JEFFERSON COUNTY ENVIRONMENTAL GEOLOGY STUDY

Geologist (125 days @ $125/day)		$ 15,600 *
Editing (65 days @ $77/day)		5,000 *
Cartography		4,000 *
Supplies.		750 *
Printing.		4,900
Travel and per diem		
Per diem - $27.50 x 60 days	$ 1,650	
Travel to job - 566 (mi. round trip) x 12 x 14¢. .	948	
Travel on job - 100 x 60 x 14¢	840	3,438 *
Overhead on * items above - $28,788 x 20%		5,757
TOTAL		$ 39,445

Maps: (1) Geology - 4 or 5 color (1 inch = 3 miles)
(2) Mineral deposits (combine with geology ?)
(3) Urban - 7½' - 1:24,000 (black and white)

Bulletin

Start August 1 if no ERDA uranium study
Start March 1, 1978, if ERDA uranium study

Contract for flat fee - 60% from county . . . . $ 24,000

JEFFERSON COUNTY

*GEOLOGIST 25 WKS		$
*EDITING 13 "		15,600
*CARTOG		5,000
*SUPPLIES		4,000
PRINTING		750
*TRANSPORT + PER DIEM		4,900
PER DIEM $25 × 5 DAYS × 12 WKS	1500	
TRAV TO JOB 283 MI × 2 × 12 × 13¢	885	
" ON JOB 100 × 5 × 12 × 13¢	780	3165
O'HEAD ON * ITEMS ABOVE $28,515 × 20%		5702
TOTAL		$39,117

MAPS

1. GEOLOGY - 4 OR 5 COLOR - SCALE?
2. MINERAL DEPOSITS (COMBINE WITH GEOLOGY?)
3. URBAN - 7½' - 1:24,000 - B&W.

BULLETIN.

NORM:

JOHN & CLIFF & I WORKED ON YOUR ESTIMATE WITH THE ABOVE RESULT.

15 minute: Quadrangles / Jefferson County

Antelope - S 1/3
Breitenbush Hot Spring SE Corner
Clarno - SW Corner
Fort Butte - S 1/2
- Mt Jefferson - East strip
Prineville - small strip NW part
Sisters - N 1/2
Three Fingered Jack - North - East Strip
Whitewater River - all
Willowdale - S 1/3

7 1/2 minute:

~~Buck Butte~~
Ashwood
Axehandle
Brewer Reservoir
Buck Butte
Culver
Dutchman Creek
Eagle Butte
Fly Creek
Foley Butte
Gateway
Gray Butte
Horse Heaven Creek
Madras East
Madras West
Metolius Bench
Opal City
Opal Mountain
Potters Ponds
Round Butte
Sandrock Mt.
Seekseequa Junction
21. Squaw Back Ridge
Steelhead Falls
Stephenson Mt.
Teller Butte
Warm Springs

Cartography	Geology	~~Report Writing~~ Editing	Transportation	Maps, photos etc. Expenses
18.00 Pokorny	1363.00	19.00 Carol	5.75	82.60
630.00 "	493.00	19.00 Carol	72.00	10.00
909.00 "	290.00	319.00 Maggie	228.25	125.00
198.00 Renond	406.00	58.00 "	116.50	2.50
60.00 "	246.50	58.00 "	488.35	58.50
30.00 "	1551.50	261.00 "	455.80	15.10
284.75 Shumacher	870.00	527.60 "	287.82	23.99
270.00 Renond	986.00	63.50 Bricker	72.00	30.00
875.00 Renond	1392.00	90.16 Drayer	1726.47 O.K.	13.58
1200.00 "	1232.50	37.10 Pavlat	1000.00 Budgeted	27.95
100.00 "	1029.50	488.03 Steere	726.47 (over)	27.75
1013.04 "	449.50	751.83 "		4.25
594.96 "	159.50	79.50 Pavlat		14.20
24.12 "	94.25	107.10 Drayer		73.00
71.44 "	29.00	101.60 Bricker		153.00
154.20 Shumacher	87.00	20.01 "		128.00
35.72 Renond	116.00	290.18 Steere		89.35
30.84 Shumacher	652.50	3288.61 - Budgeted		$878.77
107.94 "	145.00	1300.00		500.00 Budget
125.02 Renond	536.50	1988.61 (over)		378.87 (OVER)
6731.03	362.50			
2500 Budgeted	551.00			
4231.03 (over)	333.50			
	246.50			
	116.00			
	65.95			
	290.18			
	14074.88			
	8700.00 Budgeted			
	5374.88 (OVER)			

Printing

$3541.20 NOT Budgeted
$1500 from USFS Donation
$2041.20 (OVER)

Consultants

572.00
1023.00
1419.00
588.50
3602.50
2000.00 Budgeted
1602.50 (OVER)

6731.03
3288.61
1726.47
878.77
14074.88
3602.50
3541.20
33,843.46 - Total

Portland's Total 34,210.96

Geology & Mineral Resources of Jefferson County -

Deschutes Co. Estimate

Introduction

Purpose & scope

Previous Work -

Acknowledgements

Geography

Location - Topography - Access - Transportation

Industry, Population, Climate & Vegetation,

Geology -

Bedrock Units - Geology & Geologic History

Structure

Surficial Materials

Mineral Resources

Metallic -

Cu, Lead, Zinc, Silver

Quicksilver

Non-Metallic

S & G

Cinders & Scoria

Rock materials

~~Types~~ and Uses -

Deschutes

ESTIMATED SCHEDULE OF COSTS

24 weeks

A.	Field mapping and inventory of existing operations	(6 weeks)	$ 3,700
B.	Field analysis 1. compilation of base map data 2. mineral resource review	(3 weeks)	1,800
C.	Report writing and editing	(5 weeks)	3,300 8800
D.	Cartographic drafting	(6 weeks)	2,500
E.	Typing and correcting final manuscript	(4 weeks)	700 12,000
F.	Transportation and incidental expenses		1,000
G.	Map supplies and equipment		500
		TOTAL ESTIMATED COST	$13,500

Quaternary glaciation and volcanism, Metolius River area, Oregon

WILLIAM E. SCOTT* *Department of Geological Sciences, University of Washington, Seattle, Washington 98195*

ABSTRACT

Evidence of three major Quaternary glaciations is recognized in the Metolius River area on the east flank of the High Cascades. The latest glaciation (Cabot Creek glaciation) is multiple, with evidence of a late readvance (Canyon Creek advance) well displayed in cirques. Post-Altithermal glacial activity is restricted to a twofold late Neoglacial advance on Mount Jefferson and Three-Fingered Jack. Stone-weathering characteristics and soil development are used to differentiate and correlate the drifts throughout the area. The degree of soil development on the drifts suggests that there was a longer period of time between the oldest and intermediate glaciations than between the intermediate and youngest glaciations.

Volcanic activity may have been restricted to times of little ice cover, since no evidence of intraglacial volcanism was observed. Tephra and lava flows were erupted during two Pleistocene interglaciations and during Holocene time at scattered locations. The High Cascade platform and probably the stratovolcanoes were largely constructed prior to the earliest recognized glaciation (Abbott Butte glaciation).

Information on extent of ice cover during the Cabot Creek glaciation and the Neoglacial advance is sufficiently detailed to reconstruct past glacier margins and estimate former equilibrium-line altitudes (ELA). An accumulation-area ratio of 0.6 ± 0.1 was employed to calculate past ELAs. During the Cabot Creek glaciation, ELAs ranged from about 950 m lower than present at the maximum to 700 to 750 m lower than present for the Canyon Creek advance. Neoglacial ELAs on Mount Jefferson glaciers were lower than present by 200 to 250 m. ELA gradients across the Western Cascades during the Cabot Creek glaciation averaged about 5 m/km, increased to 14 m/km across the High Cascades, and were greater than 38 m/km farther east. This reflects a pattern of precipitation similar to that of the present.

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INTRODUCTION

During Quaternary time, the Cascade Range of Oregon was repeatedly subjected to both valley and ice-cap glaciation. The effects of glacial processes in modifying the original volcanic topography are well displayed by deep U-shaped valleys, numerous cirques, well-developed end moraines, and deeply eroded stratovolcanoes. However, compared with well-studied areas in Washington, California, and the Rocky Mountain states, few detailed studies of glaciation in the Oregon Cascades have been published.

The present study involved the geologic mapping of surficial deposits along the crest and eastern flank of the High Cascade Range in north-central Oregon near three large Quaternary stratovolcanoes, Mount Jefferson, Three-Fingered Jack, and Mount Washington (Fig. 1). This report describes

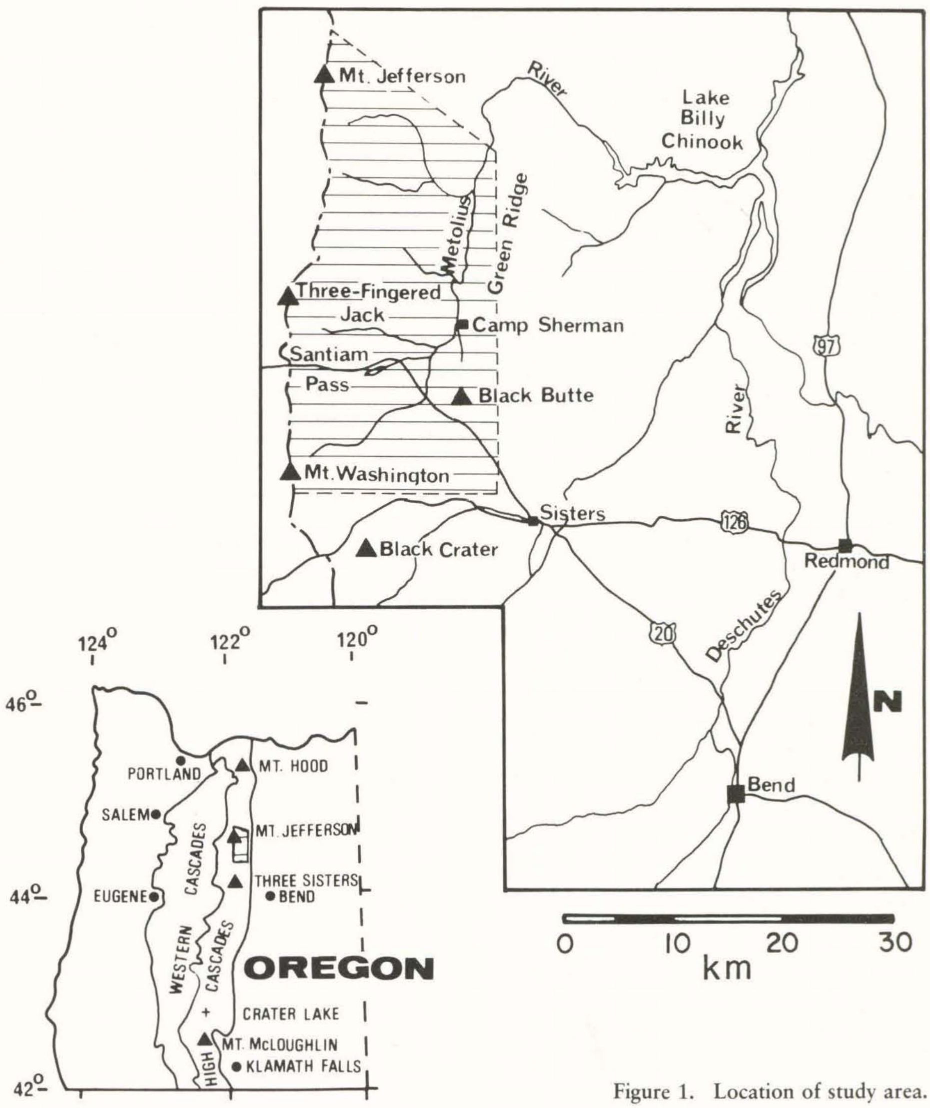


Figure 1. Location of study area.

Geological Society of America Bulletin, v. 88, p. 113–124, 12 figs., January 1977, Doc. no. 70113.

the stratigraphy of Quaternary glacial and volcanic deposits, the extent of former glaciers, and estimated equilibrium-line altitudes (ELA) of present and former glaciers.

Previous Work

From their early reconnaissance studies, Dutton (1889, p. 161) and Russell (1905, p. 30) realized that the entire summit platform of the High Cascades had been covered with an ice cap and that outlet glaciers had descended the eastern and western slopes and constructed conspicuous end moraines. Multiple Pleistocene glaciation was first suggested by Hodge (1925, p. 38–40). From studies in the valley of the North Santiam River west of Mount Jefferson, Thayer (1939) presented firm evidence for a threefold glacial sequence that he correlated with the Sherwin, Tahoe, and Tioga drifts of the Sierra Nevada. Crandell (1965) summarized glacial-geologic studies in the Pacific Northwest and delineated the extent of ice in the Oregon Cascades during the last glaciation. His map shows a continuous ice cap extending from 30 km north of Mount Jefferson to Mount McLoughlin in southern Oregon, a distance of almost 300 km; a small ice cap around Mount Hood; and small valley and cirque glaciers near the Mountain Lakes Wild Area and in the Western Cascades. Most recently, Carver (1972) completed a study of Cascade glaciation south of Crater Lake and in the vicinity of the Mountain Lakes Wild Area. Using weathering characteristics of the drifts, he differentiated six Pleistocene drifts, a Neoglacial drift, and a variety of Pleistocene and Holocene periglacial deposits.

Geologic Setting of the High Cascades

Apparently the volcanic activity that formed the Oregon Cascade Range was episodic. McBirney and others (1974) concluded that four relatively short eruptive intervals occurred during Miocene, Late Miocene–Early Pliocene, Pliocene, and Quaternary time.

The High Cascades are largely the product of Quaternary volcanism and are composed of three sequences of rocks. The earliest flows of basalt, basaltic andesite, and andesite form a platform of broad, overlapping shield volcanoes that make up the great bulk of the High Cascades (Thayer, 1939, p. 30; Williams, 1957; Taylor, 1968, p. 3). Pyroclastic rocks are volumetrically insignificant compared with flows. The second sequence, which forms the major stratovolcanoes, was built on the High Cascade platform by explosive andesitic eruptions between 700,000 yr ago (McBirney, 1968) and the last major glaciation. The third sequence is composed mostly of basal-

TABLE 1. CRITERIA USED TO DIFFERENTIATE AND CORRELATE DRIFTS

Criterion	Application	References
Discordance in moraine trends	Well displayed in some valleys with moraines of both Cabot Creek and Jack Creek age	Sharp and Birman (1963)
Morainal morphology	Made subjective judgment of crestal sharpness. Proximal and distal moraine slope angles measured by inclinometer	White (1962), Rampton (1971)
Weathering characteristics of stones		
Surface-boulder frequency	Counted number of boulders in 3 m × 30 m area on moraine crests. Of limited use due to variable tephra cover	Blackwelder (1931), Sharp (1969)
Stone-weathering ratios	Collected 40 to 186 cobbles and pebbles from surface to 30-cm depth at sites on moraine crests and high points on ground moraine. Used ratio of unweathered:partly weathered (rinds, pitting, interior staining, but cores still fresh):totally weathered (no fresh cores, easily pulverized)	Blackwelder (1931), Birman (1964), Sharp (1969), Carver (1972)
Thickness of weathering rinds	Used pebbles and cobbles from surface to 30-cm depth at sites where stone-weathering data collected. Measured rind thickness to nearest 0.1 mm under magnification on 15 to 30 stones with best developed rinds	Crandell and Miller (1974), Porter (1975a)
Degree of soil development		
Profile development	Profiles were described from similar settings on moraine crests and high points on ground moraine; all soils are developed in till from andesitic source rocks. Noted horizon thickness, color, consistence, texture, structure, and boundaries	See discussion and references in Birkeland (1974)
Free iron oxide oxide and hydroxide content	Used Jackson's (1969) citrate-bicarbonate-dithionite extraction and measured Fe on atomic absorption spectrophotometer. Determinations made on samples from each horizon or at 20-cm intervals	Ugolini and Bull (1965), Jackson (1969, p. 44, 49–51), Alexander (1974)

TABLE 2. UNITS RECOGNIZED IN THE METOLIUS RIVER AREA

Geologic time units		Glacial-stratigraphic units		Rock-stratigraphic units		
Quaternary Period	Holocene Epoch	Holocene interglaciation	Jefferson Park advance	Jefferson Park formation		Till facies Outwash facies Rock-glacier deposits Protalus deposits
			Forked Butte nonglacial interval	Forked Butte formation		
	Pleistocene Epoch	Cabot Creek glaciation	Canyon Creek advance	Cabot Creek formation	Canyon Creek member	Till facies Outwash facies Rock-glacier deposits Protalus deposits
			Suttle Lake advance		Suttle Lake member	Till facies Outwash facies Loess facies
		Cabot Creek–Jack Creek interglaciation		South Cinder Peak formation		
		Jack Creek glaciation		Jack Creek formation*		Till facies Outwash facies Loess facies
		Jack Creek–Abbott Butte interglaciation		Brush Creek formation		
		Abbott Butte glaciation		Abbott Butte formation		
				Cascade Andesite formation		

* A formal stratigraphic unit, Jack Creek Formation, was defined by N. L. Taliaferro for some Upper Cretaceous shales and silts in west-central California. The same geographic name is used in this report because it is used locally and informally for sediments of Quaternary age and because the best exposures of this geographically restricted unit occur in the Jack Creek area.

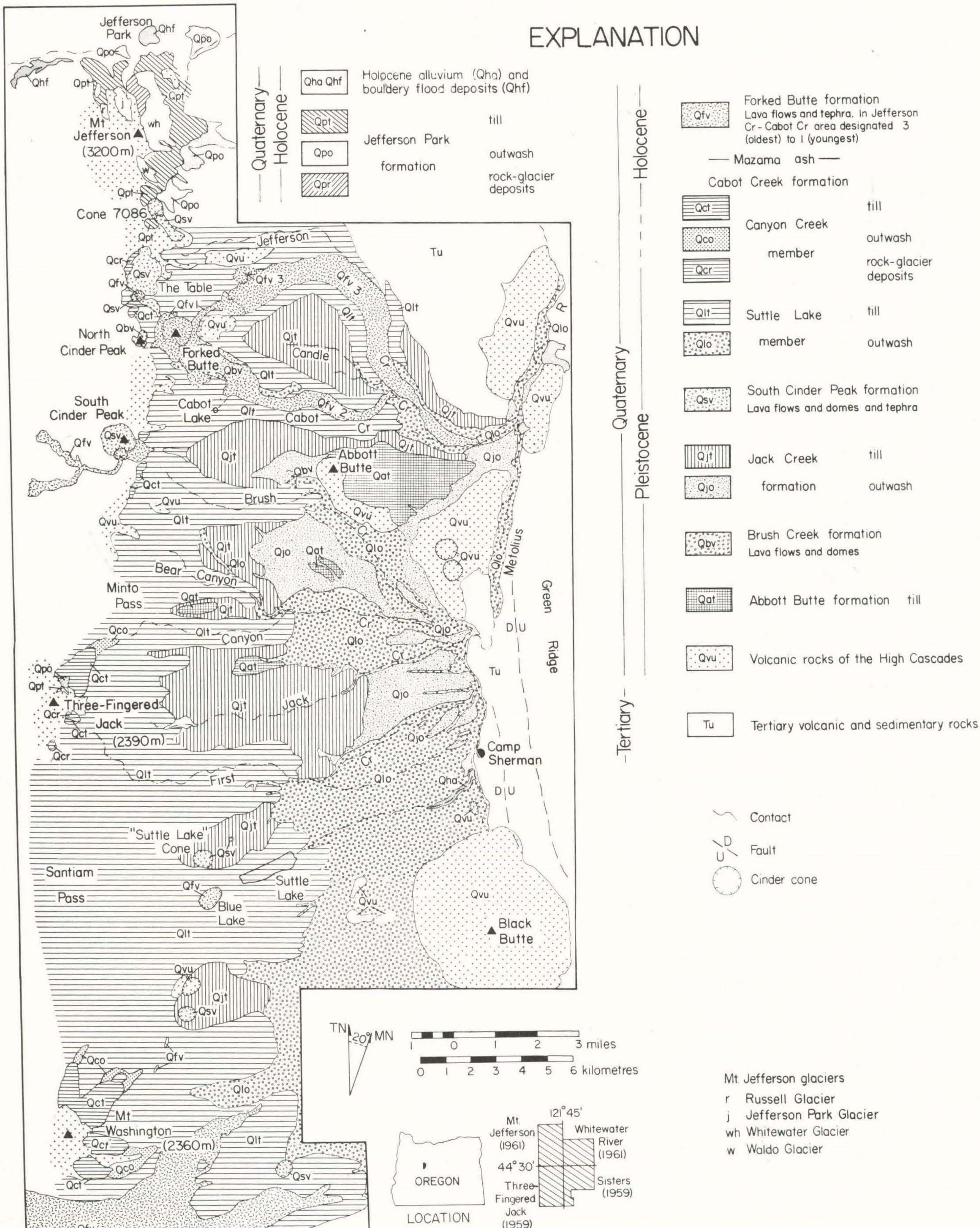


Figure 2. Generalized surficial geologic map of the Metolius River area, Oregon.

tic andesite and basalt of Holocene age and is readily identified by lack of glacial erosion. In the study area, this sequence is represented by scattered cinder cones and lava flows, whereas farther south near the Three Sisters there was greater Holocene volcanism (Taylor, 1965).

STRATIGRAPHY OF GLACIAL AND PERIGLACIAL DEPOSITS

In order to differentiate glacial and periglacial deposits in one valley and allow correlation with similar deposits in adjacent valleys, several methods were used that have been applied successfully in other glacial-geologic studies (Table 1). In this study, differentiation and correlation of glacial deposits rely heavily on their weathering characteristics and degree of soil development.

Evidence of at least five glacial advances occurs in the Metolius River area (Table 2). Glacial- and rock-stratigraphic names listed in Table 2 are used informally (Richmond and others, 1959, p. 666, 670). Following is a description of deposits of each glacial advance, from oldest to youngest.

Abbott Butte Formation

The freshest till of the Abbott Butte formation consists of cobbles and boulders of varied andesitic lithologies in a compact, light grayish-brown, sandy matrix. Exposures of till occur along the new Jack Lake road between two lateral moraines of Jack Creek age, on Abbott Butte Road south of Brush Creek, and on the southeast side of Abbott Butte (Fig. 2), for which this drift is named. No outwash facies of the Abbott Butte formation has been recognized.

Till of Abbott Butte age is highly weathered. Stone-weathering ratios average 2:55:43 (weathered:partly weathered:totally weathered) (Fig. 3), and many stones are so weathered as to be easily cut with a shovel. Weathering rinds as much as 1.5 mm thick are developed on fine-grained andesite, and mean rind thicknesses at seven sampling sites range from 0.8 to 1.0 mm (Fig. 4).

Thick, well-developed soils (Orthods, Brown Podzolic soils) have formed on till of the Abbott Butte formation. Due to limited exposure of the till; the great thickness of the soil (several metres); thick cover of loess, tephra, and colluvium; and erosion; no complete soil profiles were observed. However, several partial profiles as much as 150 cm thick were available in roadcuts and soil pits. In outcrop, the soil is very distinctive owing to its reddish-brown color (5 YR 3/4, m). Thick clay skins on stones and blocky peds are present in all profiles and indicate a greater degree of clay formation than in any of the younger soils (Table 3).

TABLE 3. REPRESENTATIVE SOIL PROFILES DEVELOPED ON TILL OF SUTTLE LAKE, JACK CREEK, AND ABBOTT BUTTE FORMATIONS

Horizon	Depth (cm)	Description
Till of Suttle Lake member		
A1	0–15	Dark brown (10 YR 3/2); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic; clear, smooth boundary; many medium and fine roots
Bs	15–50	Dark yellowish brown (10 YR 4/4); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic; gradual, smooth boundary; many medium and coarse roots
Cox	50–100	Dark grayish brown (10 YR 4/2); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic; medium roots; diffuse, smooth boundary
Cn	100–	Very dark grayish brown (2.5 Y 3/2); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic
Till of Jack Creek formation		
A1	0–15	Dark brown (10 YR 3/2); pebbly, sandy loam; massive, fine crumb structure; nonsticky, nonplastic; gradual, smooth boundary; many medium and coarse roots
B21s	25–55	Medium brown (7.5 YR 4/4); pebbly, cobbly, sandy loam; massive, fine crumb structure; nonsticky, nonplastic; diffuse, smooth boundary; medium and coarse roots
B22t	55–80	Medium brown (7.5 YR 4/4); pebbly, cobbly, sandy loam; weak, medium crumb structure; slightly sticky, slightly plastic; gradual, smooth boundary; medium roots
Cox	80–200	Dark yellowish brown (10 YR 3/4); pebbly, cobbly, sandy loam; massive, medium to coarse crumb structure; nonsticky, nonplastic; diffuse, smooth boundary; few fine and medium roots
Cn	200–	Very dark grayish brown (2.5 Y 3/2); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic
Till of Abbott Butte formation		
Removed		
Bs	0–45	Medium brown (7.5 YR 4/4); pebbly, cobbly, sandy loam; massive, medium crumb structure; nonsticky, nonplastic; gradual, smooth boundary; many medium and coarse roots
B21tb	45–85	Dark reddish brown (5 YR 3/4); pebbly, cobbly, sandy loam; weak, fine blocky structure; slightly sticky, slightly plastic; diffuse, smooth boundary; medium roots
B22tb	85–115	Reddish brown (5 YR 4/4); pebbly, cobbly, sandy loam; moderate, angular blocky structure; slightly sticky, slightly plastic; diffuse, smooth boundary; few medium roots
B23tb	115–170	Reddish brown (5 YR 4/4); pebbly, cobbly, sandy clay loam; moderate, medium angular blocky structure; sticky, plastic; few medium roots

Note: Munsell colors were determined on moist samples.

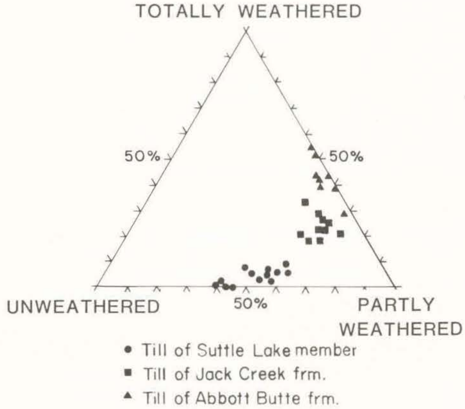


Figure 3. Stone-weathering ratios of tills. Each point represents a count of 40 to 185 cobbles from the upper 30 cm of soil on moraine crests or on high points on ground moraine.

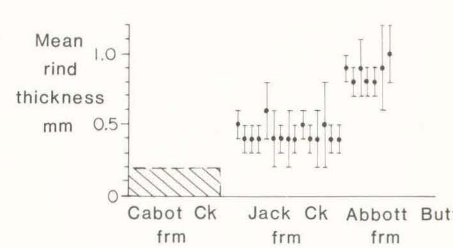


Figure 4. Weathering-rind thicknesses on stones in tills. Each point represents one sampling site from which 15 to 30 stones with the best developed rinds were sawed and rinds measured. Error bars represent ±1 standard deviation from the mean. For Cabot Creek formation, lined pattern shows range of rind thicknesses at eight sampling locations.

Of the three profiles in which free iron content was measured, one shows a maximum of 7.5 percent, while the others may have their maxima at greater depth than could be sampled in the exposure (Fig. 5).

Jack Creek Formation

Till of the Jack Creek formation (see footnote, Table 2) is composed of subangular to subrounded cobbles and boulders in a compact, very dark grayish-brown (2.5 Y 3/2, m) sandy matrix. Till is widespread on interfluves and, in some valleys, downstream from moraines of the last glaciation (Fig. 2). The largest area of exposed till is near Jack Creek, for which this drift is named.

Outwash of Jack Creek age, which is composed of grayish-brown sand and gravel near the Metolius River, becomes bouldery near terminal moraines. Outwash terraces are best developed in valleys where there was a difference of several kilometres in ice extent during the Jack Creek and subsequent Cabot Creek glaciations. In the valley of Candle Creek, terminal moraines are 3.5 km apart, and the outwash-terrace surfaces are vertically separated by as much as 8 m (Fig. 2). Abandoned braided channels on the terrace tread contain boulders as much as 1 m in diameter. In other valleys, where ice extents and meltwater-stream gradients were similar, if the surfaces are separated at all, the terrace scarps are only a few metres high.

The Jack Creek glaciation is the oldest glaciation from which moraines are preserved. The moraines are best displayed near Jack Creek (Fig. 2). A prominent left-lateral moraine and hummocky terminal moraine are analogous in form to the moraines of the Suttle Lake advance that dam Suttle Lake. A smaller recessional moraine that lies about 1 km upvalley from the terminal moraine indicates a stillstand or readvance following the maximum of the Jack Creek glaciation. Mass wasting has modified lateral moraines so that they display broadly rounded crests. Proximal slopes rise at 8° to 15° and distal slopes at 5° to 12°. Surface-boulder frequencies on moraine crests range from 4 to 14, with a mean value of 7.

Drift of Jack Creek age is oxidized to depths of 1.5 m to more than 2 m. Few stones are totally weathered, but most are pitted and stained. Stone-weathering ratios average 13:64:23 (Fig. 3). Weathering rinds are moderately common on stones and reach thicknesses of 1.2 mm. Mean values of 0.4 to 0.6 mm were measured at 15 sampling sites (Fig. 4).

Soils formed on drift of Jack Creek age are only weakly (Umbrepts) to moderately (Orthods) developed compared with soils developed on the Abbott Butte formation (Table 3). Compared with younger soils, they have a distinct color-B horizon from 40 to 70 cm thick, which is more reddish brown (7.5 YR 4/4, m) than B horizons of soils on drift of Suttle Lake age. In a few profiles, especially those at higher altitudes where precipitation is greater, field examination revealed a slight plasticity when moist, suggesting some textural development of the B horizon as well. In seven soil profiles on the Jack Creek formation, 2 to 3 percent free iron oxide occurs in the B horizon, and iron enrichment extends to depths of 1.5 m or greater (Fig. 5).

Although no exposures were seen in which deposits of Jack Creek age were deeply buried by other glacial sediments, thin (<50 cm thick), discontinuous loess of Jack Creek and Suttle Lake age covers till and outwash of Jack Creek age near moraines and outwash fans. However, the loess has been churned into the underlying till or outwash by tree fall and slope processes and usually does not form a distinct layer. Near the "Suttle Lake" cone, till of Jack Creek age is buried beneath the "Suttle Lake" cone, Sand Mountain, and Blue Lake tephras (Table 4).

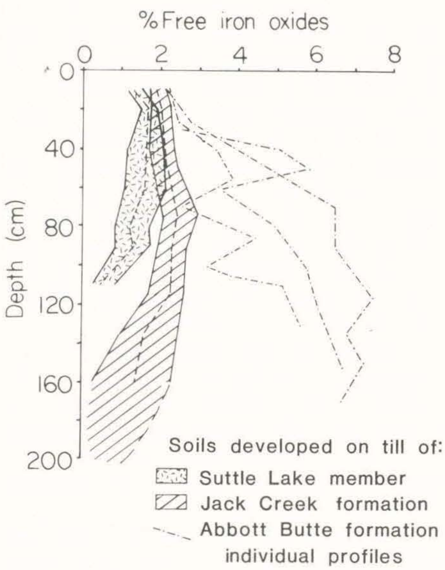


Figure 5. Percentage of free iron oxides in relation to depth in soils developed on till of Suttle Lake, Jack Creek, and Abbott Butte formations. For soils developed on till of Suttle Lake and Jack Creek age, dashed lines represent mean values for six profiles, and pattern covers range of values for given depth in soil.

Cabot Creek Formation

Cabot Creek valley, which contains prominent end moraines formed during the maximum of the Cabot Creek glaciation, is the type area for the Cabot Creek formation, which has been subdivided into the Suttle Lake and Canyon Creek members.

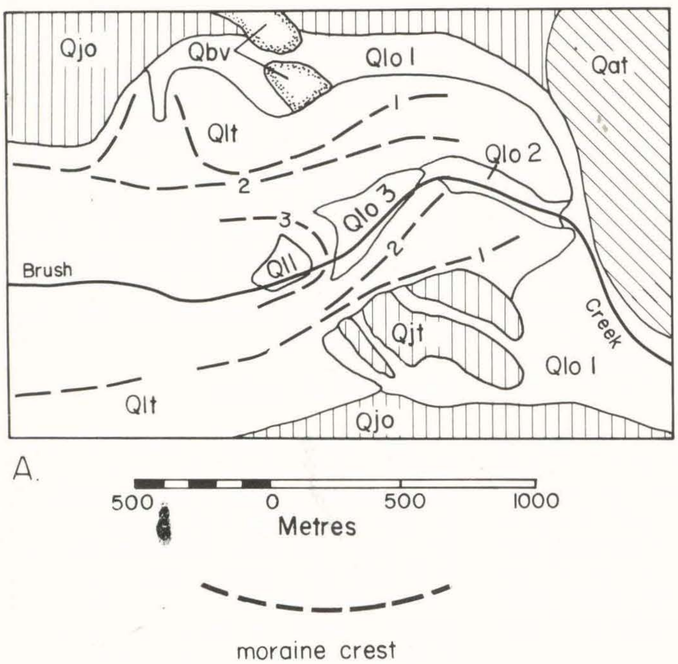
Suttle Lake Member. The Suttle Lake member is named for Suttle Lake, which is dammed by a terminal moraine of the Suttle Lake advance. Nearby roadcuts along U.S. 20 expose bouldery till with a compact, grayish-brown, sandy matrix, similar to other till of Suttle Lake age exposed widely over the study area (Fig. 2). Outwash of the Suttle Lake member covers much of the floor of the Metolius River valley and forms low terraces only a few metres above present streams. The outwash is grayish to yellowish brown and very coarse grained and bouldery near end moraines, and it becomes better sorted downstream, where it consists of sand, pebbles, and cobbles. Abandoned braided channels on the surface of outwash fans and terraces are readily visible on aerial photographs and in the field.

In most valleys there are one or more small recessional moraines upvalley from

TABLE 4. HOLOCENE TEPHRA IN THE METOLIUS RIVER AREA, OREGON

Source	Description	Distribution	Age (^{14}C yr)
Cone on south flank of South Cinder Peak	Black scoriaceous ash and lapilli, bombs near cone	Rockpile and Cabot Lakes and South Cinder Peak	About 1,000*
Blue Lake crater	Coarse scoria, black ash and lapilli, accidental fragments	Suttle Lake, First Creek	3,440 ± 250 (Taylor, 1965, p. 137)
Sand Mountain alignment	Black scoriaceous ash	Suttle Lake, First Creek, Canyon Creek	Little older than 3,440 (Taylor, 1965, p. 137)
Forked Butte	Several nearly contemporaneous layers, black scoriaceous ash, and cinders	Carl Lake/Cabot Lake cirque, Jefferson Lake, Patsy Lake, Table Lake	6,400 to 6,500*
Mount Mazama (Crater Lake)	15-cm-thick ash and lapilli, white-gray to yellowish-orange	Throughout area, best preserved in lakes, meadows, and cirques	6,640 ± 250 (Rubin and Alexander, 1960, p. 116)

* Date determined from sedimentation rate in Cabot Lake.



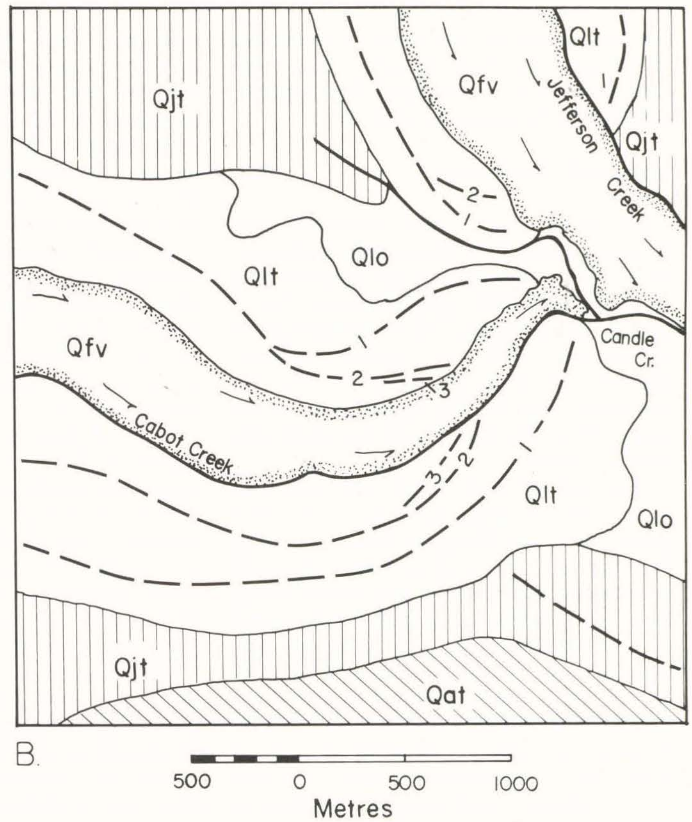


Figure 6. Terminal and recessional deposits of the Suttle Lake advance in (A) Brush Creek valley and (B) Cabot Creek valley. Qfv = Forked Butte formation; Qll = lacustrine deposits, Qlt = till (1, oldest, to 3, youngest), and Qlo = outwash of Suttle Lake age; Qjt = till and Qjo = outwash of Jack Creek age; Qbv = Brush Creek formation; and Qat = till of Abbott Butte age.

the large terminal moraine deposited at the maximum limit of the Suttle Lake advance. In Cabot Creek valley, two moraines lie within the right-lateral moraine (Fig. 6B). Weathering characteristics indicate that these moraines are all approximately the same age and are recessional moraines built during standstill or readvance. The Forked Butte lava flow has covered any recessional moraines present on the valley floor. There are also two recessional moraines in Brush Creek valley (Fig. 6A); the first is set just within the large end moraine; the second (4 to 5 m high) forms a nearly complete loop across the valley floor, breached by Brush Creek on the south side. A small outwash fan is graded to the moraine surface. In Cabot Creek, Brush Creek, and Canyon Creek valleys, Bear Valley, and at Suttle Lake, the recessional moraine or moraines lie within 2 km of the terminal moraine. In First Creek valley, evidence of recessional stands is lacking. Since the number of moraines near the maximum position of glaciers during the Cabot Creek glaciation is not identical in all valleys and no data, except for position, allow correlation of individual moraines between valleys, no subdivision has been attempted. The moraine or moraines near the maximum are referred to the Suttle Lake advance of the Cabot Creek glaciation.

In many valleys, moraines exhibit crosscutting relationships. Older moraines that are partly buried or truncated by moraines of subsequent advances indicate a period of recession between advances. Crosscutting relationships are well displayed in Candle Creek, Brush Creek, Jack Creek, and Canyon Creek valleys. Here, moraines of Suttle Lake age partly bury or truncate moraines of Jack Creek age (Figs. 2, 6A, 6B). Typically, lateral moraines of Suttle Lake age have proximal slopes of 20° to 28° and distal slopes of 5° to 22°. Terminal moraines generally have less steep slopes than their corresponding lateral moraines. The moraines also have sharp bouldery crests and surface-boulder frequencies ranging from 12 to 41.

Very few stones in drift of Suttle Lake age are totally weathered. Almost half the stones are fresh, and stone-weathering ratios average 45:51:4 (Fig. 3). Weathering rinds are scarce and where developed are discontinuous and have a maximum thickness of only 0.2 mm (Fig. 4).

Soils formed on deposits of Suttle Lake age are typically thin and weakly developed (Table 3). Wherever observed, these soils are less than 1 m thick. An A horizon of variable thickness (0 to 20 cm) overlies a poorly developed and defined color-B horizon (10 YR 4/3, m) 25 to 40 cm thick. A slight color change is all that distinguishes the lower B from the Cox horizon, which is 30 to 60 cm thick and composed of yellowish-brown (10 YR 4/2, m), slightly weathered parent material. Below the Cox lies fresh, very dark grayish-brown (2.5 Y 3/2, m) till or outwash. These young soils are very granular and stony, except where developed on fine alluvium. Commonly, the upper 50 cm of soil contains a high proportion of silt and sand where loess has been churned into the underlying till or outwash by tree fall. In the southern part of the area and near Forked Butte, this soil has been buried by local tephra on which thin (<50 cm thick) A/Cox profiles have formed.

The maximum value of free iron oxides for five soils on till of the Suttle Lake member is slightly more than 2 percent, and below a depth of 1 m, values are usually less than 0.5 percent (Fig. 5). Samples with 0.5 percent free iron oxide appear fresh, with only sparse, yellowish-brown stain on particles and cracks. The freshest till of Suttle Lake age that was sampled contained about 0.3 percent free iron oxides (Fig. 5).

Canyon Creek Member. Deposits of the Canyon Creek member are restricted to cirques and valley heads near the Cascade crest and stratovolcanoes and have been subdivided into four facies: till, outwash, rock-glacier deposits, and protalus deposits. Lodgment till of Canyon Creek age looks identical to till of the Suttle Lake member but is poorly exposed because most of the outcrops are shallow and expose only ablation till, which is composed of cobbles and boulders in a loose, grayish-brown, sandy matrix. Near moraines, outwash of Canyon Creek age is bouldery and poorly sorted, and it grades

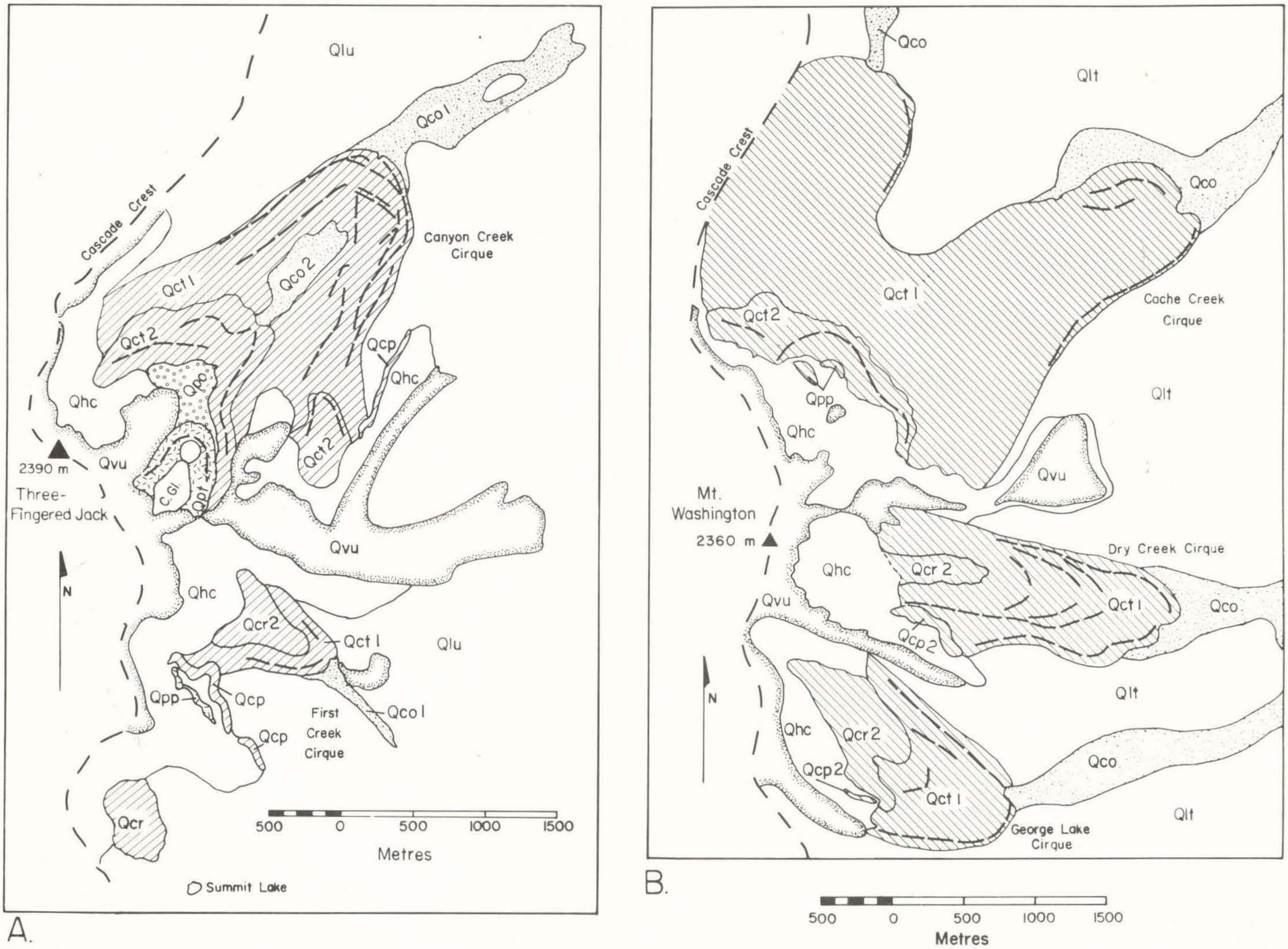


Figure 7. Deposits of the Canyon Creek and Jefferson Park advances on (A) Three-Fingered Jack and (B) Mount Washington. Qhc = Holocene colluvium; Qpt = till, Qpo = outwash, and Qpp = protalus deposits of Jefferson Park age; Qct = till (1, older, 2, younger), Qco = outwash, Qcr = rock-glacier deposits, and Qcp = protalus deposits of Canyon Creek age; Qlt = till of Suttle Lake age; and Qvu = volcanic rocks of the High Cascades.

downstream into moderately well sorted sand and gravel. Moraines are sharp crested, have steep (≤28°) sides, and are typically bouldery, with surface-boulder frequencies greater than 100. Most stones are fresh, and weathering rinds, if present, are less than 0.2 mm thick and discontinuous. Soils on the drift are thin and immature, similar to soils formed on the Suttle Lake member. Near Three-Fingered Jack, deposits of slightly weathered Holocene tephra as much as 1 m thick bury this soil.

End moraines are well displayed in the Canyon Creek cirque on Three-Fingered Jack (Figs. 2, 7A). A terminal moraine 3 to 6 m high lies at the east end of Canyon Creek Meadows. West of here, for a distance of 1.5 km, a series of loop moraines, some of which show intersecting relationships, indicates an interval of stillstand and readvance late in the retreat of the glacier from its maximum during the Suttle Lake advance. The deposits are covered with Mazama ash and younger, local, more mafic tephra (Table 4) and therefore are probably latest Pleistocene or early Holocene in age.

The moraines in Canyon Creek cirque have been subdivided into phases 1 and 2 (Fig. 2, 7A). Phase 1 deposits include terminal and lateral moraines in Canyon Creek Meadows. By phase 2, the glacier had retreated and split to form two small glaciers (Fig. 7A). A 25-m-high end moraine with an outwash fan graded to it, now incised by Canyon Creek, was built in the main valley. A smaller end moraine was formed in the tributary cirque to the southeast.

In First Creek cirque on Three-Fingered Jack (Fig. 7A), phase 1 is represented by a low terminal and right-lateral moraine. During phase 2, the glacier, covered with debris from the steep headwall, became a rock glacier. The rock-glacier deposit is lobate, and faint furrows are visible on aerial photographs; its surface is now covered with as much as 1 m of tephra, which supports meadow vegetation. The low (3 m) gentle (6° to 8°) front resembles that of inactive rock glaciers described by Wahrhaftig and Cox (1959) from the Alaska Range. The deposit has a "deflated" appearance caused by melting of the core of glacier ice. Similar glacier–rock-glacier transitions are found in George Lake and Dry Creek cirques on Mount Washington (Fig. 2, 7B). The north- and northeast-facing cirques on Mount Washington contained glaciers during both phases 1 and 2, as in Canyon Creek cirque.

During the Canyon Creek advance, snowbanks and frost action helped form protalus ramparts (Figs. 7A, 7B), which are best displayed along the south side of Cabot Creek valley and the north side of Brush Creek valley. The deposits form linear to lobate ridges, up to 3 m high, of large, angular blocks as much as 3 m in diameter. Typically, the blocks are almost completely covered with lichens (primarily *Rhizocarpon geographicum,* s. l., and a black foliose lichen). In some places thick accumulations of tephra or loess support forests. On north-facing slopes, the deposits range from altitudes of 1,500 to 1,800 m, whereas on south-facing slopes they occur near 1,700 m.

Jefferson Park Formation

Deposits of the Jefferson Park advance occur in cirques on Mount Jefferson and Three-Fingered Jack; they include till and outwash near termini of present glaciers and rock-glacier and protalus deposits (Figs. 2, 7A, 8). The formation is named for Jefferson Park Glacier, which deposited conspicuous lateral moraines during this advance.

Glacial sediments observed in Canyon Creek cirque on Three-Fingered Jack include ablation till and outwash (Fig. 7A). The ablation till, which is bouldery and very poorly sorted, contains more angular stones than the older drifts. This is probably due to the short (400-m maximum) length of transport from the 500-m-high headwall. The steep, unstable moraine dams a small lake and has a proximal slope of about 42°. The slope has numerous wet landslide scars that suggest melting of an ice core. The outwash forming the fan behind the phase 2 Canyon Creek moraine is composed of moderately well sorted sand and gravel. Deposits of Jefferson Park age are sparsely vegetated with small trees, scattered lichens (*Rhizocarpon geographicum*, s. l., up to 34 mm in diameter), and herbaceous plants. The drift is unoxidized, and moraines and till surfaces are very fresh, bouldery, and unstable. A few boulders are slightly weathered, but none display weathering rinds. No tephra (Table 4) has been found on any of the moraines of the Jefferson Park advance.

On the south slopes of Canyon Creek and First Creek cirques, small, lobate protalus ramparts, 2 to 3 m high, occur at an altitude of about 1,900 m (Fig. 7A). They are composed of angular boulders as much as 3 m in diameter and have a sparse lichen cover of *Rhizocarpon geographicum*, s. l., up to 30 mm in diameter.

On Mount Jefferson, two phases of the Jefferson Park advance are recognized (Fig. 8). During phase 1, end moraines as much as 50 m high were built by the glaciers. As on Three-Fingered Jack, the moraines are steep, unstable, and bouldery. Some are ice cored. They are sparsely vegetated except near Russell Creek, where moraines lie below timberline and support small trees. Phase 2 moraines lie less than 1.5 km upvalley from phase 1 moraines and very close to the termini of existing glaciers. The moraines of phase 2 are smaller than phase 1 moraines, sharp-crested, steep, and unstable. They are above timberline and barren of vegetation except for small

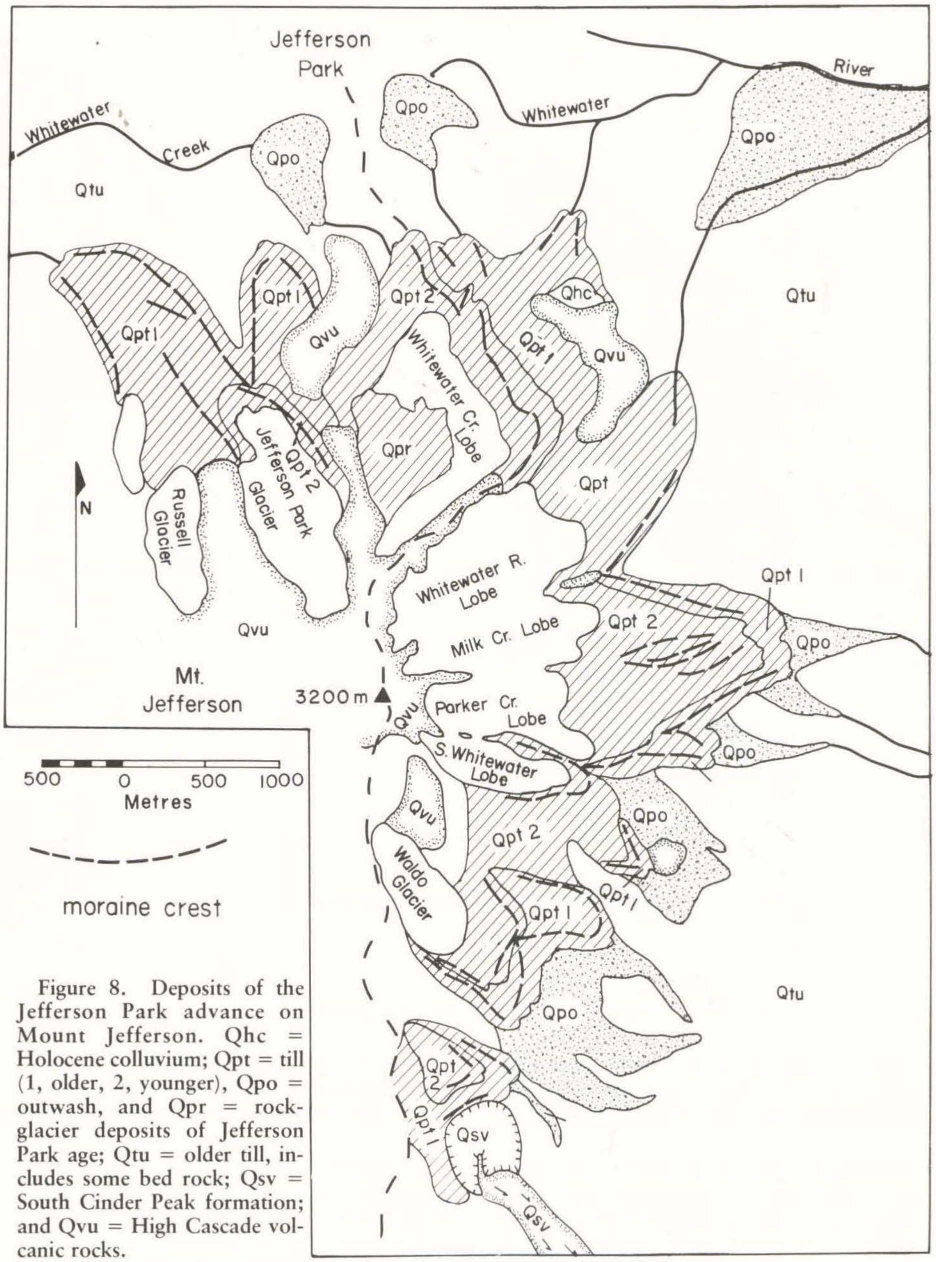


Figure 8. Deposits of the Jefferson Park advance on Mount Jefferson. Qhc = Holocene colluvium; Qpt = till (1, older, 2, younger), Qpo = outwash, and Qpr = rock-glacier deposits of Jefferson Park age; Qtu = older till, includes some bed rock; Qsv = South Cinder Peak formation; and Qvu = High Cascade volcanic rocks.

(<20 mm) scattered *Rhizocarpon geographicum*, s. l., and herbaceous plants.

The age of the oldest mountain hemlock, *Tsuga mertensiana*, growing on the moraine of Jefferson Park age in Canyon Creek cirque is 90 yr. Hemlocks of about the same age are growing on the moraines on Mount Jefferson near Russell Creek, whereas trees in the mature forest beyond this moraine are several hundred years old. Also, tephra from the eruption of the cone on the south flank of South Cinder Peak, which occurred about 1,000 yr or less ago (Table 4), does not cover the moraine of Jefferson Park age in Canyon Creek cirque although it lies on the moraine of Canyon Creek age adjacent to it. Apparently, the advance that deposited the Jefferson Park formation occurred in the past few centuries, and its drift is equivalent to Garda Drift on Mount Rainier (Crandell, 1969; Crandell and Miller, 1974) and other late Neoglacial drifts in western North America (Porter and Denton, 1967).

Chronology

In order to help place the possible ages of glaciation in the Metolius River area in perspective, Figure 9 shows a range of correlations between the oxygen isotopic record from the equatorial Pacific (Shackelton and Opdyke, 1973) and the glacial record in the Metolius River area that seems compatible with current understanding of the ages of glaciations in the Pacific Northwest.

The distribution, morphology, and weathering characteristics of drift of Cabot

Creek age are similar to those of other late Wisconsin alpine drifts in the northwestern United States. Drift of the Suttle Lake member is correlative to Waban drift in the southern Oregon Cascades (Carver, 1972), Evans Creek Drift at Mount Rainier (Crandell, 1969; Crandell and Miller, 1974), and pre-Hyak members of Lakedale Drift in the southern North Cascades of Washington (Porter, 1976). The Suttle Lake advance of Cabot Creek glaciation is broadly equivalent in age to the advances that deposited these drifts. The Canyon Creek member deposited during a late readvance of Cabot Creek glaciation is probably equivalent in age to Zephyr Lake drift in southern Oregon (Carver, 1972), Glacier Lake deposits in the Wallowa Mountains (Kiver, 1974), McNeeley Drift at Mount Rainier (Crandell, 1969; Crandell and Miller, 1974), and the Hyak Member of Lakedale Drift in the Washington Cascades (Porter, 1976).

For deposits of pre–Cabot Creek age, weathering and other criteria will only allow general speculation as to their ages. Drift of Jack Creek age displays a greater degree of modification of form, weathering, and soil development (Figs. 3 to 5, Table 3) than drift of Cabot Creek age; weathering rinds are common and well developed (about 0.5 mm thick), soil hues are redder (7.5 YR versus 10 YR); there is greater and deeper accumulation of free iron in the soil; and there is evidence of some textural development of B horizons. In comparison the differences in weathering characteristics between drift of Abbott Butte age and Jack Creek age are even more striking. Soils developed on the Abbott Butte formation contain several times as much free iron and display a much greater textural development of B horizons. Since soil formation and weathering probably progress at decreasing rates through time (Birkeland, 1967, p. 85, 1974, p. 176; Yaalon, 1971, p. 32), the time since the Abbott Butte glaciation is probably much greater than the time since the Jack Creek glaciation. The smaller difference in weathering and soil development between the Jack Creek and Cabot Creek formations suggests that the interval

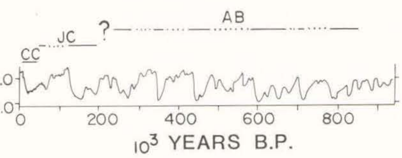


Figure 9. Correlations between oxygen isotopic record of core V28-238 (Shackelton and Opdyke, 1973) and the Quaternary glacial record in the Metolius River area that seem compatible with current understanding of glacial chronology in the Pacific Northwest. CC = Cabot Creek glaciation, JC = Jack Creek glaciation, AB = Abbott Butte glaciation. Solid lines correspond to times of high ice volume as inferred from the oxygen isotopic record.

between Jack Creek and Cabot Creek glaciations was shorter than that between the Abbott Butte and Jack Creek glaciations.

Deposits of Jack Creek age have a similar morphology and degree of weathering and soil formation to Hayden Creek Drift at Mount Rainier (Crandell and Miller, 1974, p. 21–22) and Kittitas Drift in the Washington Cascades (Porter, 1976), although the areas display great climatic differences and there is by no means close agreement between all weathering parameters. Crandell and Miller (1974, p. 55) tentatively considered Hayden Creek Drift to be 40,000 to 80,000 yr old (early Wisconsin), although it may possibly be older. Porter (1976, p. 74) regarded Kittitas Drift as pre-Wisconsin or, less likely, early Wisconsin in age. Jack Creek glaciation probably dates from either of the high ice-volume intervals between 40,000 and 80,000 yr ago or 120,000 and 200,000 yr ago indicated in Figure 9.

The modification of deposits of Abbott Butte age is so great compared with modification of deposits of Jack Creek age as to require several hundred thousand years. The Abbott Butte glaciation may correspond to any (or several?) of the high ice-volume intervals between 200,000 and 900,000 yr ago. It seems unlikely, although remotely possible, that Abbott Butte glaciation is as young as 120,000 to 200,000 yr. In the future, more precise age determinations may be possible through radiometric dating of the interglacial volcanic rocks.

STRATIGRAPHIC RELATIONSHIP OF QUATERNARY VOLCANIC AND GLACIAL DEPOSITS

Most of the High Cascade platform and stratovolcanoes were probably formed prior to the Abbott Butte glaciation. Although exposures of Abbott Butte till are few and highly weathered, lithologically the till contains clasts of most rock types exposed in the study area. However, in a terrain of such similar rock types, this information is of little value. Because patches of till of Abbott Butte age locally lie on slopes of the shield volcanoes that form the High Cascade platform, the Abbott Butte glaciation is regarded as younger than most of the platform. Highly dissected stratovolcanoes, such as Mount Washington and Three-Fingered Jack, may also date from pre–Abbott Butte time. Because Mount Jefferson is less dissected than either of these volcanoes, it may be partly younger than the Abbott Butte glaciation. Evidently, the main activity of the shield volcanoes was eruption of basaltic to andesitic lava flows, for few tephra layers are associated with them. Later eruptions that formed the stratovolcanoes must have been more explosive, because much tephra is exposed in their eroded flanks.

During the Jack Creek–Abbott Butte interglaciation, there was local andesitic volcanism in the Metolius River area (Fig. 2). In this study, rocks formed during this interval are assigned to the Brush Creek formation. Just west of Abbott Butte, near the mouth of Brush Creek valley, cumulophyric andesites were erupted along an 800-m-long fissure forming three blocky domes, the largest about 80 m in diameter and 20 m high. The rocks show no sign of glacial erosion, and no erratics were found, even though the area was covered by Abbott Butte ice; thus, they must postdate the Abbott Butte glaciation. In addition, low saddles along the fissure were breached by meltwater streams of Jack Creek age and covered with outwash, thus stratigraphically bracketing the age of eruption. A remnant of an intracanyon andesite flow more than 60 m thick forms a conspicuous bench on the north side of upper Cabot Creek valley (Fig. 2). The flow has well-developed columnar and platy jointing. The lava is similar to rocks exposed on the east side of North Cinder Peak and probably originated there. No stratigraphic evidence was found to prove that this flow postdates the Abbott Butte glaciation; however, by its position in a former glacial(?) valley, degree of erosion, and degree of erosion of its probable source (North Cinder Peak), the inferred age appears reasonable.

During the Cabot Creek–Jack Creek interglaciation, "Suttle Lake" cone (Fig. 2) erupted tephra that covered till of Jack Creek age. The fact that the left-lateral moraine formed during the Suttle Lake advance adjacent to the cone is not covered by scoria or bombs from the eruption indicates that the cone was formed during the interglaciation. A shallow crater still remains on the summit, and quarrying has exposed thin lava flows near the crater rim, but apparently no extensive lava flows were erupted. The "Cinder Pit" (Taylor, 1965, p. 124), just east of "Suttle Lake" cone, was also probably formed during this interglaciation. Most of the cone has been excavated for road metal, but a small blocky lava flow remains east of the pit. Till of Jack Creek age underlying the cone was oxidized during the eruption.

The following volcanic features are also regarded as part of the South Cinder Peak formation, which includes the eruptive products of the Cabot Creek–Jack Creek interglaciation. However, firm stratigraphic evidence is lacking. The main criterion, although not a very satisfactory one, for assigning the deposits to this formation is degree of erosion. South Cinder Peak is a 400-m-high cinder cone that lies on the Cascade crest. Glacial erosion on the north side has exposed the conduit and several dikes, but the degree of erosion has not been great enough to suggest that the cone has been glaciated more than once. The Table (Fig. 2), a dome complex composed of three overlapping domes (Brian Gannon, 1973, written commun.), occupies the floor of a cirque that was excavated prior to the Cabot Creek glaciation, since the surface of The Table was scoured by ice during the Suttle Lake advance. Because it is not extensively eroded, The Table is tentatively assigned to the South Cinder Peak formation. Other cinder cones and lava flows of the South Cinder Peak formation occur on the southeast flank of Mount Jefferson (cone 7,086 ft); just south of The Table, where an eroded cone and flow are partly buried by a Holocene cinder cone, and north of Mount Jefferson near Ollalie Butte. These features are similar in degree of erosion; pressure ridges are still discernible, although the flow surfaces are discontinuously covered with till and cinder cones are ice eroded.

In the study area, no evidence of intraglacial eruptions (tuyas, ice-chilled flow margins) has been observed. Recent evidence suggests that full interglaciations and full glaciations were only brief intervals during the past 500,000 yr (Emiliani, 1972). Therefore, during most of Pleistocene time ice cover was probably limited (in the study area, perhaps similar to ice cover during the Canyon Creek advance), and the probability of an eruption coming in contact with ice was small. It is also possible that intraglacial volcanism did occur, however, but evidence for it has either been incorrectly interpreted or eroded or buried during subsequent ice advances or volcanic eruptions.

Holocene volcanic activity between the Three Sisters and Three-Fingered Jack has covered hundreds of square kilometres with tephra and lava flows (Taylor, 1965, 1968). During the same time in the Metolius River area, volcanism has been more local than farther south (Fig. 2). All the deposits postdate the eruption of Mount Mazama, about 6,600 ^{14}C yr ago (Rubin and Alexander, 1960, p. 161; Table 4).

Forked Butte, a 150-m-high cinder cone after which the Holocene volcanic rocks are named (Forked Butte formation), erupted about 6,400 to 6,500 ^{14}C yr ago (Table 4). Black scoriaceous tephra and two basaltic andesite lava flows (Fig. 2) were probably erupted nearly contemporaneously, because there is no break in the sequence of Forked Butte tephra in a core from Cabot Lake. Following the younger Forked Butte eruption, "Horseshoe" cone, a breached cone on the south side of Bear Butte, erupted. Its lava dammed Jefferson Lake, flowed down the Jefferson Creek valley past the terminus of the Forked Butte flow in Cabot Creek valley, and then flowed down Candle Creek valley, a distance of 13 km (Fig. 2).

Other Holocene volcanism occurred west of Santiam Pass. Shortly before 3,500 ^{14}C yr ago, a tephra eruption from Sand Mountain alignment spread as much as 90 cm of black ash over the Suttle Lake area (Taylor, 1965, p. 136–137, 1968, p. 27), some 20 cm in Canyon Creek cirque, and 1 cm in Cabot Lake. At Blue Lake crater shortly after 3,440 ^{14}C yr ago, an explosion deposited accidental fragments, bombs, and scoria around the crater (Taylor, 1965, p. 132) and a coarse, 50-cm-thick scoria layer over 70 cm of Sand Mountain tephra on the left-lateral moraine damming Suttle Lake. The most recent eruption occurred on the south flank of South Cinder Peak about 1,000 ^{14}C years ago and formed a cinder cone and lava flow (Fig. 2, Table 4).

CHARACTERISTICS OF QUATERNARY GLACIERS

Extent of Former Glaciers

Several methods were used to delineate the areas covered by former glaciers. Obviously, the position of lateral and terminal moraines is the best criterion, at least below the altitude of past equilibrium lines where deposition predominated. Moraines are best developed in the lower valleys and on some broad divides. In areas where moraines are not well displayed, distribution of till and its weathering and soil characteristics provide helpful information. In areas where the dominant process was erosion, the best evidence of upper ice limits is (1) the top of truncated spurs and (2) the boundary separating glacially smoothed bed rock from sharp, rugged areas that stood above the surface of the glaciers and experienced intense frost action.

Little is known of the extent of glaciers of Abbott Butte age because of the few exposures of till. Till is largely restricted to interfluves, and no exposures are known downstream from moraines of Jack Creek age; however, till of Abbott Butte age may be buried by younger outwash. On some divides there is evidence that glaciers of Abbott Butte age were more extensive than later glaciers (Fig. 2). However, this may be due to valley deepening since the Abbott Butte glaciation, which did not permit the ice to rise as high on the interfluves during subsequent glaciations.

The extent of glaciers during the last two major glaciations is better known. Figure 10 shows the reconstructed maximum extent of glaciers during the Jack Creek and Cabot Creek glaciations. East of the Cascade crest, between Santiam Pass and Mount Jefferson, there was about 30 percent greater ice cover during the Jack Creek glaciation. Generally, the extent of glaciers in valleys during the two glaciations was similar, whereas ice extents on divide areas were quite different. (The Jack Creek area is physiographically a "divide" between the better defined valleys of First and Canyon Creeks.) Deepening of valleys and cirques during the Jack Creek glaciation and Cabot Creek–Jack Creek interglaciation (which may have included several less extensive glaciations) probably caused glaciers of Cabot Creek age to be funneled down valleys rather than spread out over broad, low-relief divides as during the Jack Creek glaciation.

Equilibrium-Line Altitudes of Existing and Former Glaciers

The equilibrium line is the boundary between areas of net accumulation and net ablation on a glacier (Paterson, 1969, p. 31). The equilibrium-line altitude (ELA) is determined by several climatic and topographic factors, including temperature, precipitation, and exposure. If the ELAs of former glaciers can be calculated and compared with those of existing glaciers, aspects of past climates can be inferred.

Although no detailed mass-balance measurements have been made on glaciers in the study area, several methods allow estimation of current ELAs. If present glaciers are in a steady-state condition, they should have accumulation area ratios (AAR; ratio of accumulation to total area) between 0.5 and 0.8 (Meier and Post, 1962, p. 70).

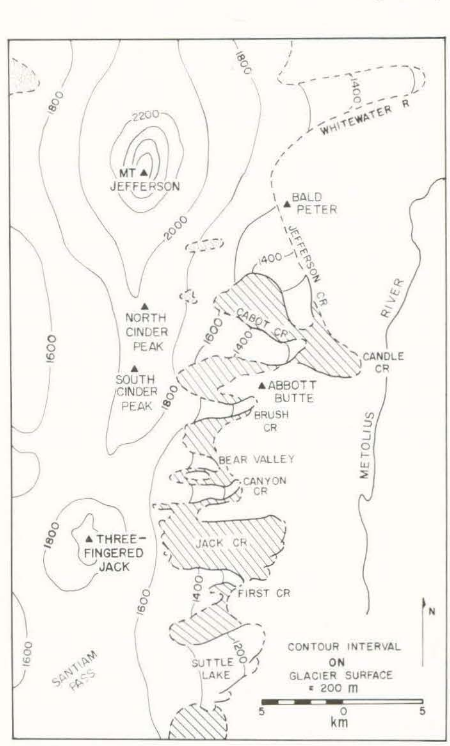


Figure 10. Extent of glaciers during Cabot Creek glaciation (contoured surface) and Jack Creek glaciation (lined pattern). Stippled areas represent probable nunataks during Cabot Creek glaciation.

However, Meier and Post (1962, p. 74) observed that glaciers in the Oregon Cascades were retreating in the early 1960s. Comparison of photographs taken in 1937 (Mazamas, 1938) and the 1960s indicates that termini have retreated several hundred metres on Mount Jefferson and that Collier Glacier on Middle Sister has retreated about 1,400 m. In 1961, glaciers in the Oregon Cascades had AARs of about 0.4 (Meier and Post, 1962, p. 71). With an AAR of 0.4, ELAs for Mount Jefferson glaciers are 2,570 m on the west side and 2,660 m east of the crest. This gradient probably reflects precipitation differences between the windward and leeward flanks of the mountain.

Another way of estimating ELAs is by determining the average altitude of the annual snowline (Flint, 1971, p. 36–37) over a period of years. Photographs taken by Austin Post of the U.S. Geological Survey provide this information for the 1960s and early 1970s. The mean firn-limit altitude during this time for Whitewater Glacier on the east side of Mount Jefferson was 2,650 m, which is approximately the same as the ELA calculated by using an AAR of 0.4.

Median glacier altitude, 2,600 m for west-side Jefferson Park Glacier and 2,675 m for Whitewater Glacier, is also comparable with the previous values for the ELA.

The approximate vertical and horizontal extent of former glaciers during the Suttle Lake advance can be delineated (Fig. 10) using geologic information from surficial deposits and erosional landforms. As noted, most modern glaciers in a steady-state condition have AARs between 0.5 and 0.8. The ELAs of former glaciers can therefore be estimated, assuming they also had steady-state AARs of 0.5 to 0.8. In this study ELAs were estimated by using an AAR of 0.6 ± 0.1. Porter (1970, p. 1444, 1975b, p. 35), Andrews and Miller (1972, p. 46), and Carver (1972, p. 66–68) have used similar AARs in calculating past ELAs in Pakistan, New Zealand, the Pacific Northwest, and the eastern Canadian Arctic.

On this basis, the cirque and valley glaciers in the Western Cascades had ELAs as low as 1,000 m during the Cabot Creek glaciation (Fig. 11), although some of the lowest cirques may have been formed during a previous glaciation and were not reoccupied during the Cabot Creek glaciation. Presumably, higher precipitation in the western portion of the range permitted glaciers to exist at lower altitudes than farther east. The distribution of individual ELAs in Figure 11 defines the regional snowline (Flint, 1971, p. 64), which lay within an altitude band of about 200 m and rose eastward at 5m/km. A steeper rise in southern Oregon, 10.3 m/km, was calculated by Carver (1972, p. 70) by using similar techniques.

In the High Cascades, the ELAs of valley glaciers and sections of the ice cap define a regional ELA gradient of 14 m/km (Fig. 11), much steeper than in the Western Cascades. This steeply rising regional snowline probably reflects an abrupt decrease in precipitation eastward, across the Cascade crest, and the orographic effect of the major volcanoes, which is similar to the present precipitation pattern. An even steeper gradient (>38 m/km) must have existed east of the range, because Black Butte (1,963 m), which lies 10 km east of the crest and is a volcano formed prior to the Cabot Creek glaciation, shows no evidence of having been glaciated. This further suggests an abrupt decrease in precipitation due to both the high precipitation over the 80-km-wide, glacier-covered area in the Cascades and the pronounced rain-shadow effect farther east.

When present ELAs of glaciers on Mount Jefferson are compared with ELAs during the Suttle Lake advance, a difference of about 950 m is evident (Fig. 11). This difference is a minimum value because present glaciers occupy protected cirques and display great variations in amount and altitude of accumulation, whereas the ice cap during the Suttle Lake advance was almost fully exposed to insolation and moist air masses. A minimum ELA lowering of 950 m generally agrees with estimates from other areas in the Pacific Northwest (Carver, 1972; Porter, 1975b, p. 45).

ELA gradients for the Canyon Creek advance cannot be calculated, because all glaciers during this time were restricted to areas near the Cascade crest, and the ELA gradient was probably perpendicular to the trend of the crest as during the Suttle Lake advance. The mean value for steady-state ELAs, 1,810 ± 30 m, is plotted in Figure 11. During the Canyon Creek advance, ELAs were approximately 250 m higher than those during the Suttle Lake advance. This difference from present ELAs of 700 to 750 m is close to that calculated for late readvances during the last glaciation elsewhere in the Cascades (Carver, 1972; Porter, 1975b, p. 45).

Orographic effects similar to late-glacial and present-day conditions also existed during the Jefferson Park advance. An ELA of about 2,400 m, 200 to 250 m lower than present, is shown in Figure 11 for Mount Jefferson glaciers. ELA gradients during the Jefferson Park advance and at present show similar, steep gradients of 36 m/km eastward.

Ice extents are too poorly known during the Jack Creek glaciation to estimate an ELA by the above method. However, by using the relationship between lowering of ELA and ice-covered area during subsequent glaciations, a minimum estimate for ELAs during the Jack Creek glaciation is 1,100 to 1,150 m below present-day ELAs (Fig. 12). This difference in ELA between present glaciers and glaciers during the Jack Creek glaciation also agrees closely with values from the southern Oregon Cascades and the Washington Cascades for broadly correlative glaciations (Carver, 1972; Porter, 1975b, p. 45). The shape of the curve in Figure 11 is largely determined by the local area-altitude distribution (Porter, 1970, p. 1445). At present, small lowerings of the ELA will not result in greatly expanded glaciers because little area lies at high altitudes. With the ELA on the lower, eastern slopes of the High Cascades, the opposite is true; small changes in the ELA will greatly affect ice cover because a large area is contained in a narrow altitudinal zone. The relatively constant slope of the High Cascades in the 1,200- to 1,800-m zone makes the projection of the curve in Figure 12 reasonable.

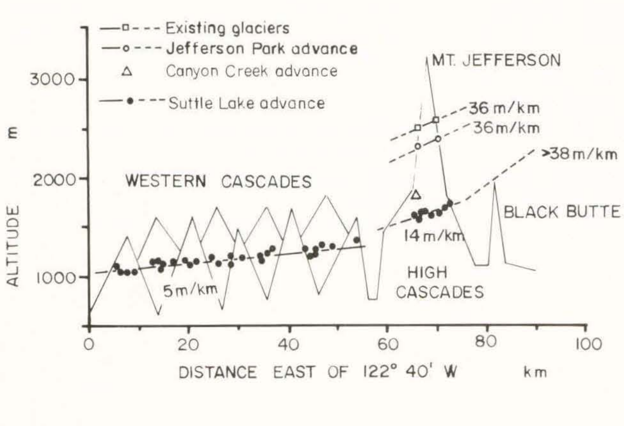


Figure 11. Calculated equilibrium-line altitudes for late Quaternary glaciers in north-central Cascade Range, Oregon. Points represent ELAs for individual glaciers, assuming accumulation area ratio of 0.6.

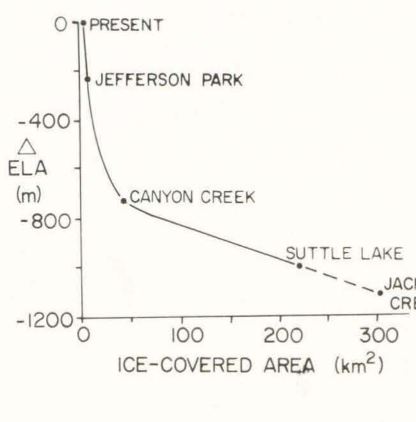


Figure 12. Relationship between lowering of equilibrium-line altitude and ice-covered area. Present equilibrium-line altitude for Mount Jefferson glaciers is about 2,650 m.

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