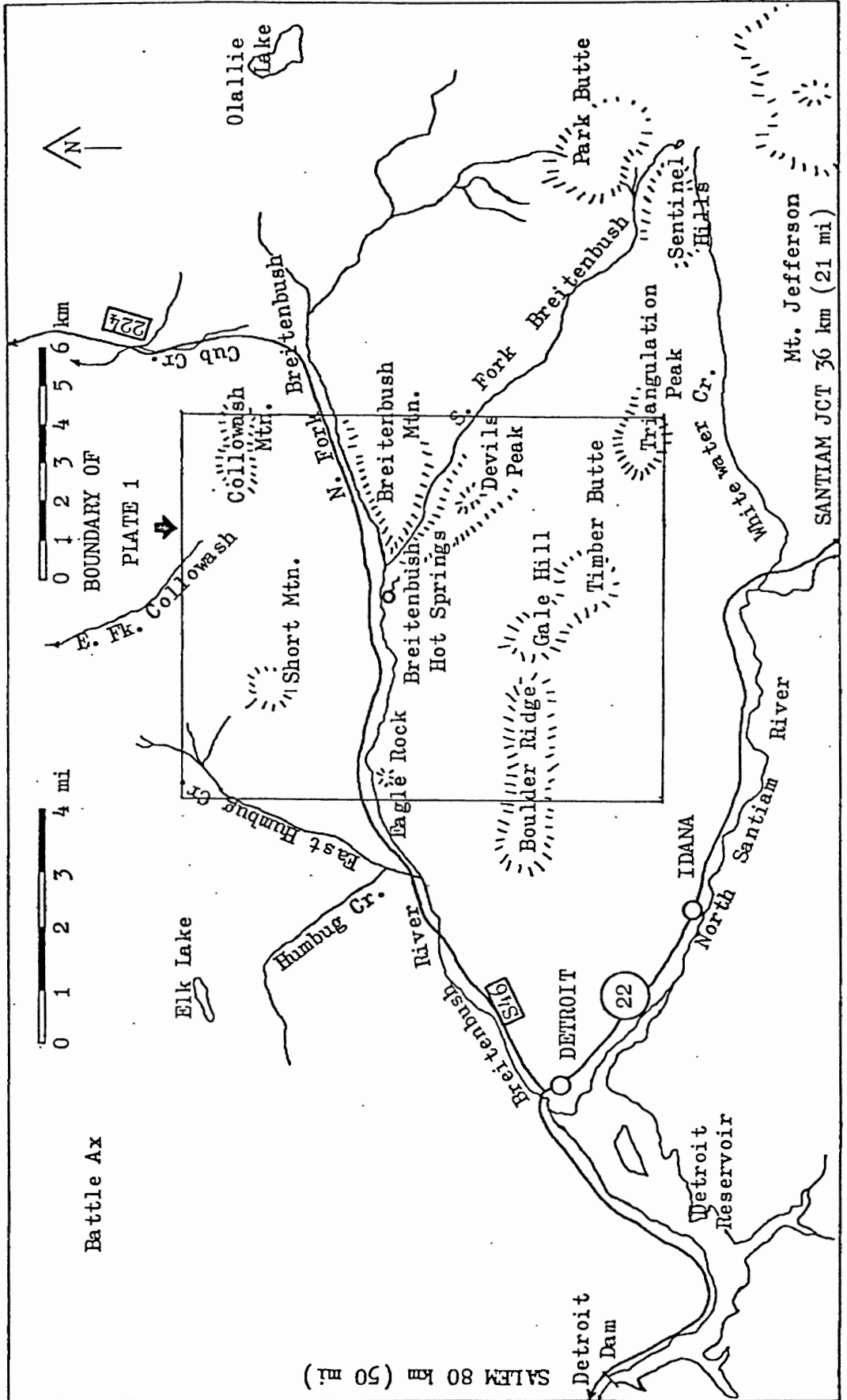
In 1970 the U. S. Geological Survey classified 3626 ha (8960 acres) around Breitenbush Hot Springs as a Known Geothermal Resource Area (KGRA). Previous mapping, reconnaissance in nature, has not satisfactorily demonstrated the contacts of the stratigraphic units, nor has the local stratigraphic and structural sequence been resolved. The purpose of this investigation was to map and describe the areal geology as part of a regional study of the geothermal potential of the northern Oregon Cascade Range. No attempt is made to evaluate the geothermal potential in this thesis, but a brief description of the geology and chemistry of the Breitenbush Hot Springs is included at the end of the thesis.

Study Area

Breitenbush Hot Springs is located in easternmost Marion County, about 100 km (63 mi) east of Salem. The main access into the area is via U. S. Forest Service road S46 east about 18 km (11 mi) from its intersection at Detroit with Oregon Highway 22 (Fig. 1). Several logging roads and trails traverse the area (Pl. 1).

Figure 1.

LOCATION MAP OF THE BREITENBUSH AREA



The study area includes about 117 sq km (45 sq mi) surrounding Breitenbush Hot Springs. The area extends east from Eagle Rock to Breitenbush Mountain and is roughly bound by the Willamette - Mount Hood National Forests boundary on the north and the old Seitzinger Road to the south. The study area includes all of the Breitenbush Hot Springs KGRA.

Regional Setting

The area straddles the boundary of the Western Cascades and High Cascades physiographic provinces. The High Cascades forms the crest of the mountain range and is comprised of Quaternary volcanic landforms. Most of the Western Cascades is composed of Tertiary volcanic rocks and a few intrusions that have been eroded to form a series of even-crested ridges separated by deep V-shaped and locally glaciated valleys. The striking dissimilarities between the rock types, landforms, and structures has long been known. However, the contact relationships and stratigraphic sequence have received little study. The few attempts (Hodge, 1928; Callaghan, 1933; Thayer, 1936, 1939; Peck and others, 1964; Wheeler and Mallory, 1969) to describe and explain the relationships have led to a confused picture. The location of the Breitenbush Hot Springs area on the joining between the two provinces has afforded an opportunity to refine the relationships.

Geography and Climate

As does most of the western slope of the Cascade Range, the area receives about 114 cm (45 in) of precipitation per year of which a large portion falls as snow (Wells, 1936). The high amount of rain fall and moderate temperature, 5.6 to 11°C (42 to 52°F) mean (Wells, 1936), contribute to good soil development and the flourishing growth of Douglas fir, red cedar, and hemlock as well as a lush undergrowth of rhododendron, vine maple, and assorted ground cover (Langille and others, 1903). The dense vegetation obscures rock exposure except on steep precipices, logging clear-cuts, and road cuts. The recent acceleration of logging activity in the area has exposed geologic features unavailable to previous workers.

Previous Work

Thayer, (1936, 1937, 1939) was the first to investigate the geology of the area. Peck and others (1964) mapped the extent of the northern Western Cascades and used the work of Thayer in compiling their map. Thayer had mapped the geology of the North Santiam River area, including the Breitenbush Hot Springs area, on the basis of mappable rock units. Peck and others incorporated Thayer's formational names into their description of two

complex stratigraphic units, the Little Butte Volcanic Series and the Sardine Formation. The Little Butte Volcanic Series of Peck and others (1964) is herein referred to as the Little Butte Formation in adherence to the Code of stratigraphic nomenclature (Amer. Assoc. Petrol. Geologists, 1961). The extreme thicknesses, complexities, and internal discontinuities within the two formations has led this investigator to return to mapping distinct lithologic units, giving priority to Thayer's nomenclature.

It is not intended that the mapped units in this report be proposed as formal names. The correlation of units in a complex volcanic sequence, as exemplified by the Cascade Range, demands that the individual rock units be traced as well as possible and their contact relationships be determined prior to the adoption of formal names. Hopefully future work will allow correlation within the formations proposed by Peck and others.

Methods of Study and Rock Nomenclature

The geology was mapped in the field onto a topographic base with a scale of 1:24,000. The area overlaps four quadrangle maps (Explanation, Pl. 1). U. S. Forest Service firemans maps were used to locate trails and logging roads. U. S. Forest Service aerial photographs, approximate scales 1:15,000 and 1:70,000, were used in stereo pairs for

location and interpretation. The field mapping was completed in the summer of 1974.

Rock nomenclature used in this report is based on hand specimen petrology. Where identification was questionable supportive petrography was used (Appendix I).

The classification of fragmental volcanic rocks is shown in Figure 2a, and is modified after Smith (1964). Tuffs were classified according to Figure 2b, modified after O'Brien (1963). Volcanic sediments were classified as shown in Figure 2c after Gilbert (1954) and Pettijohn (1957). Classification of igneous rocks is according to Jackson (1970) and Travis (1955), and is based on hand specimen identification rather than chemistry or optical petrography.

Lithologic descriptions were compiled using hand specimens and outcrop descriptions. Modal analysis of the rock units was made using 3 - 4 petrographic thin sections per rock unit. Rock color descriptions were obtained by comparison with the Rock Color Chart (Goddard, 1948).

Acknowledgements

The author is grateful for the financial and material aid and the opportunity to participate in the regional mapping project provided by the Oregon Department of Geology

Figure 2a. CLASSIFICATION OF FRAGMENTAL VOLCANIC ROCKS (after Smith, 1964).

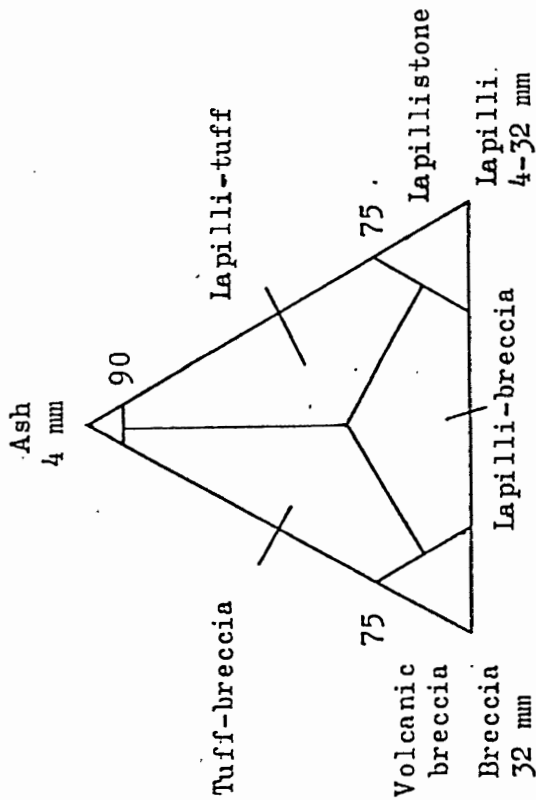


Figure 2b. CLASSIFICATION OF TUFFS (after O'Brien, 1963).

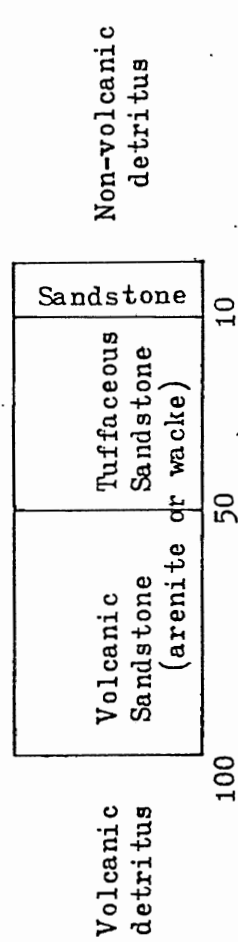
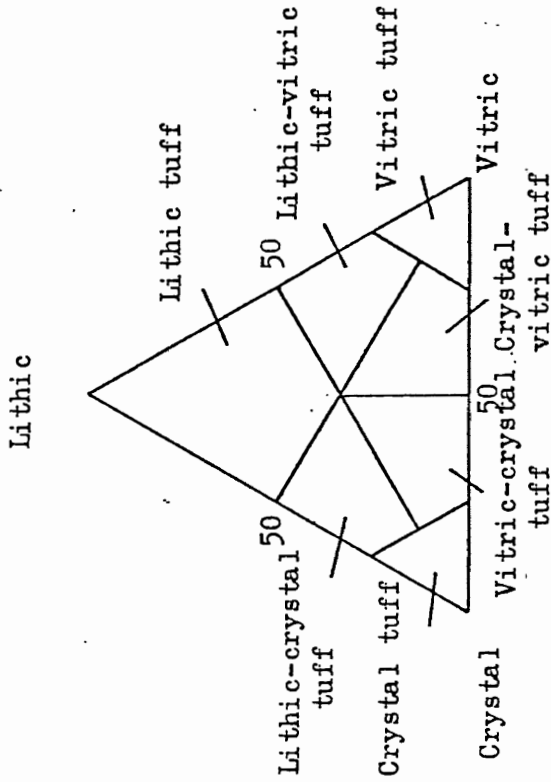


Figure 2c. NOMENCLATURE OF VOLCANIC SANDSTONES (after Gilbert, 1954, and Pettijohn, 1957).

and Mineral Industries.

Many aspects of the regional relationships were resolved in field conference under the coordination of Dr. Paul E. Hammond. Among several participants deserving of acknowledgement are Anthony Rollins and Richard Dyhrman, Department of Geology, Oregon State University.

The author also wishes to thank the several student associates who offered useful suggestions, constructive criticism, and morale encouragement. Special appreciation is owed to the author's wife, Nancy, for her patience and encouragement.

The final typescript was prepared by Ms. Gretchen M. Jones.

DESCRIPTIVE GEOLOGY

Regional Setting

Within the mapped area are six bedrock units and associated intrusions and three surficial units (Fig. 3).

The study area lies on the boundary between the High Cascade Series and Western Cascade Series (Callaghan, 1933). As described by Callaghan the High Cascade Series overlaps the Western Cascade Series with pronounced unconformity. In the Breitenbush area the Detroit Beds, Breitenbush Tuff, Outerson Formation, and Cheat Creek sediments represent the Western Cascade Series; Triangulation Peak and Collowash volcanics belong to the younger High Cascade Series.

The Western Cascade Series has been deformed by folding and faulting and has been intruded by dikes and plugs. The Breitenbush anticline trends northwards on the western margin of the map area and has been faulted and intruded; the intrusions are associated with a large volcanic complex.

The High Cascade Series was deposited along the eastern flank of the anticline and was partially deformed by the folding. There has been little faulting and the intrusions are related to a composite volcanic complex.

Figure 3. BEDROCK STRATIGRAPHIC SEQUENCE IN THE BREITENBUSH AREA

QUATERNARY		Pleistocene		Pliocene		TERTIARY		Oligocene - Middle Miocene	
		eroded							
		Collowash Volcanics	Qcv	300 - 600 m 1000 - 2000 ft					
?	?	Triangulation Peak Volcanics	TQtp	240 m 800 ft					
		Cheat Creek Sediments	Tcc	120m 400ft					
		Tuff	Tot	60 - 600 m					
		Lava and Breccia	To	200 - 2000 ft					
		Lake Leone Sediments	Tll	200 - 2000 ft					
		Basal Basalt	Tob						
		Gale Hill member							
		Boulder Ridge member	Tbt	750 - 790 m 2400 - 2600 ft					
		Cleator Bend member							
		Detroit Beds	Td	150m 500ft					
		unexposed base							

Basalt and andesitic basalt interbedded with breccia; few thin interbeds of tuffaceous fluvial sediments.

Andesitic basalt interbedded with scoriaceous breccia.

Volcanic sediments overlain by tuff

Volcanic complex comprised chiefly of basalts and breccias. Two local members; welded tuff in upper part of section, fluvial - lacustrine sediments within lower part. Base of the formation is usually dark, glassy basalt.

Ash-flow tuffs interstratified with fluvially deposited tuffaceous sandstones and pebble conglomerate.

Basal member is characteristically a welded greenish-gray pumice rich crystal-vitric tuff.

Tuffaceous lithic breccia and fluvial tuffs.

The terms High Cascade Series and Western Cascade Series will be referred to here as the High Cascade Group and Western Cascade Group in accordance with recommendations by the American Commission on Stratigraphic Nomenclature (1961).

Western Cascade Group

Detroit Beds (Td)

The Detroit Beds extend eastward from Detroit into the thesis area where only a small portion of the unit is exposed. Insufficient outcrops of the unit within the map area precludes a complete stratigraphic description of the formation. The best exposed section within the mapped area occurs between Fox Creek and Scorpion Creek in the crest and eastern limb of the Breitenbush anticline. The Detroit beds represent the oldest rocks in the stratigraphic section (Fig. 3; Pl. 1).

The unit consists of reddish brown to light brown fluviially deposited tuffs, tuffaceous sandstones and massive tuff breccias. The tuffs and tuffaceous sandstones occur as beds from less than 1 cm (0.3 in) to more than 2 m (7 ft) thick; the massive tuff breccias range from 5 - 10 m (16 - 33 ft) thick (Fig. 4). Approximately 1 km (0.6 mi) east of Scorpion Creek along road S46 the unit is in poorly exposed fault contact with Breitenbush Tuff. The

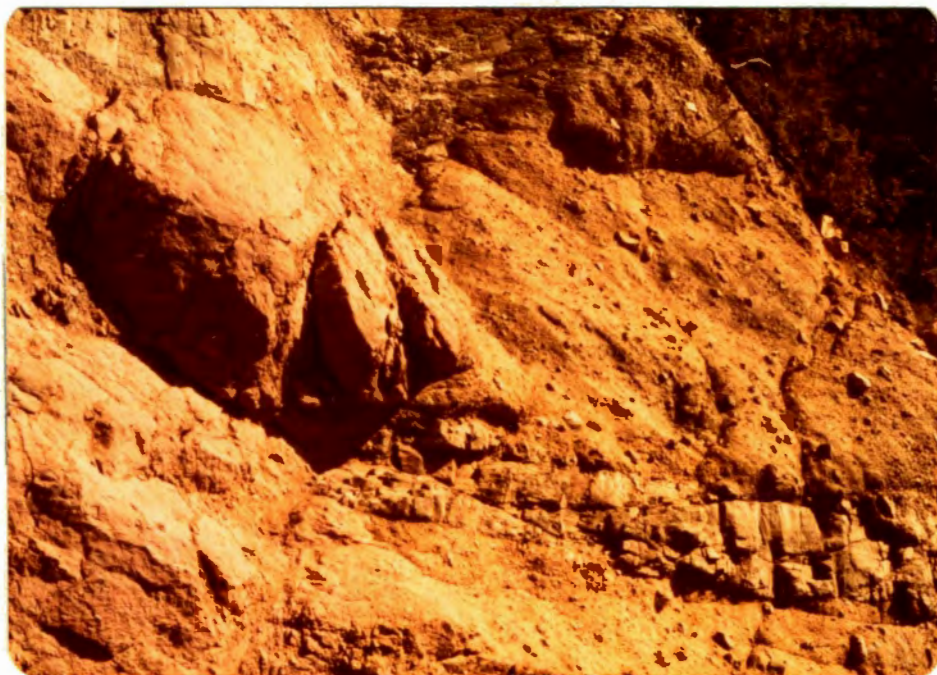


Figure 4. Outcrop of Detroit Beds 0.4 km (0.25 mi) east of Scorpion Creek along U. S. Forest Service road S46. View is to northwest. Note that the unit is faulted; the massive tuff breccia to the left (west) has been displaced downwards about 6 m (20 ft) and is the same unit as in the upper right of photograph.

stratigraphic sequence continues in outcrops exposed in sec. 26 and the NW1/4 sec. 35, T. 9 S., R. 6 E. (Pl. 1). A sequence of fluvial tuffs, similar to those near Scorpion Creek, continues upwards becoming coarser grained and richer in lithic fragments near the top of the section. A total of 150 m (500 ft) of section is exposed within the map area; Hammond (1975) reports the probable thickness of the Detroit Beds exceeds 3000 m (10,000 ft).

In hand specimen the tuff and tuff breccia range from reddish brown to light brown and grayish green. Andesite and pumice lapilli up to 20 mm in diameter constitute from 20 - 80 percent of the tuff and tuff breccia. The matrix consists of devitrified glass; less than 10 percent of the matrix consists of crystals of plagioclase, magnetite, and altered pyroxene. Quartz and hornblende are uncommon. Secondary minerals include zeolites and clay.

Tuffaceous sandstone and tuffaceous pebble conglomerate contain andesitic to basaltic clasts and granules in a matrix similar to the tuff.

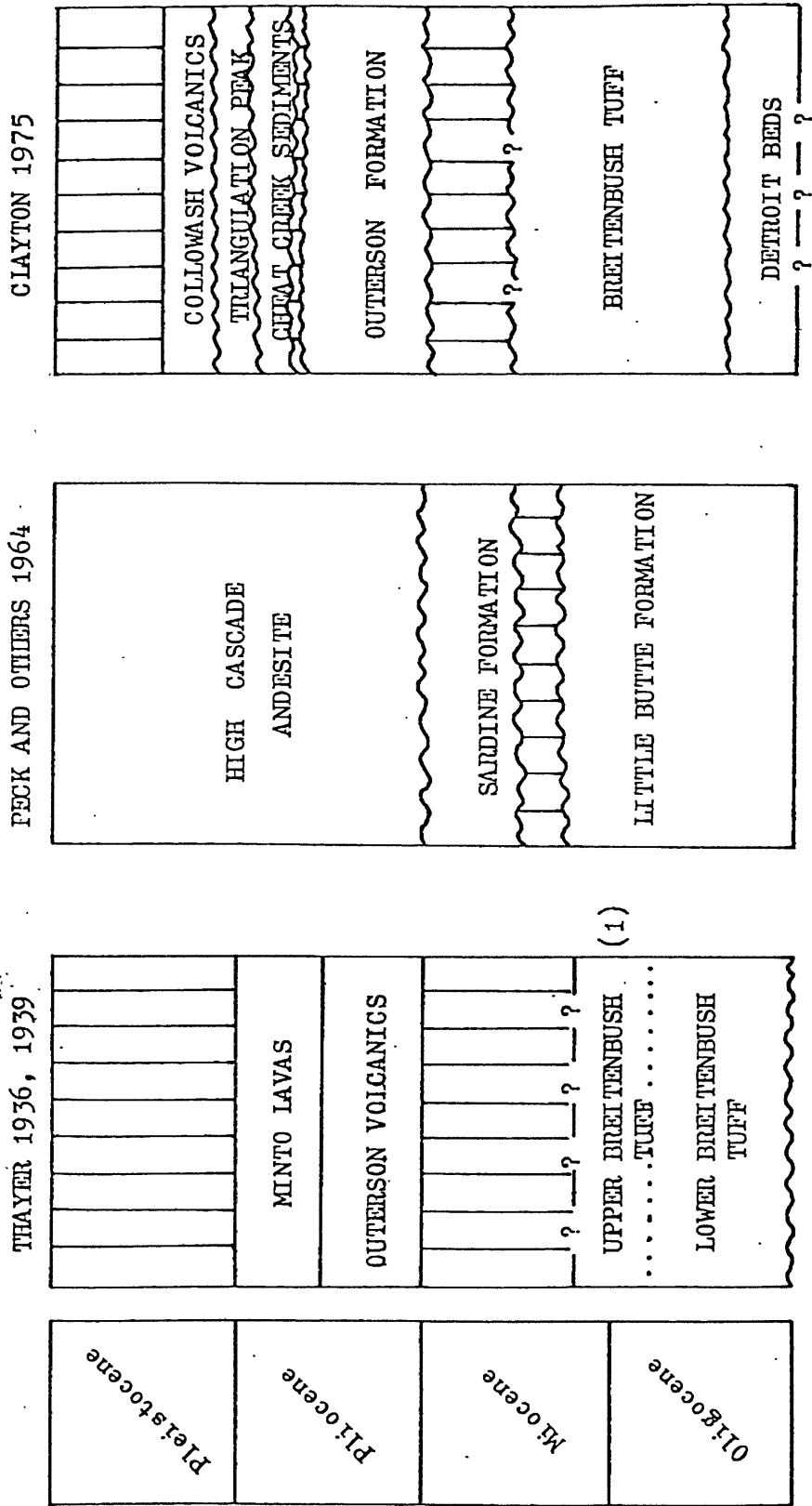
The Detroit Beds are found in steep slopes of ridges that are supported by intrusions, as at Eagle Rock, or in steep slopes beneath more resistant units, as in the ridge south of Cultus Creek, sec. 26, T. 9 S., R. 6 E. Differential weathering along weakly developed jointing is seen in some of the tuffs along the south side of the Breitenbush River in the NE1/4 sec. 24, T. 9 S., R. 6 E. Another

characteristic of the Detroit Beds is that of spheroidal weathering, especially in sedimentary and massive tuffaceous sandstones, as along road S46 between Scorpion Creek and Fox Creek.

In the SE1/4 sec. 27, T. 9 S., R. 6 E., west of the map area, greenish-gray pumice-rich lithic breccia and greenish-gray fluvial tuffs are unconformably overlain by remnants of a massive grayish-green, lithic, crystal-vitric ash-flow tuff of the Breitenbush Tuff. This is the only distinct upper contact of the Detroit Beds observed; elsewhere the effects of faulting, landsliding, and colluvium combine to make approximation of the contact necessary. The contact relationship north of the Breitenbush River is largely unknown but is inferred to be a fault contact with the overlying Breitenbush Tuff, the contact extending northwest from the concealed fault east of Scorpion Creek. The base of the Detroit Beds is not exposed within the map area.

Thayer (1936, 1939) originally mapped this unit as the upper part of his Breitenbush Tuffs (Fig. 5). He believed (Thayer, 1936, p. 9) that the exposures between Detroit and the Scorpion Creek - Fox Creek area were common to the upper part of the Breitenbush Tuff and that the massive green ash-flow tuffs containing pumice and lithic fragments belonged to the lower part of the Breitenbush Tuff. The Scorpion Creek fault contact 1 km (0.6 mi) east of Scorpion Creek reveals that the Detroit Beds have been displaced

Figure 5. CORRELATION CHART OF ROCK UNITS IN THE BREITENBUSH HOT SPRINGS AREA



(1) Thayer incorrectly placed these tuffaceous units above the green pumice-rich Breitenbush Tuff; they actually belong below the Breitenbush Tuff and are called Detroit Beds here.

upwards relative to the basal green lithic and pumice-rich, crystal-vitric tuff member of the Breitenbush Tuff, exposed in a quarry alongside road S46 about 75 m (250 ft) east of the fault. The occurrence of the same crystal-vitric tuff in unconformable contact above the less resistant Detroit Beds, south of Cultus Creek, is further evidence that the unit of fluvial tuffs, tuffaceous sandstones and tuff breccias actually lies beneath the distinctive green lithic crystal-vitric tuff. Hammond (1975) informally proposes the name Detroit Beds to distinguish the unit from the overlying Breitenbush Tuff.

Near the Detroit Dam (Fig. 1) the Detroit Beds have been intruded by the Halls Diorite Porphyry (Thayer, 1939; Peck and others, 1964) dated by the U. S. Geological Survey as 25 ± 10 m.y. old, and is considered to be of early Miocene age. Thayer regarded the tuffs (Detroit Beds) as Oligocene and possibly correlative with the Mehama Volcanics (1939).

Breitenbush Tuff (Tbt)

The Breitenbush Tuff consists of a distinctive and extensive series of ash-flow tuff and interbedded volcanic sediment. Within the map area about 800 m (2600 ft) of section is exposed dipping $10 - 15^\circ$ east from near Eagle Rock to the South Fork of the Breitenbush River (Pl. 1). The unit, originally named by Thayer (1936, 1939) is

herein separated from the underlying Detroit Beds (Fig. 5). Three units are recognizable within the study area but are not mapped individually because of the paucity of outcrops. The units are, from bottom to top, the Cleator Bend Unit, the Boulder Ridge Unit, and the Gale Hill Unit.

Cleator Bend Unit. The lowest unit, the Cleator Bend Unit, of the Breitenbush Tuff is best exposed along the Breitenbush River and cuts of road S46 from the quarry 1 km (0.6 mi) east of Scorpion Creek to 1 km (0.6 mi) east of Cleator Bend. West of the quarry the unit is in contact with the Detroit Beds along a poorly exposed fault; east of Cleator Bend the unit is mostly concealed by outwash gravels and till. This unit is the same unit exposed in contact above the Detroit Beds, south of Cultus Creek.

The Cleator Bend Unit consists of welded grayish green, crystal-vitric tuff and interbedded tuffaceous fluvial sandstone. The unit is about 240 - 275 m (800 - 900 ft) thick. The top of the unit is marked by 3 - 5 m (10 - 20 ft) of pebbly tuffaceous sandstone. The sandstone is exposed in the riverbottom of the South Fork of the Breitenbush River about 0.8 km (0.5 mi) south of the summer homes adjacent to Breitenbush Hot Springs.

A typical hand specimen contains glass (65 percent), pumice, (16 percent), crystals (12 percent), and lithic fragments (7 percent). About 85 percent of the crystals is plagioclase; the rest consists of quartz, pyroxene, and

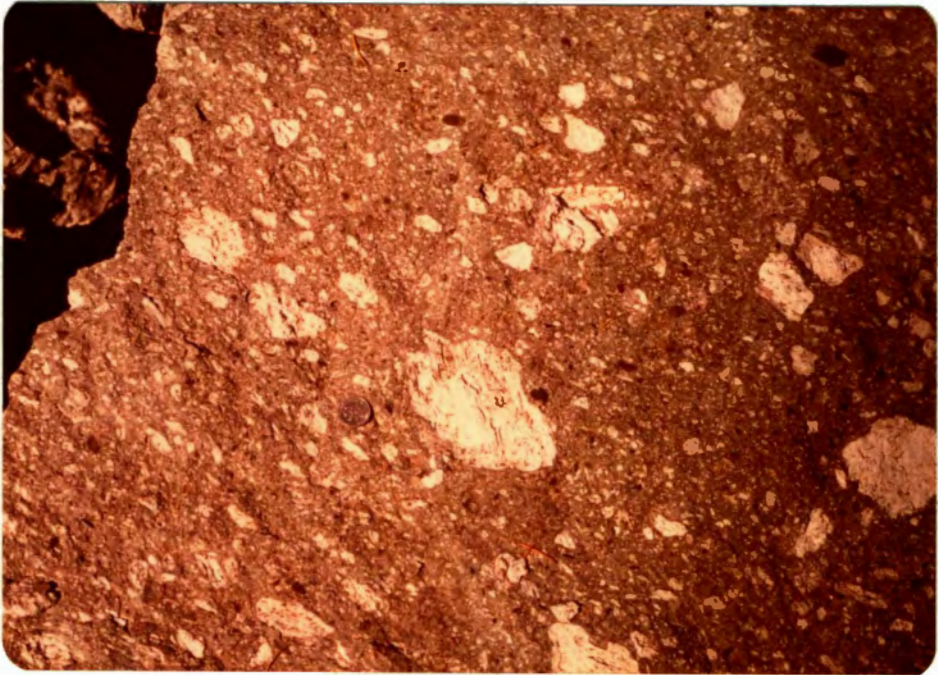


Figure 6. Typical appearance of the Cleator Bend unit, Breitenbush Tuff. Photograph taken at outcrop at Cleator Bend, 1.6 km (1 mi) west of Breitenbush Hot Springs, along U. S. Forest Service road S46. White patches are pumice lapilli, darker basalt fragments are also visible in the crystal-vitric tuff. Coin (dime) for scale.

minor biotite and hornblende. The glass and pumice are mostly unaltered but do contain small amounts of celadonite which gives the rock its characteristic greenish gray to grayish green color (Fig. 6). The tuff becomes richer in pumice and the lapilli become larger up-section. The lithic fragments are basalt; their size ranges from 0.1 mm to more than 20 mm. Locally, as at the quarry east of Scorpion Creek, carbonized wood is imbedded in the massive tuff.

Boulder Ridge Unit. The middle unit, the Boulder Ridge Unit partly exposed from about the 2800 ft contour line in the NE1/4 SE1/4 sec. 23 and NW1/4 SW1/4 sec. 24 T. 9 S., R. 6 E. (Pl. 1), about 0.8 km (0.5 mi) east of Eagle Rock, southwards to Boulder Ridge. Interbedded tuffaceous sandstone and conglomerate, lapilli breccia, and several welded lithic tuffs comprise 335 - 365 m (1100 - 1200 ft) of section.

The base of the Boulder Ridge unit is marked by a welded pinkish gray crystal-vitric tuff that lies above tuffaceous sandstone of the Cleator Bend Unit. This welded tuff is well exposed in secs. 23 and 24, T. 9 S., R. 6 E. along an abandoned logging road and also crops out 1.3 km (0.75 mi) due north of Breitenbush Hot Springs in a logging road cut. The welded tuffs near the top of this unit are up to 45 m (150 ft) thick and display columnar jointing; the columns average over 1 - 2 m (3 - 7 ft) in width. These



Figure 7. Exposure of Boulder Ridge unit, Breitenbush Tuff. View is to southwest from SW 1/4 NW 1/4, sec. 36, T. 9 S., R. 6 E. along road S916. Columns of ignimbrite 2 - 3 m (6 - 10 ft) across and 4 - 6 m (14 - 20 ft) high are exposed below trees on the skyline.

ignimbrites are the most resistant strata within the Breitenbush Tuff and are expressed as a sloping cliff or rib on the north side of Boulder Ridge and Gale Hill (Fig. 7). Road S916 parallels beneath this rib. Differential erosion has left some of the columns standing out from the cliff like statues or pillars; others have fallen and accumulated at the base of the cliff.

On the north side of the Breitenbush River the distinctive welded tuff sequence is absent. The ash-flow tuff may not have been deposited here. Also, poor exposure and/or erosion could be responsible for the apparent gradation of the sedimentary interbeds of the middle unit upwards into the upper unit without an intervening ignimbrite sequence.

Gale Hill unit. Resting on top of the middle unit are very light gray to very pale orange welded tuffs and a few thin lava flows comprising the 150 m (500 ft) section of the Gale Hill member.

The base of the Gale Hill unit is marked by a vitrophyric lava less than 10 m (32 ft) thick. The lava is distinctive (hornblende and plagioclase phenocrysts up to 10 mm long) but is found only in a saddle in the NE 1/4 SW 1/4 sec. 36, T. 9 S., R. 6 E. The lower contact suggests a slight unconformity of 2 - 3° between the Boulder Ridge unit and the vitrophyre and indicates an erosional surface atop the middle unit. Above the

vitrophyre about 30 m (100 ft) of light gray incipiently welded ash-flow tuff is overlain by a basalt flow 4 m (15 ft) thick; the basalt is overlain by 80 - 100 m (260 - 340 ft) of the same light gray to very pale orange welded crystal-vitric tuff. This tuff can be found on the north side of the Breitenbush River between Short Lake and Minnie Boo Hoo Creek but its contact relationship is not well exposed. On the south side of the ridge 0.8 km (0.5 mi) west of Gale Hill a few distinctive hoodoos have differentially eroded from the Gale Hill unit. These spires stand 1 - 6 m (3 - 20 ft) high against a steep slope that has been clear cut. The tuff is overlain by pyroclastics and welded breccia of the Outerson Formation.

The landforms of the Breitenbush Tuff are characteristically valleys of low relief slopes. Most of the tuffs are poorly resistant to weathering and alter to clays; as a consequence landslides and slumps are common features. In general the tuffs are not resistant but some of the welded tuffs are exposed on rounded slopes which support only sparse grass. Slopewash prevents the development and accumulation of soil. These patches of grass, combined with the underlying ignimbrite, which is characteristically altered to celadonite, appear from a distance as greenish gray outcrops.

The age of the Breitenbush Tuff is not known. Hammond (1975) has submitted samples for radiometric dating but the

TABLE 1

IDENTIFIED PLANT REMAINS FROM THE BREITENBUSH AREA

Plant	Age	Source
Quercus		
Cercidiphyllum	Late Miocene	Collected by Thayer; Identified by Chaney (Thayer, 1939)
Abies		
Fagus Sanctieugeniensis	Middle to Late Miocene	Collected and identified by Wolfe (Peck and others, 1964)
Quercus Chrysolepis		

results are not yet known. Fossil leaf impressions have been used in an attempt to determine the age of the Breitenbush Tuff. Thayer (1939) and Wolfe (Peck and others, 1964) have collected leaf impressions in the vicinity of Skunk Creek and Devils Creek. Table 1 lists the identified specimens.

Thayer collected specimens from the unit he mapped as Breitenbush Tuff (to which he assigned an Oligocene age). His samples were taken from a landslide boulder in Skunk Creek above its confluence with Devils Creek (1936, p. 9). It may well be that the landslide block came from the younger Lake Leone sedimentary member of the Outerson Formation (see Pl. 1), rather than the Breitenbush Tuff as it is mapped for this report.

The map by Peck and others (1964) shows a similar location but the text refers to the paleobotany location as being near Devils Creek. Examination of the map (Plate 1) reveals the potential problems of stratigraphic control. The leaves identified by Wolfe may have come from either the Breitenbush Tuff or the younger Lake Leone sedimentary beds. It is uncertain which strata were sampled.

The author was unable to find identifiable fossils but did find impressions of plant remains in the tuffaceous sediment of both units. Considering the unconformity between the Breitenbush Tuff and the Outerson Formation a careful study by a paleontologist might reveal the answer

to the problem.

The Halls Diorite Porphyry (Thayer, 1939; Peck and others, 1964), a scant 21 km (13 mi) to the west of the map area, is a sizeable pluton and could be related to the volcanic activity that produced the Breitenbush Tuff. The noticeable increase in pumice lapilli and the increase in crystals in successive ash-flows of the Breitenbush Tuff in comparison with the underlying Detroit Beds, indicates that the Western Cascades, at least locally, were beginning an episode of increased volcanic activity. The age of the stock, early Miocene, seems to be in agreement with the ages of the leaves that may have been taken from the Boulder Ridge (middle) member at Skunk Creek. The specific origin of the Breitenbush Tuff is unknown but the available evidence indicates the source area was to the west in the Western Cascades.

Outerson Formation (Tob, To, Tll, Tot)

The Outerson Formation is primarily a sequence of interbedded lava flows, breccia, and tuff breccia which are mostly basaltic in composition. Two local units interfinger with and constitute part of the Outerson Formation: the Lake Leone Sediments occur in the lower part of the formation and the Outerson Tuffs occur in the upper part of the formation. Both of the local units are underlain and overlain by lava and breccia characteristic of the

Outerson Formation. The basal part of the formation consists of several dark glassy basalt flows, ranging from 3 to 120 m (10 to 400 ft) thick, that are distinctly different in composition and texture from the Outerson lavas which overlie it. The Basal Outerson Basalt, Outerson lava and breccia, Lake Leone Sediments, and Outerson Tuff all constitute separate mappable units. The Outerson Formation is unconformably bound by the underlying Breitenbush Tuff and the overlying Cheat Creek Sediments.

The Outerson Volcanics were originally mapped by Thayer (1936, 1939 p. 11) as a series of "agglomerates, flow breccias and tuff with few thin lava flows". The name is now changed to Outerson Formation to agree with the recommendations of the Code of Stratigraphic Nomenclature (1961; Hammond 1975). The Outerson Formation as used here differs from Thayer's Outerson Volcanics in several ways. Thayer thought vents for the Outerson volcanic rocks occurred not only near Outerson Mountain but at Triangulation Peak and Mount Bruno as well. Subsequent study by Hammond (1975), Rollins (1975), and the author has shown that although in some places the volcanic rocks look similar, those at Triangulation Peak and Mount Bruno are not associated with the same episode of activity as at Outerson Mountain. The volcanic rocks at Triangulation Peak and the lava and breccia near Outerson Mountain are separated by readily identifiable deposits of interstrati-

fied sedimentary rock and basaltic lapilli-tuff, called the Cheat Creek Sediments, which extend unconformably across eroded strata of the Outerson Formation. Thayer (1939) referred to a type section for the Outerson Volcanics east of Outerson Mountain. The exact location of this section is uncertain. A good section is exposed along the Jefferson Park trail, east of Triangulation Peak, but the strata here form the overlying Triangulation Peak Volcanics.

Two locations are suggested for the type description of the Outerson Formation: (1) along road S94 from Devils Creek to about the 4300 ft contour line where the Outerson Formation is separated by a sedimentary interbed 3 - 4 m (10 - 15 ft) thick, about 0.8 km (0.5 mi) north on the upper leg of the logging road switchback, and (2) along the logging road that traverses the west side of Skunk Creek canyon southwards to the saddle in the NW1/4NW1/4 sec. 9, T. 10 S., R. 7 E. The second area exposes Outerson lavas resting unconformably above Breitenbush Tuff below the bridge where road S94 crosses Skunk Creek. The inter-tongued relationship of the Lake Leone Sediments, several feeder dikes for Outerson lavas, and the upper contact with Cheat Creek Sediments are also exposed along the Skunk Creek logging road. Representative lithologies of the Outerson Formation are exposed here except for Basal Outerson Basalt, best exposed in the NE1/4SE1/4 sec. 26, T. 9 S., R. 6 E. southeast of Eagle Rock, and the Outerson

Tuff which is best exposed in the ridge separating Rapidan and Mansfield Creeks.

The members of the Outerson Formation are discussed in stratigraphic order. However, it should be emphasized that Outerson lava and breccia are predominate in the section and in many places constitute the entire exposed section.

Basal Outerson Basalt (Tob). A basalt flow up to 120 m (400 ft) thick, unconformably overlies Breitenbush Tuff southeast of Eagle Rock. A thin breccia 2 - 3 m (6 - 10 ft) thick was found exposed beneath the basalt in the NW1/4SW1/4 sec. 25, T. 9 S., R. 6 E., about 20 m (70 ft) northwest of the fault exposed in road S921. The basalt is found capping a ridge extending north from Boulder Ridge. Similar basalt is found along Scorpion Ridge in the NE1/4SE1/4 sec. 13, T. 9 S. R. 6 E., north of the power transmission line, and is overlain by Outerson breccia. The isolated occurrence, however, precluded mapping it as part of the Basal Outerson Basalt. Also, in a quarry located at the western base of Breitenbush Mountain are exposed several flows that are interpreted as Basal Outerson Basalt; again this was not mapped separately from the overlying breccia and basalt of typical Outerson appearance because of limited exposure.

The basalt is a glassy aphanite with few small (1mm) plagioclase laths. Celadonite and sparse yellow and red

chalcedony occur along the joints of the basalt which is commonly highly fractured into brickbat sized fragments. Crude columnar jointing is exposed in a quarry located in the NE1/4SE1/4 sec. 26, T. 9 S., R. 6 E. The high glass content (15 percent), low olivine content (2.4 percent) and resistance to alteration serve to distinguish the Basal Outerson Basalt from the overlying typical lavas of the Outerson Formation which have much less glass, more olivine and a fine to medium grained and moderately altered groundmass.

The lava flows fill depressions eroded into the Breitenbush Tuff. Near Eagle Rock the lower contact is an angular unconformity atop the middle Boulder Ridge member of the Breitenbush Tuff. The basalt flows near Eagle Rock are similar in composition and texture to the plug at Eagle Rock; the flows were probably extruded from a vent at Eagle Rock. The plug at Eagle Rock and the basalt flows occur along a poorly defined shear zone. Two dikes were found and it is possible that other dikes fed the flows as well as the vent at Eagle Rock. It seems likely that the intrusive activity in this area could have been associated with weakened zones that developed in the Breitenbush Tuff during folding; Eagle Rock is near the axis of the Breitenbush anticline. Topographic position substantiates the supposition that the Eagle Rock flow predates the other lavas and breccias of the Outerson Formation.

Outerson Lava and Breccia (To). The Outerson volcanic rocks range from 60 - 600+ m (200 - 2000+ ft) in thickness and are characterized by dark basalts interbedded with scoriaceous breccias (Fig. 8) and, locally, few thin, 0.3 - 3 m (1 - 10 ft) interbeds of fluvial tuffaceous sediments. The dips of the Outerson strata range from 2 to 25° eastwards; the dips increase up to 40° near the vent areas. The breccia and lava rest with marked unconformity on top of the Breitenbush Tuff, but, as at the Breitenbush Mountain quarry, rest conformably atop Basal Outerson Basalt.

Most commonly the basalts are brownish black to olivine black but when weathered sometimes occur as grayish-red purple. The basalts are usually amygdaloidal, the vesicles filled with a dark blue-green mineraloid, and are often deeply weathered. The texture is finely porphyritic with plagioclase and serpentized olivine phenocrysts. Olivine composes about 4 to 5 percent of the rock and is often also altered to a red color due to iron oxide and iddingsite.

The breccias of the Outerson volcanics form several types of deposits. Bright red welded breccias form resistant bluffs 3 - 12 m (10 - 40 ft) high; less resistant breccia weathers to very dark red soil. Pale yellowish brown tuff-breccias are commonly less well indurated and are usually only found exposed in road cuts and cliff faces. South of Timber Butte devitrified palagonitic tuff



Figure 8. Exposure of typical Outerson basalt lava and breccia sequence. Photograph taken looking southwest along road 1071, west and above Skunk Creek. Note blocky to irregular jointing of basalt.

is exposed in cuts along road S916E. Similar palagonitic tuffs, interbedded with fluvial tuffaceous sandstones, are exposed in the NW1/4 sec. 4, T. 10 S., R. 7 E., above Skunk Creek.

The Outerson Formation represents the remains of a large shield volcanic complex that extended over most of the Breitenbush area. The entire volcanic complex has been deeply eroded so that no primary landforms remain.

The Outerson strata dip generally to the east and taper out to the west onto Breitenbush Tuff. The contact is an angular unconformity. The contact relationships on the north side of the Breitenbush basin are poorly exposed but show Outerson lavas resting at an angular unconformity of 5 to 8° on the above Breitenbush Tuff; the lavas dip up to 25° eastward and the contact dips eastward about 20°.

One source of the lavas was probably a dike swarm and a small plug near Skunk Creek 1.6 km (1 mi) northwest of Outerson Mountain. The steep dips and varied thicknesses of the breccia and lava in this vicinity also attest to the proximity of a vent. Laterally the lava and breccia become more regular in thickness and more gently dipping with the predominant dips about 5 - 15° to the east and northeast away from the volcanic center. Another swarm of dikes south of Mansfield Mountain indicates that there may well have been other centers of activity and that shield cones coalesced. South of Mansfield Mountain 1 km

(0.7 mi) near the Mansfield trail and along the logging road traversing eastward above Mansfield Creek the lava and breccia indicate by their east-southeasterly dips that a possible center may have been located near Mansfield Mountain. Between Scorpion Mountain and Mansfield Mountain, north of the map area, are outcrops of compacted breccias and tuff breccia. These appear to dip slightly north and would indicate quaquaversally dipping strata around Mansfield Mountain. Projection of the dikes above Mansfield Creek would support the possibility of a source area near Mansfield Mountain. The evidence is, however, too scant to definitely consider this as a major source area.

The angular unconformity and steeply dipping contact between the Breitenbush Tuff and the Outerson Formation indicate that the Outerson shield volcanic complex developed on the eastern flank of a highland, probably underlying the Breitenbush anticline. Drainage to the east, off of this highland, may have been empounded by the developing shield complex to form the ancient Lake Leone.

Lake Leone Sediments (T11). The lake Leone sedimentary beds are a sequence of interstratified volcanic sandstones, mudstones, and air-fall ash layers. The sediments are of fluvial and lacustrine origin and interfinger with Outerson basaltic lavas, breccias and cinders. The

sedimentary section is 300 - 335 m (1000 - 1100 ft) thick at the type locality between Gale Hill and Leone Lake, below road S916A, but thins out east and west. Glacial till covers most of the Leone Lake sedimentary beds but the sediments are well exposed by glaciation above Leone Lake. The unit is confined to the north side of Gale Hill and Timber Butte; it is also exposed in a small fault block west of Devils Creek. This suggests a localized depositional environment such as a lake, ie, ancient Lake Leone. The great thickness of the sediments is probably due to the constant accumulation of sediment in an empounded drainage as the Outerson shield volcanic complex enlarged.

The Lake Leone Sediments rest unconformably upon the upper and middle members of the Breitenbush Tuff northwest of Gale Hill and are in turn overlain by Outerson Basalt. A remnant of an Outerson basalt flow is exposed on the Thomas trail northeast of Leone Lake. The Lake Leone sedimentary beds interfinger with Outerson basalts west of Skunk Creek in the area between roads S916A and S94. The Lake Leone sedimentary section dips 5 - 15° to the southeast, indicating that the Outerson volcanic sequence was subsequently tilted.

Contained within the sedimentary unit are large blocks of sediment that have slumped and been deformed during the time of sedimentation. Deformation was probably due to nearby volcanic activity and concurrent seismicity.



Figure 9. Illustration of the size range of the volcanic sediments in samples of the Lake Leone Sediments. Thin bedded medium-grained sandstone under coin is the dominant rock type. Pebble conglomerate, upper right, and pumice lapilli tuff, upper left, are less common. Samples are from along road S916A, between Gale Hill and Leone Lake. Coin (quarter) for scale.

The lithology of the Lake Leone sediments varies from air-fall ash to deformation sandstone breccia with thinly bedded, fine-grained, volcanic sandstones predominating (Fig. 9). Olivine and augite grains in the sandstone indicate immaturity of the sediments. Carbonized and silicified wood fragments are found in some of the bedded ash layers and a few plant fragments were found in tuffaceous mudstone float near Skunk Creek. The possible age relationship of this unit was discussed with the Breitenbush Tuff.

Outerson Tuff (Tot). In the upper part of the Outerson Formation, the Outerson Tuff is locally intertongued with Outerson lava and breccia. The Outerson Tuff consists of interstratified welded tuffs and fluvial sedimentary tuffs and is exposed in the ridge separating Rapidan and Mansfield Creeks, south of Collowash Mountain. The unit can be traced from a thin layer 3 - 6 m (10 - 20 ft) thick, north of Mansfield Creek, to a maximum of about 180 m (600 ft) thick along the Rapidan trail (Pl. 1).

The welded and sedimentary tuffs occur in hill slopes and are not resistant to erosion. Within the tuffs are a few thin lava flows, one of which is a dark gray porphyritic basalt with plagioclase and hypersthene phenocrysts. The welded tuff ranges from pinkish gray to pale yellow brown and varies from a partially welded crystal - vitric tuff to a highly welded vitric tuff rich

in tabular plagioclase crystals 0.5 - 2 mm long and stretched and compacted pumice lenses up to 10 cm long. The sedimentary tuffs are pale gray to pinkish gray. The welded tuff units are usually less than 10 m (35 ft) thick; the fluvial tuff beds range from 10 cm (5 in) to 4 m (15 ft) in thickness. The sedimentary tuffs comprise about 135 m (450 ft) of the total section; nearly 45 m (150 ft) is comprised of welded tuff.

The sequence of tuff is bound on the east by a poorly exposed but traceable contact with Outerson lava and breccia. The contact dips steeply eastward and is inferred to be a fault contact. Thayer's "Cascade Fault" (1936) trends north-south near this contact. Thayer's fault was conjecture in an attempt to explain the steeply dipping contact between the Outerson volcanics and the overlying Collowash lavas. Thayer later (1939) abandoned the fault for lack of evidence. The inferred fault mapped in this report is based on the abrupt termination of the tuffs and their isolated exposure. The eastward dipping contact between the Outerson Formation and the Collowash lavas occurs 0.6 km (0.4 mi) east of the fault.

McBirney and Sutter (1974) have released radiometric dates of four samples taken from within the Breitenbush area. The age of the Outerson Formation is Pliocene as shown in Table 2. Samples 49 and 50 (Table 2) probably came from the Outerson Formation as mapped in this report.

TABLE 2

RADIOMETRIC AGE DETERMINATIONS OF BREITENBUSH AREA ROCKS

Sample No.	Locality	Apparent Age in M.Y.
47	North side of the South Fork of the Breitenbush River, on U.S. Forest Service road S918; normal polarity. (Minto lavas)	3.60 + 0.05
48	Just above Devils Creek on road S94, slightly above sample 50; reversed polarity. (Minto andesite)	4.72 + 0.19
49	About 70 meters below sample 48; reversed polarity. (Outerson basalt)	11.23 + 0.17
50	About 50 meters below sample 47; reversed polarity.	4.55 + 0.07

NOTE: (1) Data from McBirney (1974a).

(2) Unit description names in parenthesis are as used by McBirney; these were probably based on Thayer's map (1939).

Samples 47 and 48 may have been taken from what was mapped as either the Collawash Volcanics or the Outerson Formation. The Outerson Formation can be placed between early to late Pliocene. Sample 49 is thought by McBirney and others (1974) to represent an older sequence of volcanism. No field evidence was found to support the subdivision of the Outerson Formation. It might be noted that no rocks of the Basal Outerson basalt were found in the Devils Creek area (where sample 49 was taken). Evidence for two episodes of volcanism might be found, however, in that two sequences of intrusion are found associated with the Outerson Formation (see Tertiary Intrusions).

Cheat Creek Sediments (Tcc)

Volcanic sedimentary beds with an upper distinctive basaltic tuff overlies with angular unconformity an erosional surface of the Outerson Formation. These beds are called the Cheat Creek Sediments by Rollins (1975) who has traced the beds from the southeast side of Triangulation Peak near the head of Cheat Creek. The unit is overlain by basaltic andesite lava of the Triangulation Peak Volcanics.

The Cheat Creek Sediments are best exposed about 0.8 km (0.5 mi) southwest of Outerson Mountain on the south side of a hill, 5210 ft elevation. The sediments are fluviially deposited tuffs and tuffaceous sandstones. The overlying basaltic tuff, over 60 m (200 ft) thick is light

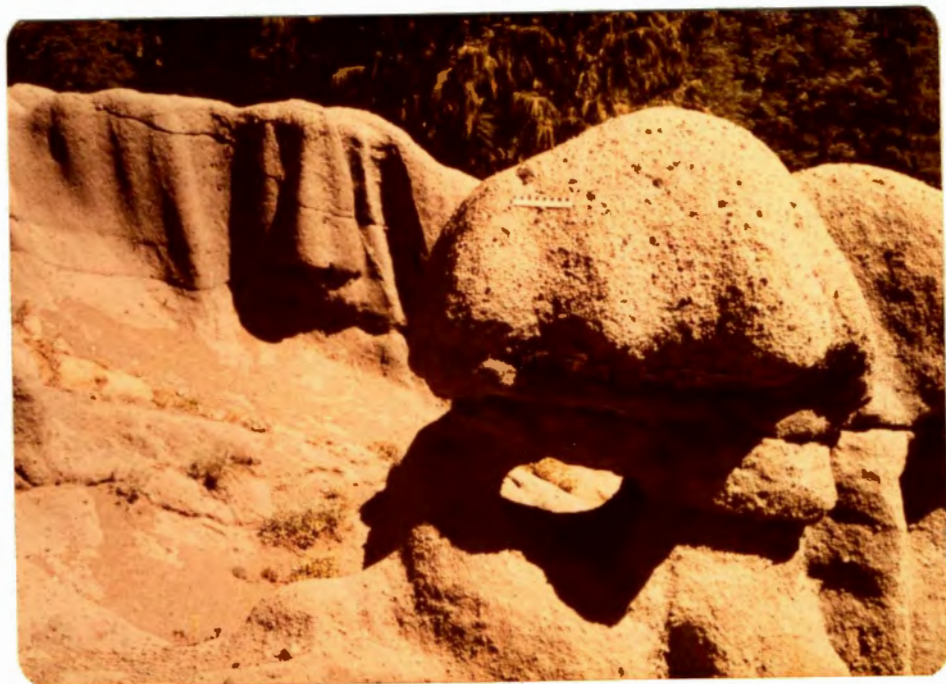


Figure 10. Outcrop of basaltic tuff at top of Cheat Creek Sediments. Note layering that indicates tuff may be water lain. Outcrop located 0.4 km (0.25 mi) southwest of Outerson Mountain summit. Scale is in centimeters.

gray, and contains angular basaltic scoria and yellowish gray pumice ranging from 5 - 40 mm in diameter (Fig. 10).

The Cheat Creek sediments were deposited on a flat lying surface which truncates the Outerson Formation. The unit has been subsequently tilted 5 - 7° southeastward. The alignment and blockage of some of the scoriaceous fragments indicates that the flow direction was to the southeast. The tuff may be of ash-flow origin but the aligned layers of scoriaceous lapilli causes some doubt; this may represent bedding, especially in the lower portion of the tuff. The angularity of the lapilli and the glass fragments suggests an ash-flow origin. The deposit also appears to be slightly welded. The tuff weathers to form distinctive hoodoos 0.5 - 2 m (1 - 6 ft) high.

The Cheat Creek sedimentary unit is traceable to the east about 3.2 km (2 mi) around the south flank of Triangulation Peak. The basaltic tuff is found resting against Outerson basalts and breccia on the south side of Outerson Mountain. The sedimentary beds can be traced to the north side of the hill, 5210 ft elevation.

Tertiary Intrusions (Ti)

All of the intrusions within the map area are fine grained to porphyritic dikes, sills and plugs of hypabyssal origin and are considered to be related to past volcanic activity. Basalt is the most common, forming glassy

porphyritic intrusions. The dike swarms north of Mansfield Creek and west of Skunk Creek are of this type. The intrusions fed Outerson lava flows. A porphyritic hornblende andesite plug, located 0.8 km (0.5 mi) north of Gale Hill, is the largest intrusion in the study area. Lake Leone sedimentary beds are displaced by the intrusion but are not contact metamorphosed. No flow rock similar in composition to the andesite intrusion has been found in the Breitenbush area.

Two episodes of basalt dike intrusion are interpreted. The first episode is probably related to fractured rock along the axis of the Breitenbush anticline. The dikes 1 km (0.6 mi) south of Mansfield Mountain, near the Mansfield trail, the dikes on Scorpion Ridge, and the plug at Eagle Rock and nearby dikes are all representative of the earliest intrusion. The dikes are commonly 1 - 3 m (3 - 10 ft) in width and can be traced only for short distances because of their weathered and fractured nature. Their trends usually range from N 30 W to N 30 E. The dike basalt has a glassy groundmass and is extensively fractured and altered. The younger episode of intrusion is related directly to the Outerson volcanic complex. The plugs east and west of Skunk Creek are of this episode. The younger dikes range up to 2 m (7 ft) in width and are essentially vertical. There is a radial trend around vent areas but this is not well defined. These dikes are less

fractured, coarser grained, and less weathered than the older dikes. The age of the intrusions is bracketed as they are found within and associated with the Outerson Formation: the older dikes with Basal Outerson Basalt and the younger dikes with Outerson lava and breccia. The dikes were probably emplaced in the Pliocene.

High Cascade Group

Triangulation Peak Volcanics (TQtp)

Triangulation Peak Volcanics was named by Rollins (1975) for the lava and breccia that comprise Triangulation Peak. Several plugs and feeder-dikes are associated with the lava and breccia.

Most of the lava forms thin flows 3 - 10 m (10 - 30 ft) thick and are interstratified with scoriaceous breccia; jointing of the lava is platy to irregular. The lavas rest unconformably above the Outerson Formation at Gale Hill and the Cheat Creek Sediments west of Triangulation Peak. The volcanic rocks of Triangulation Peak comprise about 240 m (800 ft) of section in the mapped area.

The Triangulation Peak andesitic basalts are medium gray to grayish black and are hypocrySTALLINE, fine-grained porphyritic. The basalt is characterized by 14 - 15 percent olivine, commonly altered to iddingsite. Plagioclase phenocrysts up to 5 mm in length are also common. The



Figure 11. View southwest towards Triangulation Peak and Spire Rock from near Devils Peak. Plug on right is Spire Rock; the two plugs on the left are unnamed. Triangulation Peak is the remains of a dissected composite volcano.

lavas display both normal and reversed magnetic polarity.

Similar lavas also cap Timber Butte and hill 5210 ft, southwest of Outerson Mountain, as well as the ridge separating Cascade Creek and Devils Creek. The lavas of Triangulation Peak were not found on Devils Peak ridge.

Only a reconnaissance traverse was made of the Triangulation Peak area in order to correlate the lavas capping Timber Butte and near Outerson Mountain with those at Triangulation Peak. More detailed mapping has been done by Rollins (1975).

The Triangulation Peak lavas and their source are better preserved than the older volcanics in the area. The dissected and well exposed vent area explicitly reveals the inner structures and form of a composite volcano (Fig. 11). Spire Rock is the largest of five plugs on Triangulation Peak; it is composed of glassy porphyritic basalt with plagioclase phenocrysts. A line of plugs and large dikes extends southeastward from Triangulation Peak toward Sentinel Hills, indicating a zone of weakness through which the lavas were extruded. Boca Cave has formed through collapse and weathering of a large dike that penetrated pyroclastic breccia; the cave subsequently enlarged from a rock overhang to a wide shelter primarily by the repeated collapse and erosion of the ceiling.

Triangulation Peak lavas are considered to belong to the High Cascade Group because they overlie with marked

unconformity the Outerson Formation and Cheat Creek Sediments, and because the structural features of the volcano are still well preserved. The age is believed to be late Pliocene to Pleistocene because the underlying rock is Pliocene and the flow remnants of Triangulation Peak lavas are separated by glacial valleys as at the heads of Devils Creek, Cascade Creek and Skunk Creek.

Collowash Volcanics (Qcv)

The name Collowash Volcanics is taken from Collowash Mountain; on the south flank, east of Mink Creek, a cirque exposes nearly 300 m (1000 ft) of stratified lava and breccia typical of the formation. Over 600 m (2000 ft) of section composed of Collowash lava and breccia is found in the Breitenbush area. Thayer (1936, 1939) called these strata Minto lavas and recognized Park Butte as one of the sources. The term Minto is not used because Rollins (1975) believes the lavas found near Minto Mountain are not the same as those exposed south of Collowash Mountain.

On the south side of Collowash Mountain the lavas are found in contact over the Outerson Formation with marked unconformity. The contact dips steeply eastward 20 - 30° and demonstrates the transition from onlap to overlap of the Collowash against an erosional scarp of the Outerson Formation (Fig. 12). The Collowash lava dips eastward 3 - 4° near the bottom of the section and near the top of

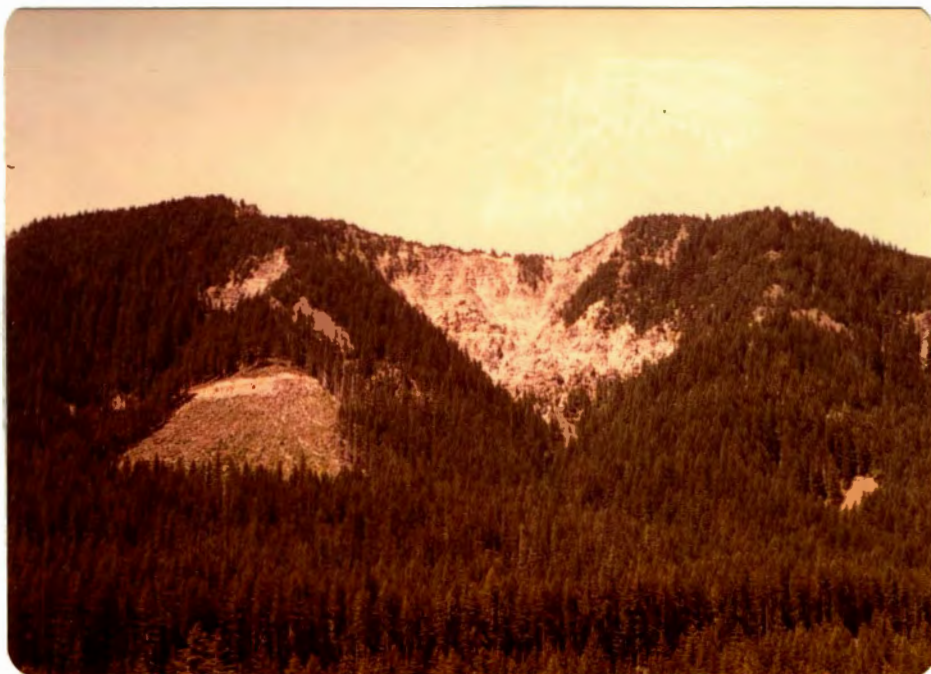


Figure 12 a. View to south side of Collowash Mountain from south side of the North Fork of the Breitenbush River. See sketch below.

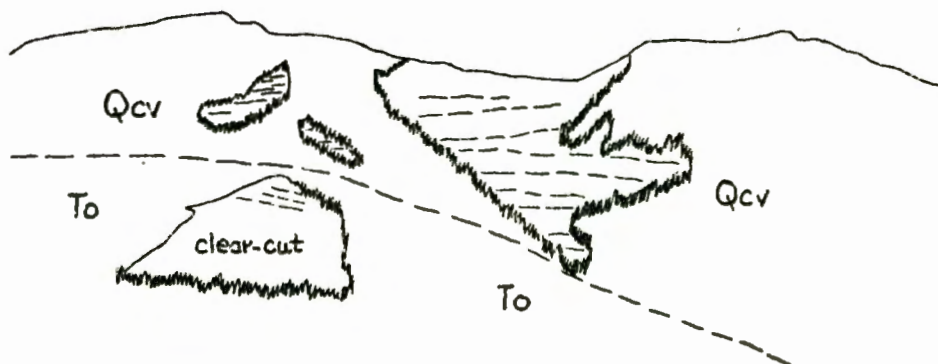


Figure 12 b. Sketch of photograph above. Note that lower Collowash lavas dip eastward $3 - 4^\circ$ while upper Collowash lavas dip westward $3 - 4^\circ$. Outerson lavas in clear-cut east $10 - 15^\circ$.

the section dips westward 3 - 4°. Continued uplift, responsible for the angular unconformity and erosion, may have deformed the lower portion of the Collowash lavas shortly after they were extruded. Another explanation for the reversal of dips could be that different sources contributed lavas to the Collowash section; there is no evidence to support this however. The lavas are consistent in composition and texture throughout their extent.

In outcrop the Collowash lava and breccia is found as alternating flows ranging from 3 - 10 m (10 - 30 ft) thick. Most of the breccia is scoriaceous basalt; a few are welded flow breccias. The lavas are andesites and andesitic basalts. Platy jointing and fractures are commonly well developed; blocky jointing is less prominent. A few sedimentary interbeds 3 - 5 m (10 - 16 ft) thick are found exposed in a logging road cut near the summit of the south flank of Breitenbush Mountain.

The Collowash basalts are similar to some of the Outerson lavas in outcrop habit and mineralogy making determination of the contact between them difficult. In general, the Collowash basalt contains more olivine but lacks the amygdules and zeolites found in the Outerson basalts. Also Collowash breccia is much less consolidated or weathered than Outerson breccia.

The Collowash andesite and basalt is typically light gray to dark gray. The textures range from diktytaxitic

lavas commonly have glomerophenocrysts of yellow green to glassy gray olivine. Plagioclase feldspar is usually pilotaxitic and intergranular with augite.

In the course of the investigation several oriented rock samples were tested with a portable flux-gate magnetometer to ascertain the polarity of remnant magnetism. The earth's magnetic pole was last reversed between 690,000 and 1.6-1.7 m. y. ago (Cox, 1969). The Collowash lavas are distinguished by normal polarity and from their stratigraphic position are believed to be of Quaternary age.

Triangulation Peak and Collowash volcanics represent the renewed episode of volcanism that built the platform atop which the High Cascade volcanoes were established.

Surficial Deposits

Glacial Deposits (Qg)

Till and outwash gravel form extensive glacial deposits in the Breitenbush area. Most deposits are fresh and well preserved. These deposits are considered probably equivalent to Frasier Glaciation (latest Wisconsin) in the Washington Cascade Range (Crandell, 1965). Till is oxidized to depths of less than 1 m (3 ft). The most porous boulders and cobbles have a weathering rind up to a few millimeters thick.

Well exposed moraines in various states of preservation

are found throughout the area. A moraine exposed in a clear cut northwest of Gale Hill impounds Leone Lake. Hill Creek and its tributaries have many remnants of lateral moraines, one of the largest being where Hill Creek joins the Breitenbush River. Lateral moraines 15 - 20 m (50 - 65 ft) high are also well exposed along the south facing slopes, for example between the lower reaches of Rapidan and Mink Creeks northwest of Breitenbush Hot Springs. Ground moraine mantles the valley bottoms above Cleator Bend to depths of several meters.

A few scattered and discontinuous remains of deeply weathered till are found along Hill Creek about 1 km (0.6 mi) southeast of Cleator Bend near road S916. Evidence for older glaciations has been found at lower elevations in the North Santiam River (Thayer, 1939). Such deposits possibly were not extensive in the Breitenbush area. However, they could have been eroded by subsequent glaciation and/or covered by recent glacial drift.

Outwash deposits are primarily restricted to the main valley floor of the Breitenbush River, extending up the North Fork of the Breitenbush River from Cleator Bend. The South Fork contains much less outwash, especially in its lower reaches where a small but spectacular gorge has been cut into bedrock of Outerson lavas. The confluence of five valley glaciers formed the intermontane Breitenbush basin and deposited terminal and recessional moraine

as they receded; the ground moraine was partly reworked and redeposited as outwash gravel. Outwash deposits are also found outside the study area and are well exposed near Humbug Creek.

Landslides (Qls)

Landslides are common in the Breitenbush basin. There are many small landslides that were not mapped due to the difficulty in recognizing all but the most recent movements. Those that were recognized are outlined on the map (Pl. 1).

Some landslides are large slump blocks. In the drainage of Scorpion Creek are two slump blocks with prominent head scarps and backward rotation of the block surfaces there is rotation of the blocks. Each slump involves 16 - 20 ha (40 - 50 acres) of land surface. The underlying bedrock is either Breitenbush Tuff or Detroit Beds. The tuffs are rather impermeable rocks. Bedding is presumed to be the primary failure plane of the slumps. The largest slump lies along a fault which may have initially weakened the strata that failed.

In secs. 24, 25, and 36, T. 9 S., R. 6 E. within the Breitenbush basin and near Eagle Rock are several debris landslides. These landslides range in size from 2 - 28 ha (5 - 70 acres). Tilted trees betray the presence of most of these landslides which also display a hummocky surface and deranged drainage pattern. Sag ponds are found near

the heads of the two largest landslides (Pl. 1). Till, Outerson volcanic rocks, and the Breitenbush Tuff are the units associated with the landsliding. As with the slump blocks, the groundwater penetrates the till and porous Outerson rocks but is perched on top of the impermeable Breitenbush Tuff. Clays form from devitrified and altered scoriaceous Outerson breccia as well as the Breitenbush Tuff provide an unstable condition on dip slopes. The landslides on the western and southwestern margin of the basin have slipped on dip slopes and bedding planes of the Breitenbush Tuff. The tuffaceous sedimentary rocks and poorly selded tuffs of the middle (Boulder Ridge) member of the Breitenbush Tuff are especially prone to landslides.

The most recent landslides are small slumps along the North Fork of the Breitenbush River; these occur in outwash gravels. The slumps, which involve 0.5 - 2 ha (1 - 5 acres) are primarily the result of river course changes of the Breitenbush River.

All of the identified landslides within the Breitenbush area are Holocene in age, because they are post-glacial and have tilted trees on their surfaces.

Alluvium (Qal)

The recent alluvium is confined to the proximity of the Breitenbush River and the lower reaches of Devils Creek. The alluvium consists primarily of reworked till

and outwash gravels; lateral migrations of the river into easily erodible banks has formed a widened channel with steep 3 - 6 m (10 - 20 ft) banks. The wide gravelly channel is confined to the Breitenbush River above Cleator Bend and extends up the North Fork of the Breitenbush River. The South Fork of the Breitenbush and the river below Cleator Bend have cut gorges into bedrock and contains little alluvium.

STRUCTURAL GEOLOGY

Folds

Thayer (1936, 1939) noted that the Breitenbush River cuts through a fold which he named the Breitenbush anticline. The axis of the anticline is rather poorly defined but trends north-south between Eagle Rock and Scorpion Creek (Pl. 1) Fig. 13. This fold axis may represent only one of several minor folds that occur as crenulations on the Breitenbush anticline, a broad-crested regional anticline immediately west of the map area (Hammond, 1975). More detailed mapping to the west and north may be necessary for refinement of the hinge line for the Breitenbush anticline. The map area lies largely on the eastern limb of the anticline. Thayer (1936, 1939) and Hammond (1975) have shown that the anticline is asymmetrical, steeper on the western limb, and plunges northwards; the western limb of the fold, near Detroit along Oregon Highway 22 and road S46, dips westward 30 - 50° (Thayer, 1939).

In the map area (Pl. 1) the folding was gradual and semicontinuous through the late Tertiary and into the early Quaternary. Each of the rock units has been tilted from its original attitude; successive units have been inclined less than preceding units. This is shown by the

attitudes of the units and the angular unconformities between the units.

The folding could be the result of two sequences of orogeny. The marked unconformity between the Breitenbush Tuff and the Outerson Formation indicates a period of uplift and extensive erosion. This may be a manifestation of orogeny.

Faults

Most faulting has been along a north-northeasterly trend, but northwesterly faults also occur. Nearly all of the faulting is confined to Western Cascade rocks.

The majority of the faults have high angle reverse movement with the down-thrown side to the west. The faults exposed in the NW1/4 sec. 24, T. 9 S., R. 6 E. display this relationship along road S46; in this area Detroit Beds are repeated several times by faulting.

The Eagle Rock - Short Mountain fault extends about 5 km (3.2 mi) N 30° E but due to the lack of stratigraphic marker horizons the displacement is not known. Another northeasterly trending fault extends west of Mansfield Creek from about 0.8 km (0.5 mi) north of the hot springs. The N 20° E trending fault is nearly vertical and displaces Outerson lava and breccia as exposed in road S46L 0.3 km (0.4 mi) west of the dike swarm southeast of Mansfield Mountain.

The second longest fault in the Breitenbush area, the Scorpion Creek fault extends 3.7 km (2.3 mi) up Scorpion Creek from west of the quarry alongside road S46, 1 km (0.6 mi) east of Scorpion Creek. The fault is concealed along road S46 but the displacement is about 200 m (650 ft) as determined from the offset of the basal (Cleator Bend) member of the Breitenbush Tuff.

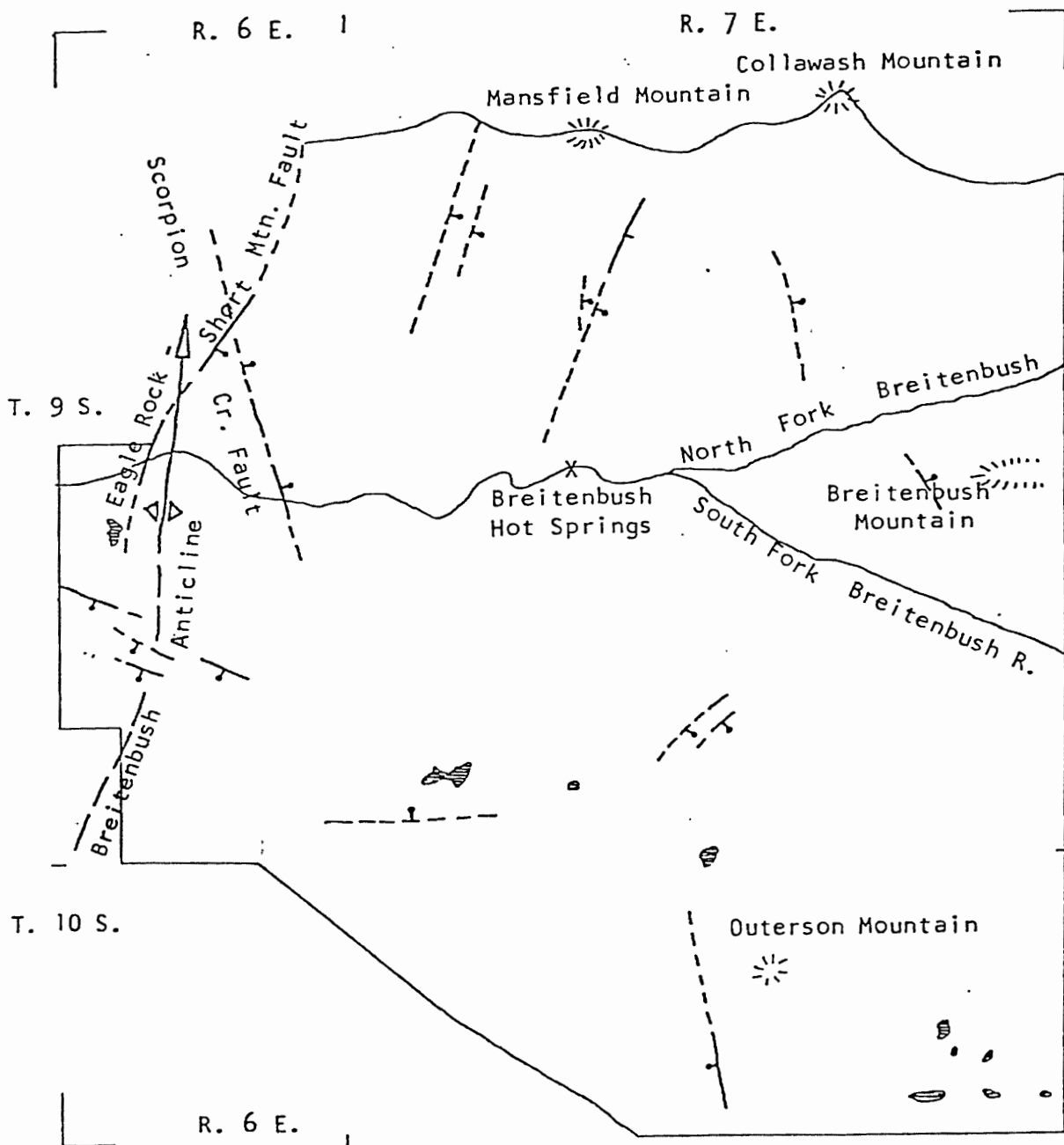
The largest fault displacing post-Outerson rocks occurs 0.8 km (0.5 mi) west of Outerson Mountain. Cheat Creek sedimentary rocks are displaced about 75 m (250 ft) with the east side up. The fault is vertical and is traversed by the Jefferson Park trail. The fault does not offset the overlying Triangulation Peak lava flow.

One small low angle fault is seen west of Skunk Creek in a road cut about 0.5 km (0.3 mi) south of the northernmost dike (Fig. 13). A small dike is horizontally offset about 2 m (7 ft) by a fault that dips 20° N and follows the contact between an Outerson tuff breccia and a tuffaceous conglomerate.

Many small faults seen in road cuts have no topographic expression. Some large faults have been interpreted from aerial photographs and poorly exposed field relationships. The easterly trending fault between Leone Lake and Gale Hill is clearly seen on aerial photographs, but surface exposures of the faulting relationships are indefinite. The Lake Leone Sediments have been badly fractured and

FIGURE 13.

MAJOR STRUCTURAL FEATURES OF THE BREITENBUSH HOT SPRINGS AREA



Scale
 1 mi
 1 km

Anticline
 Faults
 Plugs



Figure 14. Outerson basalt dike is offset to right by a low angle fault. Dike width is 0.6 m (2 ft). View is to southwest from road 1071 above Skunk Creek.

broken up by many small faults not traceable.

The age of the faulting cannot be well assessed. Very few faults displace Quaternary rocks; the majority of the faults are found in Western Cascade rocks which were formed in the late Tertiary. The majority of the faults are probably associated with the early orogeny and displace Detroit Beds, Breitenbush Tuff, and Outerson Formation rocks; the rest probably were active during the later orogeny and displace Cheat Creek Sediments and Collowash lavas only slightly.

Lineations

Lineations taken from aerial photographs are plotted on the map (Pl. 1). Nearly every lineation was carefully traced on the ground; most are in areas of dense vegetation. Evidence for the cause of the lineations was rarely found but some are caused by faults. Where no evidence could be found the major linear features were simply plotted as lineations; lineations believed not related to geology such as tree alignments, were not plotted.

All of the lineations are in the Western Cascade rocks. Most linear features follow the same trend as the major faulting. A few of the lineations may be due to dikes, such as the northwesterly trending lineation between Short Mountain and Mansfield Mountain.

The lineations near Mansfield Creek and west of Cleator Bend are thought to be related to faulting but this is uncertain. Some of the shorter lineations within the Breitenbush basin could be alignment of trees on the margins of mass movements; this feature was noted along a landslide 0.8 km (0.5 mi) southwest of Breitenbush Hot Springs.

Devils Creek follows a suspiciously straight course towards the hot springs but no evidence for a fault was found.

There is considerable evidence of mid-Tertiary tectonism in the Breitenbush area: The marked angular unconformity between the Breitenbush Tuff and the Outerson Formation, the deformation of Western Cascade rocks into the Breitenbush anticline, nearby plutonic intrusions such as the Halls Diorite Porphyry (Thayer, 1939; Peck and others, 1964), and propylitic alteration of rocks in the region about the Halls Diorite Porphyry (Peck and others, 1964). Basalt was also intruded along weaknesses in the folded and faulted rocks of the axial area of the Breitenbush anticline.

The Outerson Formation represents a sequence of deposition where uplift and erosion were not dominant in the Breitenbush area. The Outerson Formation was, however, folded and eroded prior to the deposition of the Cheat Creek Sediments which rest upon it with angular

unconformity.

The Cheat Creek Sedimentary rocks, the Triangulation Peak lavas, and the lowermost Collawash lavas have been tilted from their original attitudes in an eastward direction, indicating renewed uplift of the Breitenbush anticline to the west in Plio-Pleistocene time.

The evidence for semicontinuous uplift of the Breitenbush anticline is in close agreement with Wheeler and Mallory's (1969) concept of the evolution of the Cascade Range although they believe there were two separate episodes of orogeny, one mid-Tertiary and the other late Tertiary to Pleistocene in age. McBirney and others (1974) however interpret the events in terms of pulses of episodic volcanic eruptions, namely, a large pulse during the middle Miocene time forming the Outerson Formation (?) followed by smaller episodes of volcanism such as the Triangulation Peak and Collawash volcanics.

GEOMORPHOLOGY

The Breitenbush area includes landforms resulting from volcanism, alpine glaciation, mass wasting, and fluvial processes.

Volcanic Landforms

Primary volcanic landforms of the Western Cascades have been destroyed by erosion. Skeletal features of Western Cascade volcanoes consist of dikes and dike swarms associated with the Outerson Formation. Also included as a skeletal feature would be the plugs at Eagle Rock and north of Gale Hill and Timber Butte. The High Cascade volcanic landforms are also deeply dissected in the Breitenbush area and reveal skeletal dikes and plugs as at Triangulation Peak. Remnants of the cones are, however, evident. The basalts capping the hills near Outerson Mountain and Timber Butte - Gale Hill are remnants of the composite Triangulation Peak volcanic cone which was built by explosive eruption of lava and pyroclastic material. Similarly the basalt ridge caps of Devils Peak ridge, Collawash Mountain, and Mansfield Mountain are probable remnants of a shield volcano. Cross sections (Pl. 1) and contact relationships suggest that

the Breitenbush Mountain - Colowash Mountain area may represent an ancient valley that was eventually filled and finally over-topped by successive lava and breccia flows.

Glacial Landforms

Alpine glaciation has carved several features into the rocks of the Breitenbush area. The Devils Creek and North and South Forks of the Breitenbush River valleys display the broad "U" shape characteristic of well developed glacial valleys or troughs (Fig. 15). The North Fork of the Breitenbush River valley begins at a cirque on the northeast side of Park Butte; the South Fork valley leads to the Jefferson Park Glacier of Mt. Jefferson. The heads of Leone Creek, Hill Creek, Skunk Creek, and Mansfield Creek begin in glacial cirques. A small cirque pond, not seen on the map, rests in a depression or threshold at the head of Hill Creek. Discordant entries of Cascade Creek into Devils Creek and Roaring Creek into the South Fork of the Breitenbush River indicate that these valleys are hanging valleys.

The depositional landforms of glaciation have been discussed under the heading of glacial deposits. Lateral moraine and drift from each of the valley glaciers are found in various states of preservation. The Breitenbush basin is an intermontane valley formed where glaciers



Figure 15. View east to Breitenbush Mountain. Note U-shaped glacial valleys of the North Fork (left) and South Fork (right) of the Breitenbush River. Breitenbush Hot Springs is in valley, center of photograph. Olallie Butte on left skyline.

from the surrounding valleys met and coalesced. The basin floor is an irregular and hummocky surface of glacial drift.

Landforms of Mass Wasting

Slumps and debris landslides have been discussed; several recent landslides have been mapped (Pl. 1). The steep terrain contributes also to soil and rock creep. The valleys of the North and South Forks of the Breitenbush River are littered with accumulations of frost wedged and transported rock that has crept or fallen downslope. The north side of Boulder Ridge is strewn with broken ignimbrite columns. The several months when freeze and thaw take place account for the large accumulations. Debris and rock avalanches are common to the south facing slopes where freeze and thaw are at a maximum; the south side of Collowash Mountain has several exposed rock avalanche chutes.

Fluvial Landforms

The Breitenbush River Valley, below Cleator Bend, is representative of late youthful middle stage of valley development. The local relief of the map area is 1070 m (3500 ft). Interstream divides are narrow, and a well integrated drainage system has developed on the rim of the basin. Thayer (1939) originally discussed the headward development of the Breitenbush River. The river once was

consequent on the western slopes of the Western Cascade Range. Through headward erosion the river has breached the axis of the Breitenbush anticline and traversed several faults. The river may be classed as also subsequent in part now, for it has breached the structures. The river is also in part superimposed on the structures.

Skunk Creek, Devils Creek, and the South Fork of the Breitenbush River are in part consequent and superimposed from the flanks of eroded volcanoes. Scorpion Creek and, in part, Mansfield Creek are developed along fault valleys.

GEOLOGIC HISTORY

The Breitenbush Hot Springs area is underlain by six bedrock units that have undergone at least two episodes of orogeny, concurrent stream erosion, and, recently, extensive glaciation. The geologic history is summarized below by a review of the stratigraphic and structural relationships of the rock units.

Summary of Events

(1) The Detroit Beds, fluviially deposited tuffaceous sediments and altered tuffs, are the oldest rocks exposed in the map area. Little is known of the origin or age of the beds.

(2) The Detroit Beds were deformed and tilted eastward in the area and eroded by streams probably in the Oligocene epoch.

(3) Ash-flow tuffs rich in crystals, pumice, and rock fragments were deposited on top of the Detroit Beds and accumulated to a thickness exceeding 800 m (2600 ft). The source of the Breitenbush Tuff is not known. The Halls Diorite Porphyry, an intrusion west of Detroit, may have been associated with the vulcanism contributing material to the formation of the Breitenbush Tuff in the area.

(4) Strata of the Breitenbush Tuff were folded to form the Breitenbush anticline. Erosion removed much of the middle and upper members.

(5) Fractures and faults, which developed during the deformation, provided conduits for basaltic intrusions. At Eagle Rock the basalt reached the surface and flowed across the eroded Breitenbush Tuff to form the base of the Outerson Formation.

(6) A large shield volcanic complex developed on the eastern limb of the Breitenbush anticline. The Outerson lavas and breccias accumulated to thicknesses of over 600 m (2000 ft) and impounded westward drainage from the eastern slopes of the ancestral Cascade Range, forming Lake Leone. Sedimentation kept pace initially with the growing volcanic complex and sedimentary deposits accumulated to a thickness of over 300 m (1000 ft). Later, ash-flow tuffs were erupted from the Outerson volcanic complex and were localized in a narrow valley in the northeastern part of the area; younger Outerson basalt flows and breccia buried the sedimentary beds of Lake Leone and the welded tuff deposits. Pliocene Outerson volcanism, was accompanied by intrusion of a large hornblende andesite plug and numerous basalt dikes.

(7) The area was again deformed and uplifted; subsequently several north-trending faults formed and the Outerson complex was eroded to moderate relief with a

steep eastward facing erosional scarp.

(8) Volcanic Cheat Creek sediments were deposited locally atop a nearly flat, broad, erosional surface truncating Outerson lavas. They were subsequently tilted and eroded.

(9) The Triangulation Peak and younger Collawash lavas were extruded, respectively, from composite and shield volcanoes. The earliest lava flows were slightly tilted; later lavas remain undeformed except for minor faulting.

(10) Pleistocene glaciers, following stream courses consequent on the slopes of the volcanoes, deeply eroded much of the area and left accumulations of drift over much of the area. Recent landslides have occurred in incompetent volcanic materials and till.

BREITENBUSH HOT SPRINGS

About 40 hot springs are located along a 0.4 km (0.25 mi) stretch of the Breitenbush River at Breitenbush Hot Springs (Bowen and Peterson, 1970). Three of the springs were found to occur along and within Outerson basalt dikes intruding Breitenbush Tuff in the riverbottom. One spring is located behind the bathhouse, NE 1/4 SE 1/4 NW 1/4 sec. 20, T. 9 S., R. 7 E., another on the north side of the river, NE 1/4 SW 1/4 NE 1/4, sec. 20, and the third in the NW 1/4 SW 1/4 NE 1/4 sec. 20. The rest of the springs occur to the east of these dikes in alluvium and outwash gravel.

The surface temperature of the hot springs water is about 92°C; geochemical data indicate that the subsurface equilibrium temperature ranges between 130 - 150°C (Mariner and others, 1974). Chemical data for the hot springs is included in the Appendix B. There is little deposition at the springs; sinter, primarily silicious tufa is found near some springs in the outwash gravels. Travertine deposits are also present. The area near the NW 1/4 NW 1/4 SE 1/4 sec. 20, T. 9 S., R. 7 E. has been prospected for mercury which occurs in some of the springs.

The basalt dikes are important in channeling the

thermal water to the surface. The dikes have intruded along fractures in the Breitenbush Tuff and have a high secondary permeability due to cooling joints. The fractured tuff, Cleator Bend member, is impermeable because of devitrification and secondary mineralization including zeolites and clays, which tend to seal any joints or fractures. Because of surficial cover the dikes are not tracable.

A low ridge trends southwestward from the hot springs and is suspected to be structurally controlled. The trend of the ridge is discordant with what would be expected for a glacial moraine. It rises 25 - 35 m (80 - 120 ft) above the general level of the valley floor. It is possible that a basalt dike extends beneath this ridge. A lineation trends northeastward along this ridge but no cause for the lineation was determined by examination of the area.

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APPENDIX A. PT. I TABLE SUMMARIZING PETROLOGY OF LAVAS

COLLAWASH VOLCANICS: TRIANGULATION PEAK OUTERSON BASALT: BASAL OUTER-
 andesite, andesitic VOLCANICS: andesitic basalt SON: basalt
 basalt, basalt

TEXTURE

Phenocrysts Porphyritic to Fine-grained to Very fine-grained
 glomeroporphyritic porphyritic porphyritic inter- to glassy
 Groundmass Diktytaxitic, drusy, Fine-grained granular Subophytic, Pilotaxitic
 pilotaxitic pilotax

Optic Angle 80 85 85+ 85

Alteration Augite rims, iron Iddingsite, iron Iddingsite, Iron oxide
 oxide, iddingsite oxide serpentine

Size: pheno- 1 mm 1 mm 0.2 mm 0.15 mm
 crystals
 ground- 0.1 mm 0.1 mm 0.05 mm 0.05 - 0.15 mm
 mass

OLIVINE

Occurrence phenocrysts and phenocrysts and phenocrysts and
 groundmass groundmass groundmass

Grain Shape Anhedra Anhedra Anhedra Anhedra

Modal Percent 5.7 14.5 4.4 2.4

Optic Angle 55 - 60 60 55 - 65 55 - 60

Size: pheno- - 1 mm - 0.1 mm
 crystals

ground- 0.1 mm 0.05 mm 0.01 - 0.05 mm 0.01 mm
 mass

PYROXENE

APPENDIX A (CONTINUED)

Occurrence	Groundmass	phenocrysts and groundmass	phenocrysts and groundmass	phenocrysts and groundmass
Grain Shape	Subhedral, reaction rims on olivine	anhedral to euhedral	anhedral to euhedral	anhedral to euhedral
Modal Percent	29.2	26.9	34	26
An Composition	55	60 - 65	60 - 62	58 - 62
Optic Angle	75 - 78	85 - 87	80	78 - 82
Size: pheno-crysts	1 - 2 mm	2 - 5 mm	0.1 mm	0.15 mm
ground-mass	0.1 mm	0.05 mm	0.01 mm	0.01 mm
Occurrence	phenocrysts and groundmass	phenocrysts and groundmass	phenocrysts and groundmass	phenocrysts and groundmass
Grain Shape	euhedral to anhedral	euhedral to anhedral	euhedral to anhedral	euhedral to anhedral
Modal Percent	60.5	47.1	51.1	47.7
Size	0.1 mm	0.05 - 0.1 mm	0.01 - 0.1 mm	0.01 mm
Occurrence	Groundmass	Groundmass	Groundmass	Groundmass
Grain Shape	anhedral to euhedral	anhedral to euhedral	anhedral to euhedral	anhedral to euhedral
Modal Percent	3.3	6.2	4.5	5.7

PYROXENE

PLAGIOCLASE

MAGNETITE

APPENDIX A (CONTINUED)

GLASS	Occurrence	Interstitial, globules	Brown globules	Interstitial globules
	-	5.3	3.5	14.5
	-			
	Modal Percent			

APPENDIX A. PT. 2 TABLE

SUMMARIZING PETROGRAPHY OF BREITENBUSH ASH-FLOW TUFF

TEXTURE	Eutaxitic, welded compacted	
	An composition	25 - 50
	Optic angle	80 - 85
PLAGIOCLASE	Occurrence	phenocrysts
	Size	.01 - 2 mm
	Grain shape	anhedral to euhedral
	Modal %	10.6
GLASS	Occurrence	interstitial matrix ash fragments
	Modal %	64.5
PUMICE	Occurrence	pumice fragments
	Size	.01 - 20 mm
	Modal %	16.2
LITHIC	Occurrence	basalt fragments occidental and accessory
	Size	.01 - 20 mm
	Modal %	6.3
QUARTZ	Occurrence	phenocrysts
	Size	0.1 - 2 mm
	Grain shape	anhedral
	Modal %	1

APPENDIX A. PT. 2 (CONTINUED)

CLINO-PYROXENE	Optic angle	~60
	Occurrence	phenocrysts
	Size	.05 - 1 mm
	Grain shape	anhedral
	Modal %	0.8
MAGNETITE	Occurrence	dusty grains in glass
	Size	.05 - 1 mm
	Grain shape	anhedral
	Modal %	0.6

APPENDIX B

CHEMICAL DATA OF BREITENBUSH HOT SPRINGS

Temperature	92°C, 198°F		
Flow rate	3400 l/min, 900 gpm		
PH	7.31		
Specific conductance	4030		
Silica (SiO ₂)	83 ppm	Bicarbonate (HCO ₃)	142 ppm
Calcium (Ca)	100	Carbonate (CO ₃)	<1
Magnesium (Mg)	1.3	Sulfate (SO ₄)	140
Sodium (Na)	720	Chloride (Cl)	1300
Potassium (K)	31	Fluoride (F)	3.4
Lithium (Li)	1.8	Boron (B)	4.1

Estimated Thermal Aquifer Temperature

Method	Temperature (°C)
Silica conductive	127
Silica adiabatic	124
Na - K - 1/3Ca	149
Na - K - 4/3Ca	128

NOTE: (1) Table after Mariner and others (1974).

(2) CaCO precipitation may have altered water chemistry of 3 water outlet.