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 $15,600
- EDITING 13 " 5,000
- CARTOES
- SUPPLIES 4,000
- PRINTING 750
- TRANSPORT + PER DIEM 4,900

PRE DIRE 25 x 5 days x 12 wks = 1500
Tour to Joe 283 mi x 2 x 12 x 13% = 385
" On Fort 100 x 5 x 12 x 13% = 780 - 3165

O'HERO ON * ITEMS ABOVE 28,515 x 20% = 5703

TOTAL $39,117

MAPS
1. GEOLOGY - 4-005 COLOR - SCALE 7
2. MINERAL DEPOSITS (COMBINE WITH GEOLOGY) 7
3. URBAN - 7½ - 1° 24,000 - BW

SUMMARY:

Norm: John & Cliff & I worked on your estimate with the above result.
15 minute: 信德 / 杰斐逊县

Antelope - 3 1/3
Breitenbush Hot Spring - 1 1/2
Fort Battle - 5 1/2
Miner Valley - small strip NW part
Lisette - N 1/4
Three Fingered Jack - 4
Whitewater River - all
Willowdale - 5 1/3

7 1/2 minute:

Ashwood
Ashland
Brewer Reservoir
Buck Butte
Cawker
Dutchman Creek
Eagle Butte
Fly Creek
Foley Butte
Gateway
Gray Butte
Horse Heaven Creek
Madras East
Madras West
Opal City
Opal Mountain
Potter Pond
Quad Butte
Sandrock Mt.
Seekseequa Junction
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<tr>
<th>Cartography</th>
<th>Geology</th>
<th>Editing</th>
<th>Transportation</th>
<th>Map, Photo, etc.</th>
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<td>30.84</td>
<td>362.50</td>
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<td>107.44</td>
<td>333.50</td>
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**Consultants**

- 572.00
- 1023.00
- 1419.00
- 588.50

**Printing**

- $3541.20 Not Budgeted
- $1500 [Note: USFS Donation]
- 2041.20 (over)

- Pattland's Total 34,710.96
- 33,843.46 = Total
Geology and Mineral Resources of Jefferson County

Introduction

Purpose and Scope

Previous Work

Acknowledgments

Geography

Location - Topography - Access - Transportation

Industry, Population, Climate, and Vegetation

Geology

Bedrock Units, Geology, and Geologic History

Structure

Surficial Materials

Mineral Resources

Metals

Copper, Zinc, Gold, Silver

Non-Metals

Salt and Gypsum

Cinders and Soils

Rock Materials

Types and Uses
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<tr>
<th>Task</th>
<th>Duration</th>
<th>Cost</th>
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<td>B. Field analysis</td>
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<td>l. compilation of base map data</td>
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<tr>
<td>2. mineral resource review</td>
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<td>C. Report writing and editing</td>
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<td>D. Cartographic drafting</td>
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<td>$2,500</td>
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<td>E. Typing and correcting final manuscript</td>
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<td>F. Transportation and incidental expenses</td>
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<td>G. Map supplies and equipment</td>
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<td><strong>$13,500</strong></td>
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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 (Abbot 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.

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.
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 basaltic andesite form a platform of broad, overlying 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 basaltic andesite form a platform of broad, overlying 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 basaltic andesite form a platform of broad, overlying 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 basaltic andesite form a platform of broad, overlying strutovolcanoes, 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 basaltic andesite form a platform of broad, overlying 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 basaltic andesite form a platform of broad, overlying 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 basaltic andesite form a platform of broad, overlying stratovolcanoes, was built on the High Cascade platform by explosive andesitic eruptions between 700,000 yr ago (McBirney, 1968) and the last major glaciation.

### TABLE 1. CRITERIA USED TO DIFFERENTIATE AND CORRELATE DRIFTS

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discordance in moraine trends</td>
<td>Well displayed in some valleys with moraines of both Cabot Creek and Jack Creek age</td>
<td>Sharp and Birman (1963)</td>
</tr>
<tr>
<td>Morainal morphology</td>
<td>Made subjective judgment of crestal sharpness. Proximal and distal moraine slope angles measured by inclinometer</td>
<td>White (1962), Rampton (1971)</td>
</tr>
<tr>
<td>Stone-weathering ratios</td>
<td>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)</td>
<td>Blackwelder (1931), Sharp (1969)</td>
</tr>
<tr>
<td>Thickness of weathering rinds</td>
<td>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</td>
<td>Crandell and Miller (1974), Porter (1975a)</td>
</tr>
</tbody>
</table>

### TABLE 2. UNITS RECOGNIZED IN THE METOLIUS RIVER AREA

<table>
<thead>
<tr>
<th>Geologic time units</th>
<th>Glacial-stratigraphic units</th>
<th>Rock-stratigraphic units</th>
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<tbody>
<tr>
<td>Jefferson Park advance</td>
<td>Forked Butte formation</td>
<td>Till facies</td>
</tr>
<tr>
<td>Jefferson Park formation</td>
<td>Forked Butte formation</td>
<td>Outwash facies</td>
</tr>
<tr>
<td>Till facies</td>
<td>Rock-glacier deposits</td>
<td>Protalus deposits</td>
</tr>
<tr>
<td>Canyon Creek advance</td>
<td>Canyon Creek member</td>
<td>Till facies</td>
</tr>
<tr>
<td>Suttle Lake advance</td>
<td>Suttle Lake member</td>
<td>Outwash facies</td>
</tr>
<tr>
<td>Rock-glacier deposits</td>
<td>Protalus deposits</td>
<td>Loess facies</td>
</tr>
<tr>
<td>Canyon Creek formation</td>
<td>South Cinder Peak formation</td>
<td>Till facies</td>
</tr>
<tr>
<td>Jack Creek formation*</td>
<td>Outwash facies</td>
<td>Loses facies</td>
</tr>
<tr>
<td>Brush Creek formation</td>
<td>Loses facies</td>
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</tr>
<tr>
<td>Abbott Butte formation</td>
<td>Abbott Butte formation</td>
<td></td>
</tr>
<tr>
<td>Cascade Andesite formation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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.
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 meters); 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**

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till of Suttle Lake member</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>0–15</td>
<td>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</td>
</tr>
<tr>
<td>Bs</td>
<td>15–50</td>
<td>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</td>
</tr>
<tr>
<td>Cox</td>
<td>50–100</td>
<td>Dark grayish brown (5 YR 3/4); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic; medium roots; diffuse, smooth boundary</td>
</tr>
<tr>
<td>Cn</td>
<td>100–200</td>
<td>Very dark grayish brown (2.5 Y 3/2); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic</td>
</tr>
</tbody>
</table>

Till of Jack Creek formation

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0–15</td>
<td>Dark brown (10 YR 3/2); pebbly, sandy loam; massive, fine crumb structure; nonsticky, nonplastic; gradual, smooth boundary; many medium and coarse roots</td>
</tr>
<tr>
<td>B21s</td>
<td>25–55</td>
<td>Medium brown (7.5 YR 4/4); pebbly, cobbly, sandy loam; massive, fine crumb structure; nonsticky, nonplastic; diffuse, smooth boundary; medium and medium roots</td>
</tr>
<tr>
<td>B22r</td>
<td>55–80</td>
<td>Medium brown (7.5 YR 4/4); pebbly, cobbly, sandy loam; weak, medium crumb structure; slightly sticky, slightly plastic; gradual, smooth boundary; medium roots</td>
</tr>
<tr>
<td>Cox</td>
<td>80–200</td>
<td>Dark yellowish brown (10 YR 3/4); pebbly, cobbly, sandy loam; medium, medium to coarse crumb structure; nonsticky, nonplastic; diffuse, smooth boundary; few fine and medium roots</td>
</tr>
<tr>
<td>Cn</td>
<td>200–300</td>
<td>Very dark grayish brown (2.5 Y 3/2); pebbly, cobbly, sandy loam; massive, very fine crumb structure; nonsticky, nonplastic</td>
</tr>
</tbody>
</table>

Till of Abbott Butte formation

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removed</td>
<td></td>
<td>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</td>
</tr>
<tr>
<td>Bs</td>
<td>0–45</td>
<td>Dark reddish brown (5 YR 3/4); pebbly, cobbly, sandy loam; weak, fine blocky structure; slightly sticky, slightly plastic; diffuse, smooth boundary; medium roots</td>
</tr>
<tr>
<td>B21tb</td>
<td>45–85</td>
<td>Reddish brown (5 YR 4/4); pebbly, cobbly, sandy loam; moderate, blocky structure; slightly sticky, slightly plastic; diffuse, smooth boundary; medium roots</td>
</tr>
<tr>
<td>B22tb</td>
<td>85–115</td>
<td>Reddish brown (5 YR 4/4); pebbly, cobbly, sandy loam; moderate, medium angular blocky structure; slightly sticky, slightly plastic; diffuse, smooth boundary; medium roots</td>
</tr>
<tr>
<td>B23tb</td>
<td>115–170</td>
<td>Reddish brown (5 YR 4/4); pebbly, cobbly, sandy clay loam; moderate, medium angular blocky structure; sticky, plastic; few medium roots</td>
</tr>
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</table>

Note: Munsell colors were determined on moist samples.

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 or 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).

**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**

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

* Date determined from sedimentation rate in Cabot Lake.
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 laya 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...
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 (Figs. 2, 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

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**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.
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.
Evans Creek Drift at Mount Rainier (Crandell, 1969; Crandell and Miller, 1974), and Cine (Carver, 1972) Glacier Lake deposits Wisconsin alpine drifts in the northwestern Wallowa Mountains (Kiver, 1974), 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), McNeely 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 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 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.

Figure 9. Correlations between oxygen isotopic record of core V28-238 (Shackleton and Opdyke, 1973) and the Quaternary glacial record of 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.
Other Holocene volcanism occurred west of Santiam Pass. Shortly before 3,500 \(14\text{C}\) 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 \(14\text{C}\) 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 \(14\text{C}\) 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 (Patersom, 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).
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 deposits and erosional landforms. As noted, Lake advance can be delineated (Fig. 10) most modern glaciers in a steady-state condition. The mean value for steady-state AARs of 0.5 to 0.8. In this study ELAs were estimated 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. 55), 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 occupied 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 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.
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