Quaternary alpine glaciation in Alaska, the Pacific Northwest, Sierra Nevada, and Hawaii

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Introduction

This chapter deals with mountain glaciation in the North American Cordillera and Hawaii, exclusive of the Rocky Mountains (Pierce, this volume) and Canada. We focus on a few critical areas in each of these regions where research since 1965 has produced significant new results that advance our understanding of the extent, chronology, and dynamics of mountain glaciers, and enhance the paleoclimatic inferences that can be drawn from them.

Alaska

Unlike other high-latitude areas of North America, much of Alaska was never glaciated (Fig. 1). Even more land area lay exposed to the arid Pleistocene climate during intervals when sea level was lower than present. Despite the vastness of its unglaciated area, Alaska’s mountainous terrain generated a mass of glacier ice on a par with all the rest of the western United States combined. The largest expanse of glaciers comprised the coalescent ice caps and piedmont lobes that extended from the Alaska Range to the Gulf of Alaska and from the southeastern panhandle to the Aleutian Islands. This amalgamation formed the western extension of the North American Cordilleran Ice Sheet, and it contained most of the glacier ice in Alaska. The ice caps that grew in the Brooks Range, a northern extension of the Rocky Mountain system in northern Alaska, and the Aleutian Mountains in southwestern Alaska were the only other major centers of ice accumulation in the state. Lower uplands across the state supported hundreds of smaller valley glaciers; most notable are the small ranges of Seward Peninsula and the Yukon-Tanana Upland. In all, glaciers once covered about 1,200,000 km² of Alaska and its adjacent continental shelf; during late Wisconsin time, the area was 727,800 km² (Manley & Kaufman, 2002). Presently, 74,700 km² of Alaska is covered by ice, or 4.9% of the state; most of the present volume of glacier ice is in the coastal ranges proximal to moisture sources around the Gulf of Alaska.

Because most of Alaska was not glaciated, mountain glaciers were free to expand onto adjacent lowlands where they left a rich record of moraines and morphostratigraphically related glacial-geologic features. Evidence for the extent of glaciers around the Gulf of Alaska is now submerged and obscure, but a succession of moraines is preserved along most mountain fronts. Evidence for multiple glacier fluctuations is also preserved in successions of glacially influenced deposits of lacustrine (e.g. Lake Atna: Ferrrians, 1963; Lake Noatak: Hamilton, 2001), marine (e.g. Yakataga Formation: Pfaffker & Addicott, 1976; Hagenemester Island: Kaufman et al., 2001a), fluvial (e.g. Epigurak Bluff: Hamilton et al., 1993), and eolian systems (loess and sandsheets: Bégét, 2001; Lea & Waythomas, 1990; and dunes: Carter, 1981; Mann et al., 2002). The glacial history is often better dated in these depositional settings where volcanic products and organic material are more commonly preserved. The available age control shows that Alaska has a glacial record as long as that of anywhere else in the Northern Hemisphere. The geochronology also shows that glaciers fluctuated on time scales ranging from tens of thousands of years to decades, consistent with other records of global climatic changes. The ages of Holocene (e.g. Calkin et al., 2001) and late Wisconsin (e.g. Porter et al., 1983) glacier fluctuations are best documented. The ages and correlations of glacier deposits of the next-older (penultimate) ice advance are beyond the range of 14C dating and have remained controversial. Considering the vastness of the glaciated area in Alaska, the diversity of its glacial systems, and the widespread impact of glaciers on the non-glaciated regions, a single review cannot include a full account of Alaskan glacial geology. Instead, this section presents a brief summary of the major developments in Alaskan glacial geology prior to 1990, then highlights some of the progress in the last 10 years, since the last state-wide summaries of the Pleistocene-Pliocene (Hamilton, 1994) and Holocene (Calkin, 1988) glacial chronologies.

Status in 1965

Prior to the widespread use of helicopters, glacial-geologic research in Alaska was focused in the south-central part of the state, particularly in areas accessible by road (Péwé, 1965). The first attempt at a state-wide summary of Pleistocene glacier extents was by Péwé (1953). This effort led to the state-wide surficial map (Karlstrom et al., 1964) and its derived map of glacier extents (Coulter et al., 1965), both published about the time of the VII INQUA Congress.

By the mid-1960’s, the overall distribution of Quaternary glaciers in Alaska was known generally. Fifteen local Quaternary glacial sequences had been studied and the major
advances in each sequence were tentatively correlated (Péwé et al., 1965). Drift was subdivided into three principal units: Wisconsin, Illinoian, and pre-Illinoian, based mainly on semi-quantitative relative-weathering criteria and comparison with the mid-continent region. About half of the local sequences included a two-fold subdivision of the Wisconsin glaciation (early and late) and many authors recognized evidence of multiple advances during the early Holocene. Drift interstratified with marine deposits around Nome, Kotzebue (Hopkins et al., 1965), and Cook Inlet (Karlstrom, 1964), provided additional age control based on the now-discredited Th/U dating of molluscs, and a few 14C ages had been determined; these were some of the first 14C analyses (ca. 1953) ever made. The dramatic difference between the limited extent of late Wisconsin glaciers and the vast extent of pre-Wisconsin ice was identified in most areas, and the exceptionally long record of glacial-marine sedimentation dating back to the latest Miocene had been recognized around the Gulf of Alaska (Miller, 1957).

Glacial-Geologic Research Between 1965 and 1990

Péwé (1975) reviewed the Quaternary geology of Alaska. His comprehensive synthesis included the first and only statewide compilation of glaciation thresholds. By the 1980s, widespread application of 14C dating had greatly refined the chronology of late Wisconsin glacier fluctuations; in Alaska, the technique was then, and has been since, most extensively applied to deposits of the Cordilleran Ice Sheet (Hamilton & Thorson, 1983) and in the Brooks and northern Alaska ranges (Porter et al., 1983). These studies demonstrated that the most recent glaciation in Alaska occurred between 24,000 and 11,500 years ago and was therefore broadly synchronous with late Wisconsin glaciation elsewhere in North America. Hamilton et al. (1986) compiled the most complete collection of glacial-geologic studies in Alaska yet published. The volume includes detailed reports on ten different glaciated regions of the state, including: central Brooks Range (Hamilton, 1986), Seward Peninsula (Kaufman &
Progress During the Last Decade

With the recent retirement and death of several prominent Alaskan Quaternary geologists, research into the glacial geology of Alaska has slowed during the last decade. In the recently published volume on the Quaternary Paleoenvironments of Beringia (Elia, 2003), for example, only five of 35 chapters are devoted to the glacial geology of Alaska. Nonetheless, significant progress has been made as the research has shifted from the first-generation, regional mapping (mainly by the U.S. Geological Survey) to technique- and hypothesis-driven investigations at smaller scales (mainly by university scientists and their students). Areas of active glacial-geologic research include the Brooks Range, Ahklun Mountains, and Pacific coastal mountains.

Brooks Range

Building on decades of systematic, surficial-geologic mapping across the central Brooks Range, Hamilton (2002) recently completed a detailed glacial-geologic study of the Ilulissat-Sagavanirktok River area. He identified six distinct late Pleistocene moraine sets, the most complete subdivision of the Ilulissat-Wisconsin glaciation yet discovered in the Brooks Range. The glacial history of the western and eastern sectors of the Brooks Range remains uncertain, however. In the west, Hamilton’s (2003) recent study of the stratigraphic record exposed in the Noatak River basin has revealed evidence for multiple expansions of glaciers from the DeLong Mountains that dammed a succession of proglacial lakes. New photo-interpretive mapping and 14C dating (T.D. Hamilton, unpbl. data) indicate that glaciers were considerably less extensive (by an order of magnitude) in the DeLong Mountains during the late Wisconsin than has been depicted in previous state-wide compilations. Restricted ice in the DeLong Mountains during the late Wisconsin is consistent with the near absence of glaciers in the Baird Mountains south of the Noatak River (D.S. Kaufman, unpbl. data).

Ahklun Mountains

The Ahklun Mountains of southwestern Alaska supported the largest center of Pleistocene glaciers outside the Cordilleran Ice Sheet and the Brooks Range. Research during the last decade has clarified the age and extent of multiple Quaternary glacier advances. Amino acid analysis of mollusc shells from glacier advances beyond the range of 14C dating regardless of whether they predated or postdated the last interglaciation, and he assigned the next older drift, known to predate the last interglaciation, to the middle Pleistocene. Several new studies (see below) have amassed geochronological evidence favoring an early Wisconsin (s.l.) age for the penultimate drift.
et al., 1990; Pushkar et al., 1999) indicates that glaciers attained their maximum Pleistocene extent prior to the buildup of Northern Hemisphere ice sheets. The transitions between the interglacial stages of marine oxygen-isotope stages (MIS) 11 and 5 and the subsequent glacial intervals are likely times when high sea level, warm sea-surface temperatures, and decreasing summer insolation conspired to generate the largest volumes of glacier ice in Alaska. The expansion of ice over high-latitude landmasses may have had an important positive feedback in the climate system during the onset of global glaciations.

The first published exposure ages for moraines in Alaska (Briner & Kaufman, 2000; Briner et al., 2001) and 14C ages from lake-sediment cores (Kaufman et al., in press) clarify the ages of late Pleistocene glaciations in the Ahklun Mountains. No evidence for an extensive ice advance during MIS 6 has yet been discovered. Instead, outlet glaciers in the southwestern part of the mountain range advanced beyond the present coast and reached their maximum late Pleistocene extent ~60,000 years ago. Glaciers attained their maximum late Wisconsin extent ~24,000–20,000 cal yr B.P. when they terminated more than 60 km upvalley from their early Wisconsin limits. They then experienced a series of fluctuations as summer insolation increased, sea level rose, and ocean-atmospheric circulation shifted to its interglacial mode. The most dramatic readvance culminated at the end of the Younger Dryas interval (Briner et al., 2002), consistent with emerging paleoenvironmental evidence for cooling around the state at that time (e.g. Bigelow & Edwards, 2001; Hu et al., 2002; Mann et al., 2001). In the Brooks Range (Hamilton, 1986) and Cook Inlet region (Reger & Pinney, 1996), however, prominent readvances occurred ~1500 to 1000 years before the Younger Dryas, and no Younger Dryas advances have been recognized in these two regions. Glaciers retreated during an interval of early Holocene warmth, then reformed in the highest elevations of the Ahklun Mountains beginning ca. 3400 cal yr B.P. (Levy et al., in press).

The North Pacific Coast

Motivated by continued interest in biotic exchanges between the old and new worlds, Mann & Hamilton (1995) recently reviewed the paleogeography of the North Pacific coast since the last glacial maximum. They summarized evidence from around the southern margin of the Cordilleran Ice Sheet for time-transgressive glacier fluctuations and for several major climatic transitions between about 26,000 and 10,000 cal yr B.P. The understanding of the glacial history of the Cook Inlet region has been improved recently with work by Schmoll et al. (1999), Reger & Pinney (1996), and Reger et al. (1995). On the Alaska Peninsula, recent work by Wilson & Weber (2001) has attempted to correlate multiple Pleistocene drift units, and to understand the interaction of volcanic and glacier activity. These efforts have been frustrated, however, by differential glacier response of different source areas (Stilwell & Kaufman, 1996), and by the recognition that many of the moraines surrounding Bristol Bay are glacially tectonized ridges that do not necessarily record climatically significant ice-marginal positions (Kaufman & Thompson, 1998).

Recent studies of the dendrochronology, lichenometry, and moraine geomorphology of the coastal mountains rimming the northern Gulf of Alaska (Barclay et al., 2001; Calkin et al., 2001; Wiles & Calkin, 1994; Wiles et al., 1999) and the Wrangell Mountains (Wiles et al., 2002) provide the most detailed and geographically most extensive record of late Holocene glaciation in the state. Neoglacial expansions of many glaciers took place by about 4000–3500 cal yr B.P. Glaciers retreated by ~2000 cal yr B.P. before expanding again during the Little Ice Age advances of the 13th, 15th, middle 17th, and second half of the 19th centuries A.D.

On-Going Efforts

Three decades after the last Alaska-wide compilation of glacial geology (Coulter et al., 1965), a collaborative effort has produced a new synthesis of reconstructed Pleistocene glacier extents (Manley & Kaufman, 2002). The Alaska PaleoGlacier (APG) Atlas integrates the results of glacial-geologic studies from 26 publications and 42 source maps into a Geographic Information System (GIS) targeted for a scale of 1:1,000,000. Maps and several GIS layers are available online (http://instaar.colorado.edu/OGHSL/ak_paleoglacier_atlas).

The APG Atlas is part of a larger effort led by the INQUA Commission on Glaciation to create a global GIS database of Pleistocene glacier extents. The atlas depicts several glaciated masses that were not previously recognized by Coulter et al. (1965), mainly in the Yukon-Koyukuk region and the Kuskokwim Mountains. On-going spatial analysis based on more detailed digital mapping is aimed at reconstructing equilibrium-line altitudes (ELAs) and their paleoclimatic forcing using Pleistocene valley and cirque glaciers across Alaska (e.g. Manley & Kaufman, 1999).

Despite substantial progress since 1965, our understanding of the Alaskan glacial record is hindered by major gaps in ground-based mapping and geochronologic control. Recently, for example, interpretations made from satellite images led to the inference that a major Pleistocene ice sheet covered much of central Beringia (the “Beringian Ice Sheet”; Grosswald, 1998). New research in far eastern Russia (e.g. Gualtieri et al., 2000), and previous studies (summarized by Brigham-Grette, 2001), refute the existence of this former ice sheet. New research is needed to address: (1) the age of the penultimate glaciation; (2) teleconnections to the global record of rapid climatic changes; (3) relation of the Alaskan glacial record to that in adjacent regions of the Yukon Territory (e.g. Froese et al., 2000; Westgate et al., 2001) and western Beringia (e.g. Glushkova, 2001; Heiser & Rousch, 2001); and (4) the role of sea level, atmospheric moisture, continentality, and other physiographic effects in controlling regional-scale response of glaciers to climate forcing.
Fig. 2. (a) Shaded relief map of Olympic Mountains and Cascade Range of Washington and Oregon showing localities mentioned in the text. (b) Shaded relief map of western Washington showing localities mentioned in the text.

Cascade Range and Olympic Mountains, Washington and Oregon

The glaciated Cascade Range and Olympic Mountains of Washington and Oregon (Fig. 2) contain a wealth of data bearing on the Quaternary climatic and environmental history of the Pacific Northwest. The record of Pleistocene alpine glaciation is juxtaposed to a long record of ice-sheet glaciation found in adjacent lowlands, and terrain adjacent to hundreds of modern glaciers contains evidence of Holocene glacier variations.

During their greatest Pleistocene advance, alpine glaciers in the Washington Cascade Range and Olympic Mountains terminated as much as 70–80 km from their sources. During the last glaciation, the largest glaciers were only half as long. In the Oregon Cascades, glacier tongues terminated 10–30 km from ice fields that mantled the range crest.

The glaciated region encompasses a wide range of environments resulting from strong longitudinal and altitudinal climatic gradients. Cool, moist climates of western Washington and high snowfall zones on the western flank and crest of the Cascades and Olympics contrast with rainshadow conditions and drier climate farther east. Not surprisingly, radiocarbon dating of events during the last glaciation and the Holocene is largely restricted to the wetter flanks and crests of the mountains. Only recently have other dating methods become available that have the potential of developing a chronological framework spanning a significant part of the glacial history of these ranges.

Status of Alpine Glacial Studies in 1965

Pleistocene Glaciation in the Cascade Range

In his review of the Quaternary glacial record of the Puget Lobe of the Cordilleran Ice Sheet and the adjacent Cascade Range, Crandell (1965) recognized four Pleistocene drift units. The two youngest, Salmon Springs and Fraser, he
Fig. 2. (Continued)

Fig. 3. Map of glaciated region of upper Yakima River drainage basin showing extent and inferred ages of Pleistocene drifts.
inferred to be of early to middle Wisconsin age and late Wisconsin age, respectively. Crandell divided the alpine glacial record into pre-Salmon Springs (?), Salmon Springs (?), Fraser, and Neoglacial drifts. Evidence of multiple glaciations had been found in valleys of the Entiat, upper Wenatchee, upper Yakima, Puyallup, Carbon, and White rivers, and at Mount Mazama (Fig. 2). Along much of the western range front in Washington, alpine limits were overlapped and obscured by drift of the Puget Lobe.

In 1965, the general advance-retreat chronology of the Puget Lobe was based on constraining $^{14}$C dates, but age limits for alpine chronologies were based mainly on dated Holocene tephra layers. Crandell (1965) inferred that Evans Creek drift near Mount Rainier (ca. 20,000 $^{14}$C years old) predated the maximum (Vashon) advance of the Puget Lobe (ca. 15,000–13,000 $^{14}$C yr B.P.). According to prevailing opinion, by the time of the Vashon advance, the largest alpine glaciers had greatly shrunk in size or even disappeared. Crandell (1965) summarized previous studies of the Oregon Cascades, noting that ice had covered the High Cascades at least once in late Pleistocene time. He also reported evidence of more-extensive glaciation in the west-draining valleys, as well as in the North Santiam River basin.

Pleistocene Glaciation on the Olympic Peninsula

Crandell (1964, 1965) focused his reconnaissance study of the glacial record on the southwestern part of the peninsula where glaciers spread across low terrain and advanced toward the Pacific coast. He recognized three drifts of likely Wisconsin age (early, middle, and late), as well as one or more of pre-Wisconsin age, distinguishing them on the basis of extent and contrasts in weathering.

Holocene Glaciation in the Cascades

In 1965, Crandell & Miller (1965) proposed a chronology for post-Hypothermal (middle Holocene) glacier advances on Mt. Rainier based on limiting tephra ages and dendrochronology. Moraines of the Burroughs Mountain advance are overlain by tephra layers Wn (AD 1480) and C (ca. 2200 $^{14}$C yr B.P.), but are younger than layer Yn (ca. 3300 $^{14}$C yr B.P.). Moraines of Garde age were deposited during the Little Ice Age and were dated by tree-ring measurements (Sigafoos & Hendricks, 1972). An initial advance began in the late 12th or early 13th century and culminated variously in the mid-14th century to the mid-19th century.

Post-1965 Studies of Pleistocene Glaciation

Washington Cascades

Mapping and Relative-Age Control. During the past 30 years, most of the major Cascade valleys have been mapped and attempts made to derive a chronology of glaciation based

| Table 1. Post-1965 glacial-geologic studies in the Cascade Range and Olympic Mountains. |
|---------------------------------|----------------------------------|--------------------------------|
| Western Drainages               |                                  |                                 |
| Mt. Baker                       | Thomas et al. (2000)             |                                 |
| Nooksack                        | Kovanen & Easterbrook (2001)     |                                 |
| Skagit                          | Heller (1980)                    |                                 |
| Glacier Peak and vicinity       | Begét (1981), Davis & Osborn (1987) |                                 |
| Tolt                            | Knoll (1967)                     |                                 |
| Middle Fork Snoqualmie          | Williams (1971)                  |                                 |
| South Fork Snoqualmie           | Porter (1976)                    |                                 |
| Cedar                           | Hirsch (1975)                    |                                 |
| White Pass                      | Clayton (1983)                   |                                 |
| Toutle                          | Hyde (1973)                      |                                 |
| Lewis                           | Mundorf (1984), Hammond (1987)   |                                 |
| Eastern Drainages               |                                  |                                 |
| Mt. Adams and vicinity          | Hopkins (1976)                   |                                 |
| Yakima                          | Porter (1976)                    |                                 |
| Wenatchee                       | Hopkins (1966)                   |                                 |
| Icicle                          | Merrill (1966)                   |                                 |
| Chumstick                       | Nimick (1977)                    |                                 |
| Upper Wenatchee                 |                                  |                                 |
| Entiat                          | Thorp (1985)                     |                                 |
| Olympic Mountains               |                                  |                                 |
| Wynooche                        | Carson (1970)                    |                                 |
| Quinault                        | Moore (1965)                     |                                 |
| Queets                          | Thackray (2001)                  |                                 |
| Hoh                             |                                  |                                 |
| Metolius                        | Scott (1977)                     |                                 |
| Mt. Jefferson and vicinity      |                                  |                                 |
| Mountain Lakes                  | Carver (1973)                    |                                 |

a Numerous unpublished manuscripts by William A. Long on various aspects of Quaternary glaciation in the Cascades and Olympics are housed in the library of the Quaternary Research Center, University of Washington.

largely on relative-age criteria (Fig. 2A and B and Table 1). As a result, limits of the last glaciation are well-delineated in major drainages. In most valleys evidence of two or more glaciations has been recognized, and in the most-thoroughly studied examples, evidence of at least nine ice advances has been documented.
Earliest-Dated Cascade Glaciation. The earliest evidence of glaciation that is at least partially controlled by radiometric ages is found southeast of Mt. Rainier in the southern Cascades, where Clayton (1983) found an alpine till near Penoyer Creek on the Tumac Plateau beneath a basalt flow with a K/Ar age of 1.75 ± 0.35 myr. Another till along the South Fork of Clear Creek, lies beneath a basaltic-andesite flow having a K/Ar age of 0.65 ± 0.08 myr. The regional extent of these tills is unknown.

Glaciation of Mt. Rainier Volcano. In their exhaustive study of Quaternary glaciation on and near Mt. Rainier volcano, Crandell & Miller (1974) recognized the deposits of four Pleistocene glaciations and two Holocene ice advances. At least one early glaciation is inferred from an intracanyon lava flow dating between 600,000 ± 60 K/Ar yr (for a mineral separate) and 325,000 K/Ar yr (whole-rock sample) that flowed down a glaciated valley. The largest glacier of the Wingate Hill glaciation extended 105 km from the mountain. Wingate Hill drift was differentiated from the subsequent Hayden Creek drift on the basis of weathering characteristics. The last glaciation (Fraser) is represented by the Evans Creek till, deposited by glaciers as much as 64 km long. A late-Fraser advance (McNeeley) left moraines far upvalley from their Evans Creek limit. No radiometric dates are available for these drifts, but Crandell and Miller inferred that the Evans Creek advance preceded the Vashon advance of the Puget Lobe. The McNeeley advance occurred prior to ca. 8850 14C years ago, the age of Rainier tephra layer R that mantles McNeeley moraines.

Glaciation of Upper Yakima River Drainage. The glacier system that occupied the upper Yakima River drainage was one of the longest in the Cascades and its record one of the most detailed (Fig. 3). Porter (1976) mapped the extent of eight glacier advances and determined their relative age based on various weathering parameters. 36Cl ages for moraines of the Dome River advance, which impound three large lakes in the major tributary valleys, cluster in two groups, averaging ca. 23,200 ± 1000 and 16,300 ± 1600 years. Only a few preliminary ages are available for the next-older (pre-Dome River) Ronald and Bullfrog moraines, but both apparently are older than 50,000 36Cl years (T.W. Swanson, unpublished data). Three still-older drifts (Indian John, Swauk Prairie, and

Fig. 4. Map of Leavenworth in the Wenatchee River drainage basin showing extent and ages of Pleistocene moraines of Icicle Creek glacier.
Fig. 5. Cosmogenic isotope (36 Cl) ages of moraine systems in Icicle Creek valley compared with the standard marine oxygen-isotope record (Martinson et al., 1987). The 36 Cl curves represent the collective probability distribution of individual samples (±1σ).

Lookout Mountain have not been dated, but likely are early to middle Pleistocene in age.

Glaciation of Icicle Creek Drainage. Right-lateral moraines of the Icicle Creek glacier, which occupied the next major valley north of the Yakima River, record seven advances that reached to or beyond the town of Leavenworth (Fig. 4). Two additional late-glacial moraines are found in tributary valleys upriver. The original sequence proposed by Page (1939) has been expanded with the discovery of five additional moraine systems. More than 100 36 Cl ages have been obtained for moraine boulders and provide a chronology of late Pleistocene glacier variations for four of these moraines (Figs 5 and 6) (Swanson & Porter, 1997, and unpublished data). Prior to this study, the only age control was the presence of Mazama tephra (ca. 6800 14 C yr B.P.) on late-glacial moraines of the Rat Creek advance (Stuart glaciation of Page, 1939). Two moraines of the last glaciation (Leavenworth I and II) have mean 36 Cl ages of 20,000–18,000 and 18,000–15,000 years, respectively. Ages for the next older drift (Mountain Home) range from 77,000 to 71,000 years. Nine boulders on the Peshastin-age moraines range from 112,000 to 103,000 years and average 107,700 years. The oldest, strongly weathered drift (Boundary Butte) has not yet been dated. In addition, two late-glacial (late-Leavenworth) moraines have been dated (see below).

Time of Maximum Late Pleistocene Advance. Moraines marking the greatest expansion of ice in the mountains of western conterminous United States have often been inferred to predate the last interglaciation and correlate with MIS 6 or earlier isotope stages. The 36 Cl ages for Peshastin drift in the Icicle Creek drainage, however, imply an early last-glaciation age (i.e. equivalent to MIS 5d; Swanson & Porter, 2000). If this chronology is correct, it raises a question as to whether moraines marking maximum ice extent in other mountain ranges may also have formed early in the last glacial cycle. The difficulty is that surface exposure ages for moraines this old can be seriously affected by boulder weathering and moraine degradation, therefore requiring careful sample selection and interpretation. Nevertheless, these old moraines, heretofore largely “undatable” except by using relative-age criteria, may now be amenable to dating in carefully selected areas.

Late-Glacial Ice Advances. Was there an advance of Cascade glaciers during the Younger Dryas Stade (11,000–10,000 14 C yr B.P., ca. 12,900–11,600 cal yr B.P.)? This question has motivated several investigations during the past two decades. Moraines of presumed late-glacial age have been found in almost every glaciated valley investigated, but dating them has proved difficult. Often the only age control is the age of overlying Mazama tephra. Three recent studies
provide closer-limiting ages based on radiocarbon and $^{36}$Cl surface-exposure dating.

Late-glacial moraines in the Yakima River and Icicle Creek valleys have been dated by the $^{36}$Cl method. In the former valley, two post-Domeier (i.e. late-glacial) moraines at Snoqualmie Pass have mean $^{36}$Cl ages of 14,100 ± 500 and 12,700 ± 800 yr. The age of the younger moraine is consistent with a minimum limiting radiocarbon date from a bog inside the moraine of 11,050 ± 50 $^{14}$C yr B.P. (ca. 12,600 cal yr B.P.) (Porter, 1976). In the Icicle Creek drainage, two late-glacial moraines (Rat Creek I and Rat Creek II) have mean $^{36}$Cl boulder ages of 14,000–13,000 and 13,000–12,000 years, respectively. In each of these drainages the paired moraines are closely nested.

Kovanen & Easterbrook (2001) reported that three forks of the Nooksack valley in the western North Cascades contained long glacier systems during late-glacial time. Logs in a lateral moraine of the Nooksak Middle Fork glacier, lying 3 km beyond the ferminus of Derning Glacier have ages of 10,680 ± 70 and 10,500 ± 70 $^{14}$C years. However, outwash heading at a moraine in the lower North Fork valley, some 50 km from the glacier source area at Mt. Shuksan (2782 m) and Mt. Baker (3285 m), overlies glacialmarine drift dated 11,910 ± 80 yr and contains charcoal dated 10,605 ± 70 and 10,790 ± 80 $^{14}$C yr B.P., implying an ice tongue of exceptional length during Younger Dryas time.

The proposed exceptional extent of the Nooksack Valley glaciers at a time when glaciers along much of the crest of the Cascades were confined to valley heads and cirques is puzzling. Only on the north side of the Stuart Range, the source area of the type Rat Creek glacier, were late-glacial valley glaciers unusually long (ca. 8–10 km). Presumably this was because of their high accumulation area (1800–2200 m), as well as the potential for enhanced nourishment related to avalanching from steep valley slopes onto glacier surfaces. Mount Rainier, which is more than 1000 m higher than Mt. Baker and receives comparable record-high precipitation, supported long outlet glaciers during full-glacial time, but late-glacial ice was restricted in extent (see below).

A record of late-glacial glacier variations in Mt. Rainier National Park is based on mapping of moraines and radiocarbon dating of lake and bog sediments associated with the moraines (Heine, 1998). The outer of two moraines (McNeeley 1) in cirques and valley heads was deposited before 11,320 ± 60 $^{14}$C yr B.P., and therefore predates the Younger Dryas interval. Moraines of a subsequent readvance (McNeeley 2) are overlain by layer R tephra (8850 $^{14}$C yr B.P.). Basal organic matter at one site gives a minimum age of 9140 ± 100 $^{14}$C yr B.P. for this advance. Detrital sediment layers in peat bogs that are inferred to be outwash from McNeeley 2 moraines are bracketed by ages of 10,080 ± 60 and 9120 ± 80 $^{14}$C yr B.P. at one site, and between 9850 ± 60 and 8990 ± 60 $^{14}$C yr B.P. at another site. These ages imply a post-Younger Dryas age for the advance. Heine therefore inferred that glaciers in this area were less extensive during the Younger Dryas interval than either before or after, possibly due to colder temperatures and diminished precipitation at that time.

These contrasting local moraine chronologies within the same mountain range, reflecting: (1) moderate advance; (2) exceptional advance; and (3) retreat during Younger Dryas...
time, raise questions about interpretations of the geology, the chronology, and the paleoclimatic environment, that will require additional research to resolve.

A recent study in southern British Columbia <100 km north of the international boundary bears on this question. Friel & Clague (2002) have reported evidence of a glacier readvance in the Squamish valley at the end of the last glaciation. Wood in till deposited by the glacier is 10,000–10,700 14C years old (ca. 12,500–12,900 cal yr), consistent with a Younger Dryas age.

Olympic Mountains

Two studies of glaciation in the Olympics have been reported since 1965. Carson (1970) established a relative sequence of glacial events in the Wynnocohee River drainage of the southern Olympics, where he recognized two alpine drifts that pre-dated the Salmon Springs glaciation (inferred at that time to be the penultimate glaciation), as well as one equated with the Salmon Springs. Drift of the last glaciation was divided into six phases, based on moraines and terraces.

Thackray's (2001) study of glacial landforms and thick stratigraphic sections exposed along the seacoast and the Hoh and Queets river valleys of the western Olympic Mountains demonstrated the Outermost Waban moraines and to record the last glacial maximum. The occurrence of moraines near valley heads, and/or distal to Neoglacial moraines, that are mantled with Mazama tephra (ca. 6800 14C yr B.P) has led to speculation about their ages. Those who regard the tephra as providing a close minimum age suggest that the moraines are early Holocene in age, whereas others regard such a limiting age as permissible of a late-glacial advance. Purported evidence of an early Holocene advance of glaciers has been reported from sites at Mount Rainier and in the North Cascades.

Oregon Cascades

The glacial record of the Cascade volcanoes has been a primary glacial-geologic focus in Oregon. Two studies, in the northern and southern sectors of the range, demonstrate the general pattern and chronology of glaciations.

**Mount Jefferson.** Scott's (1977) study of Mt. Jefferson disclosed evidence of multiple drifts that he assigned to three glaciations based on relative-age criteria. The last glaciation (Cabot Creek) included two ice advances, Suttle Lake (last glacial maximum) and Canyon Creek (late-glacial). Multiple Suttle Lake moraines imply several stadial events. Canyon Creek moraines lie in valley heads and cirques, and are mantled with Mazama tephra (ca. 6800 14C yr B.P.). Moraines representing two phases of this glacial episode were detected in some cirques. Two older drifts (Jack Creek and Abbott Butte) pre-dated the pre-Cabot Creek interglaciation. The former is the oldest drift with preserved moraines. Scott inferred that Jack Creek drift correlates with MIS 4 or 6, and that Abbott Creek drift likely is Middle or Early Pleistocene in age.

**Mountain Lakes Wilderness.** Carver (1973) studied the glacial record in a region of ca. 1000 km² in the southern Oregon Cascades, focusing especially on the Mountain Lakes Wilderness area. Weathering parameters and morphology were used to characterize and correlate six drifts found in five valleys that radiate from the crest of a basaltic-andesitic volcano. At least four early drifts (unnamed, Winema, Moss Creek, Verney) predate a weathering interval preceding deposition of two drifts of the last glaciation (Waban, Zephyr Lake). Carver inferred that these younger drifts correlate with Evans Creek and McNeely deposits, respectively, at Mt. Rainier. The Verney drift may correlate with Hayden Creek at Mt. Rainier, and the Moss Creek drift with Wingate Hill drift. Zephyr Lake drift predates the Mazama tephra, and likely was deposited close to the time of the Pleistocene-Holocene transition.

A recent study of sediment cores from nearby Upper Klamath Lake has provided a chronology for the Waban glaciation (J.G. Rosenbaum and R.L. Reynolds, pers. comm., 2002). Glacial rock flour produced by Cascade glaciers west of the lake, including those of the Mountain Lakes volcano, accumulated in the lake. Magnetic and grain-size data spanning the last ca. 37,000 yr, regarded as proxies for sediment flux, display a prominent peak between ca. 19,200 and 17,800 cal yr B.P. This peak is inferred to correlate with the outermost Waban moraines and to record the last glacial maximum.

**Holocene Glacier Advances**

**Early Holocene (?) Advance**

The occurrence of moraines near valley heads, and/or distal to Neoglacial moraines, that are mantled with Mazama tephra (ca. 6800 14C yr B.P) has led to speculation about their ages. Those who regard the tephra as providing a close minimum age suggest that the moraines are early Holocene in age, whereas others regard such a limiting age as permissive of a late-glacial advance. Purported evidence of an early Holocene advance of glaciers has been reported from sites at Mount Rainier and in the North Cascades.

At Mount Rainier National Park, an advance of cirque glaciers between ca. 9800 and 8950 14C yr B.P. has been suggested by Heine (1998), based on radiocarbon ages bracketing inferred meltwater sediment in lakes and bogs downstream from cirque glaciers.

Near Glacier Peak, in the North Cascades, moraines lying just beyond Neoglacial moraines are overlain by Mazama tephra. The drift overlies Glacier Peak tephra (ca. 11,250 14C yr B.P.), and charcoal from the purported till has an age of 8,300 ± 8,400 14C yr B.P. (Begg, 1981), however, Davis & Osborn (1987) have questioned the interpretation of the sediment from which the dated samples were obtained. In the Enchantment Lakes basin, moraines lying just beyond Neoglacial moraines are mantled by Mazama tephra (Waitt et al., 1982), and at Mount Baker, scoria from a local eruption (8,420 ± 70 14C yr) predate moraines that are overlain by Mazama tephra (Thomas et al., 2000). The scoria overlies adjacent moraines that may be equivalent to those of the inferred early Holocene advance at Mount Rainier.
Neoglacial Ice Advances

Washington Cascades. Miller (1965) used lichenometry and dendrochronology to date moraines in the Dome Peak area of the North Cascades. An early advance (ca. 4900 \(^14\)C years ago) was inferred from \(^14\)C-dated wood exposed by recent retreat of South Cascade Glacier. Evidence of an advance at that time is rarely seen in North America, for later advances apparently were more extensive. The oldest moraine of Chick-amin glacier dates to the 13th century or earlier, but the main Little Ice Age moraine limits for most glaciers date to the 16th and 19th to 20th centuries. No moraines comparable to the Burroughs Mountain moraines at Mt. Rainier were found.

Burbank (1981) expanded on the work of Crandell & Miller (1965) by using a growth curve developed at Mt. Rainier for the lichen Rhizocarpon geographicum (Porter, 1981) to date moraines of four glaciers on the volcano. He showed that these glaciers built moraines in the early and middle 16th century, early, middle and late 17th century, early and middle, and late 18th century, early middle and late 19th century, and early 20th century. Moraines also have been dated by dendrochronology to the 13th and 15th centuries, although tephra stratigraphy suggests that they may instead predate tephra layer C (ca. 2200 \(^14\)C yr B.P.).

Olympic Mountains. Outermost Neoglacial moraines of Blue Glacier in the Olympic Mountains remain poorly dated. The earliest dated moraine remnant likely was constructed in the mid-17th century, and the maximum late Little Ice Age ice limit dates to the early 19th century, possibly just prior to 1815 (Heusser, 1957). Spicer (1989) synthesized subsequent retreat of the glacier between 1815 and 1882 by assembling a discontinuous photographic record of the terminus.

Oregon Cascades. Scott (1977) mapped Neoglacial moraines on Three-Fingered Jack volcano and on Mt. Jefferson, where two phases were recognized. Some of the moraines are ice-cored. The oldest tree cored on the moraines is 90 years old, and R. geographicum thalli are \(\sim\)20 mm, implying that the glacier advance(s) occurred late during the Little Ice Age. Two Neoglacial periglacial phases in the southern Oregon Cascades are represented by rock glaciers, protalus ramparts, and block fields, but age control is limited (Carver, 1973). Rhizocarpon thall on deposits of the early phase reach a diameter of 100 mm; those of the younger phase are \(<\sim25\) mm. The present recession of glaciers in a time of warming climate may lead to exposure of terrain that has remained ice-covered for hundreds – even thousands of years. This should afford an opportunity for obtaining datable samples to assess the extent of glaciers during major episodes of retreat, including the early to middle Holocene warm period prior to Neoglacialization.

Reconstructed Equilibrium-Line Altitudes

In several studies, estimates of the ELAs of former glaciers have been reconstructed, generally along west-east transects parallel to precipitation gradients. Most of these studies used the accumulation-area ratio method (AAR) (Porter, 2001), or a variant of it. Insufficient data are available to assess the three-dimensional full-glacial ELA surface, but this was possible for late-glacial time in a few areas where multiple small valley or cirque glaciers were clustered. Where modern glaciers exist, ELA depression (\(\Delta\)ELA) was also obtained.

The reconstructed full-glacial ELA of (Domerie) glaciers in the upper Yakima river valley lay close to 1100 m, and the \(\Delta\)ELA, relative to ELAs of nearby modern glaciers, was ca. 700 m (Porter et al., 1983). The earlier Bullfrog ELA was about 100 m lower. Hurley (1996) made a study of late-glacial (Hyak/Rat Creek) ELAs for a population of 25 glaciers, based on the AAR and median altitude methods, along a west-to-east transect across the Cascades at this latitude. He showed that the regional ELA surface rose from 900 m at the western margin of the range to 1840 m in the east. Late-glacial \(\Delta\)ELAs averaged ca. 600 m, some 300 m higher than Domerie ELAs.

Near Mt. Rainier, the full-glacial \(\Delta\)ELA was estimated by Heine (1998) to be ca. 950 m. Late-glacial to early Holocene (McNeely) ELAs were ca. 400–500 m below recent (late Holocene) ELAs.

Burbank (1981) calculated the average ELA of the late 18th to early 19th centuries for four valley glaciers on Mt. Rainier and arrived at a value of 1945 \(\pm\) 65 m. His estimates were made relative to a modern steady-state value of 2105 \(\pm\) 115 m. The average rise in ELA has therefore been ca. 160 m. However, he noted considerable variation among individual glaciers (e.g. 60–300 m); those showing the least change have a cover of supraglacial debris.

In the Oregon Cascades, reconstructed ELAs of Suttle Lake glaciers at Mt. Jefferson suggest a \(\Delta\)ELA of ca. 950 m during the last glaciation (Scott, 1977). The late-glacial Canyon Creek ELA depression was ca. 700–750 m. In the Mountain Lakes Wilderness, reconstructions by Carver (1973; AAR 0.65 \(\pm\) 0.1) indicated that Varney Creek ELAs were 75–150 m lower than those of Waban glaciers, and that Zephyr Lake ELAs were 300–400 m higher. Total ELA depression could not be calculated because no glaciers now exist in the area.

Sierra Nevada, California

Small modern glaciers are sheltered in cirques high among the ridges and peaks of the Sierra Nevada. The modern climate is influenced by local topography. Mean annual temperature and precipitation vary considerably within the Sierra Nevada and are especially sensitive to changes in summer temperature and winter precipitation. At present, the Sierra Nevada receives moisture mainly from winter low-pressure systems from the Pacific Ocean guided by the jet stream.
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precipitation on the eastern slope of the Sierra Nevada at \( \sim 37^\circ \text{N} \) ranges from \( \sim 100 \text{ cm/yr} \) at the crest to \( \sim 25 \text{ cm/yr} \) at the range front (Danskin, 1998); east of the crest it is controlled by a strong rainshadow. During Pleistocene glaciations, the jet stream shifted south so that precipitation increased and temperatures were reduced, although not necessarily in phase. Antevs (1938, 1948) first proposed this modern view of the ice-age climate, with Sierra Nevada precipitation controlled by intensified winter Pacific storms, driven farther south than today due to the influence of the Cordilleran and Laurentide ice sheets.

The modern framework of the Sierra Nevada glaciations was well understood by 1965 (Warhaftig & Birman, 1965, Table 1, p. 308), but numerical age control was weak or lacking. Major advances since INQUA VII have focussed on refinements to the glacial sequence, especially using numerical dating, and on inference of glacial history from lake-sediment cores. In addition to Warhaftig & Birman (1965), reviews of Sierra Nevada glaciations may be found in Porter et al. (1983) and Fullerton (1986).

Refinements to the Glacial Sequence

Major areas of activity have included: (1) additions to the list of recognized pre-MIS 6 glaciations; (2) reorganization of and controversy over MIS 3–6 glacial history; and (3) new insights into post-Tioga glacial history. Most of the research has taken place in the eastern Sierra Nevada. The improvements to the glacial history are based on continued exploration and mapping, new methods of numerical dating, and extraction and analysis of sediment cores from lakes and bogs. The recognized glaciations of the Sierra Nevada are summarized by Fullerton (1986, Chart 1, Table 1); those discussed in this Chapter are listed in Table 2.

Pliocene and Early Pleistocene Glaciations

The early record of glacial landforms and deposits is incomplete, and our understanding of this period remains sketchy. The most significant advances in our understanding
involve the Sherwin till. Sharp (1968) demonstrated that the

till underlies the Bishop Tuff (759,000 years: Sarna-Wojcicki

et al. (1980) discovered an older till underneath the

Bishop Tuff (759,000 years: Sarna-Wojcicki

et al. (1980) estimated an age at burial of ~50,000 years, and

Nishiizumi et al. (1989) analyzed cosmogenic nuclides to

estimate ~67,000 to 53,000 years. Thus, the Sherwin glacia-

tion probably occurred ~820,000 years ago (i.e. late Early

Pleistocene).

Sharp (1968) discovered an older till underneath the

Sherwin till on Little Rock Creek. Birkeland et al. (1980)
estimated from relative dating that the paleosol on this buried
till represented ~100,000 years of development. A similar
till with a comparable paleosol underlies till mapped as Sherwin

by R.P. Sharp (unpublished data, 1979) near the downvalley

end of the left-lateral moraine of Big Pine Creek, ~50 km to

the south.

Both the Sherwin and the older till were deposited in the
vicinity of late Pleistocene moraines. This suggests that
both tills are significantly younger than the oldest tills of
the Sierra Nevada, such as the Pliocene (?) McGee Till, which
is found on the shoulder of McGee Mountain ~800 m

or more above the late Pleistocene moraines of McGee

Creek.

A number of diamictons are locally preserved on old
erodion surfaces now at or near the crest of the Sierra Nevada,
and some of these diamictons may be glacial drift (Gillespie,
1982). Therefore, it seems likely that the long gap between
the McGee and Sherwin glaciations does not indicate a
million-year-long interglaciation; instead, it is an artifact of
poor preservation of glacial evidence.

A few "tills" lie stratigraphically between the Sherwin and
middle Pleistocene Mono Basin and Tahoe tills. One is from
the West Walker River, east of Sonora Pass (Blackwelder,
exposes fluvial gravel of Wheeler Flats that contains a tephra
identified as Rockland Ash-Tuff by Sarna-Wojcicki
et al. (1985), now dated at ~550,000 years (A.M. Sarna-Wojcicki,
quoted in Gillespie et al., 2003). If the gravel is glaciofluvial,
as seems likely, the tephra may date an unnamed, pre-Tahoe

glaciation. Mathieson & Sarna-Wojcicki (1982) found the
Rockland ash in a similar stratigraphic relation in the
Mokuh Valley in the northern Sierra Nevada.

Fullerton (1986) discussed a till from Reds Meadow, near
Devils Postpile, that overlies the Bishop Tuff and underlies an
andesite, the age of which has been very loosely constrained
by K/Ar to 650,000 ± 350,000 years. This till also is a
candidate for a post-Sherwin, pre-Tahoe advance. Curry
(1971) and Sharp (1972) presented evidence for other tills of

Table 2. Recognized glaciations of the Sierra Nevada, their ages, and east-side ELAs relative to Tioga and interpolated to 37°N.

<table>
<thead>
<tr>
<th>Glaciation</th>
<th>Mean Age (ka)</th>
<th>ΔELA (m)</th>
<th>Age References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathies (Little Ice Age)</td>
<td>0.6-0.1†</td>
<td>480 ± 25</td>
<td>Wood (1977), Stine (1994)</td>
</tr>
<tr>
<td>Recess Peak</td>
<td>14.2–13.1†</td>
<td>335 ± 20</td>
<td>Clark (1997)</td>
</tr>
<tr>
<td>Tioga (retreat)</td>
<td>15–14</td>
<td>125 ± 30</td>
<td>James et al. (2002), Clark &amp; Gillespie (1997)</td>
</tr>
<tr>
<td>Tioga (start)</td>
<td>21–20</td>
<td>0</td>
<td>Clark et al. (2003)</td>
</tr>
<tr>
<td>Tioga (“Tioga 2–4”)</td>
<td>&lt;25</td>
<td>0</td>
<td>Bursik &amp; Gillespie (1993)</td>
</tr>
<tr>
<td>Tenaya (“Tioga 1”)</td>
<td>31</td>
<td>~45 ± 15</td>
<td>Phillips et al. (1996)³, Benson et al. (1996)</td>
</tr>
<tr>
<td>Sherwin</td>
<td>32–50</td>
<td>~95 ± 10</td>
<td>Bursik &amp; Gillespie (1993)</td>
</tr>
<tr>
<td>Tahoe I³</td>
<td>?</td>
<td>~100?</td>
<td>Phillips et al. (1996)</td>
</tr>
<tr>
<td>pre-Tahoe</td>
<td>220–140</td>
<td>?</td>
<td>Phillips et al. (1990), discussed in Gillespie et al. (2003)</td>
</tr>
<tr>
<td>Mono Basin</td>
<td>80–60</td>
<td>~195 ± 50</td>
<td>Phillips et al. (1990)³</td>
</tr>
<tr>
<td>Walker Creek³</td>
<td>~550</td>
<td>?</td>
<td>Clark (1968); A. Sarna-Wojcicki, quoted in Gillespie et al. (2003)</td>
</tr>
<tr>
<td>Sherwin</td>
<td>~820</td>
<td>~200</td>
<td>Sharp (1968), Birkeland et al. (1980), Nishiizumi et al. (1989)</td>
</tr>
<tr>
<td>Lower Rock Creek</td>
<td>~920</td>
<td>?</td>
<td>Sharp (1968), Birkeland et al. (1980)</td>
</tr>
</tbody>
</table>

* Ages are shown as ranges or approximate values. Uncertainties may be found in text and/or references.
† Elevation differences are relative to the lowest Tioga ELA (~3040 ± 150 m) and interpolated to 37°N (Gillespie, 1991).
‡ Most ages are ±1σ and are random and do not include the systematic uncertainties of ~150 m. Accuracy depends critically on assignment of moraines to the correct glaciation. Regression was done on ≥70 glaciated drainages.
³ 10⁶ cal yr B.P.
⁴ Reused (see discussions in James et al., 2002, and Phillips et al., 2001).
⁵ Nomenclature from Gillespie et al. (2003).
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Fig. 8. Map of the Bloody Canyon moraines (after Gillespie, 1982). Jl, Ka, and Kja are plutonic rocks. Qal is Quaternary alluvium and Qls is colluvium. Qsh is Sherwin till of Sharp & Berman (1965). QpMB I and QpMB II are pre-Mono Basin moraines; QMB is Mono Basin moraines. QpTa is the oldest set of moraines (pre-Tahoe) along Walker Creek (“older Tahoe” of Phillips et al., 1990). QTa I and QTa II are the Tahoe I and II moraines (Gillespie, 1982). QTe (shaded for clarity) is the Tenaya moraine, and Qti are the undifferentiated Tioga moraines. Contour interval is 24 m (80 ft).

this same general period from Rock Creek and the Bridgeport Basin.

Gillespie (1982) described two pre-Mono Basin moraines at Bloody Canyon (Fig. 8), the type area of Mono Basin till. This finding together with those cited above suggests that the interval between the Mono Basin and Sherwin glaciations was marked by a number of ice advances, many to about the same maximum positions. In the absence of accurate and precise numerical dates, correlation of tills and elucidation of the glacial history from this interval remains problematical.

Mono Basin and Tahoe Glaciations

The Mono Basin and Tahoe moraines are well-preserved, yet their history is not well-understood. Age estimates for the Tahoe glaciation range from early MIS 6 to MIS 3, and even the relative age of the Mono Basin and Tahoe glaciations is controversial.

One key area of debate has been the partitioning of the glacial record into stades and glaciations. The distinction is only partly semantic. The larger issue involves the length of time that glaciers were at or near their maximum limits, and the length of time the Sierra Nevada was largely ice-free between advances. Although a number of interpretive schemes have been advanced (cited by Fullerton, 1986), it seems unlikely that definitive answers will be forthcoming until the records of glacial and lacustrine sediments for the Sierra Nevada have been integrated.

The current status of this debate is that multiple advances have been recognized for many of the glacial periods named by Blackwelder (1931), who noted that there were commonly two Tioga moraines in Sierra Nevada valleys. Burke & Birkeland (1979) used relative dating to regroup the moraines at Bloody Canyon into multiple advances, or stades, within only two glaciations, the Tioga and Tahoe. They regarded the Tenaya and Mono Basin glaciations of Sharp & Berman (1963) as early stades of the Tioga and Tahoe glaciations, respectively. Gillespie (1982) subdivided the Tahoe glaciation there (Fig. 8), and suggested that the two “Tahoe” stades were not necessarily related to the same glaciation, a conclusion supported by the soil-development data of Birkeland & Burke (1988) (R.M. Burke, pers. comm., 1998). There is no general consensus concerning the best classification, and the frustration in dealing with this thorny issue is evident in Fullerton’s (1986) attempt to rationalize the Middle and Late Pleistocene glacial histories set forth by several researchers.

Direct, numerical dating of the glacial landforms and drift should cast the glacial history into sharp focus, yet this is not yet the case. The best dates for the Mono Basin and Tahoe glaciations are from $^{10}$Be cosmogenic exposure ages for boulders from moraine crests at Bloody Canyon (Phillips et al., 1990, 1996). These dates have been revised downward
as production-rate estimates have been refined. The age for the Mono Basin moraine at Bloody Canyon, its type area, has been reduced from ~103,000 14C years in Phillips et al. (1990) to ~80,000-60,000 13C years at present (Phillips et al., 2001, revised as discussed in James et al., 2002). The current "best estimate" for the "younger Tahoe" (Tahoe II) moraine is now ~50,000-42,000 13C years, reduced from ~60,000 13C years. The best dates for the "older Tahoe" (pre-Tahoe I, post-Mono Basin: Fig. 8) moraines at Bloody Canyon are ~220,000-140,000 13C years (Phillips et al., 1989) (i.e., MIS 6). Although these older Tahoe values have not been adjusted downward, it is clear that they are greater than the 13C ages for the Mono Basin moraines ~1 km away, and Phillips et al. (1990) regarded the older Tahoe as predating the Mono Basin glaciation. These findings contradict the field relations among the moraines, from which a clear stratigraphic sequence is inferred, with both Tahoe I and Tahoe II tills overlying Mono Basin till. It is noteworthy that only a small number of boulders have been dated (8 for Mono Basin, 5 for older Tahoe), and scatter among dates for each till is large. The dating studies have cast in sharp focus the conflicts between stratigraphic and chronologic analyses, and the current strengths and deficiencies in each.

A number of other tills have been identified from the eastern Sierra Nevada that may date from the same general period as the Tahoe and Mono Basin tills. One is the pre-Tahoe Casa Diablo till near the town of Mammoth Lakes, weathered to a similar degree as nearby Tahoe till (Burke & Birkeland, 1979; Birkeland et al., 1980). Although it is interbedded with basalt flows that should afford a good dating opportunity, K/Ar analyses by Curry (1971) and by Bailey et al. (1976) are in substantial disagreement, constraining the age of the till either to ~453,000-288,000 or 126,000-62,000 years, respectively. Fullerton (1986) pointed out that the absence of 185,000-year-old quartzite boulders in the Casa Diablo till, and their presence in the nearby Tahoe till, suggests that the Casa Diablo till may pre-date MIS 6. However, recent field work shows that the quartzite boulders do occur in the Casa Diablo till, and the dates of Bailey et al. (1976) are now generally accepted as the age range for the till (R.M. Burke, pers. comm., 2003). Another till from the same general age range as the Casa Diablo till occurs in the oldest moraine in Sawmill Canyon, Inyo County. It, too, is also interbedded with basalt flows, but their dates only loosely constrain the moraine to ~455,000-130,000 years ago (Gillespie et al., 1984).

Late Pleistocene Glaciations

The glacial history of the Sierra Nevada becomes a little clearer for the post-Tahoe period. Only two post-Tahoe glaciations have been proposed: Blackwelder's (1931) Tioga, and Sharp & Birman's (1963) Tenaya. Even so, the number of stades is variously counted, and the existence of the Tenaya as a glaciation separate from the Tahoe has been debated.

At Bloody Canyon, Sharp & Birman (1963) counted two Tenaya moraines, Burke & Birkeland (1979) grouped them with Sharp & Birman's (1963) Tioga moraines for a three-stade Tioga glaciation (Fullerton, 1986, Fig. 2a). From 13C1 cosmogenic exposure ages at Bloody Canyon and other canyons, Phillips et al. (1996) inferred four separate Tioga stades ranging in age from 25,000 to 14,000 13C years, revised for the changes in production rates as discussed above. Their dates did not resolve the Tenaya as a separate glaciation at Bloody Canyon.

Based on 14C ages of ostracodes in Mono Lake sediments interbedded with basaltic ash at nearby June Lake, Bursik & Gillespie (1993) inferred an age of 25,200 ± 2500 cal yr B.P. for the maximum Tioga advance, which overrode one cinder cone. They inferred an age of 31,700±2000 cal yr B.P. or more for the Tenaya moraine, through which an eruption may have occurred while ice was present. The two cinder cones are the only sources that have been discovered for the ash in the lake sediments. Bursik & Gillespie (1993) regarded the Tenaya as a separate advance. Clark et al. (2003) cored Grass Lake Bog, south of Lake Tahoe, and dated a sharp transition from Tioga glacial drift to underlying non-glacial sediments at 21,130–19,850 cal yr B.P. This may be the best date for the beginning of the Tioga maximum advance.

James et al. (2002) obtained 10Be and 26Al cosmogenic exposure ages for the Tioga glaciation and suggested that its maximum in the South Fork of the Yuba River was 18,600 ± 1200 years ago. Basal lake sediment elsewhere on the western slope of the Sierra Nevada yielded a minimum age for the beginning of Tioga retreat of 15,570 ± 820 13C yr B.P. (Wagner et al., 1982, cited in Fullerton, 1986). James et al.'s (2002) cosmogenic data show that the Tioga glaciers retreated rapidly from the middle elevations of the Yuba River 18,000–15,000 years ago. Clark & Gillespie (1997) are in agreement that the Tioga glaciers vanished entirely or were restricted to cirques during this same interval.

Post-Tioga Advances

The Hilgard glaciation, proposed by Birman (1964), was regarded as a very late Tioga advance by Birkeland et al. (1976), and as a recessional standstill by M. Clark (pers. comm., 1988). Thus, the Hilgard advance is no longer regarded as a separate glaciation, and the Recess Peak advance is the oldest post-Tioga advance in the Sierra Nevada for which evidence has been discovered.

As first described by Birman (1964), Recess Peak moraines are restricted to the vicinity of Pleistocene cirques. Because of their fresh character, most early workers concluded that the Recess Peak moraines were Neoglacial in age, and constructed within the past 2000–3000 years (Birman, 1964; Curry, 1969; Scuderi, 1987). However, soil work by Yount et al. (1982) suggested that Recess Peak deposits were early Holocene or older. Firm numerical constraints on the moraines from sediment coring of nearby lakes demonstrated that the Recess Peak advance began by ~14,200 ka B.P. and ended before ~13,100 cal yr B.P. (Clark, 1997). Plummer's (2002) 36Cl cosmogenic ages of 12,600 ± 1300 years (production rate uncertainties included)
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overlap Clark’s (1997) age range. Therefore, the Recess Peak advance in the Sierra Nevada preceded the North Atlantic Younger Dryas event.

Curry (1971) recognized two Neoglacial advances having lichenometric ages equivalent to \( \sim 1100 \) and \( \sim 970 \) \(^{14}\)C yr B.P., and coring of the Conness Lakes indicates that Neoglacial began by \( \sim 3200 \) \(^{14}\)C yr B.P. (3400 cal yr B.P.) (Konrad & Clark, 1998). Curry (1971) dated the Matthes advances at 620–55 \(^{14}\)C yr B.P. The absence of a \( \sim 700 \) \(^{14}\)C yr B.P. (\( \sim 630 \) cal yr B.P.) tephra blanketing Matthes moraines, as well as dendrochronology (Wood, 1977), indicate that Matthes glaciers reached their maximum positions after that eruption. Stine (1994) identified two droughts at about A.D. 1112–900 and 1350–1250, just before the onset of the Matthes advances in the Sierra Nevada.

The absence of any moraines between the Recess Peak and Matthes moraines, as well as the absence of any outwash deposits between 13,100 and 3400 cal yr B.P., indicates that no significant glacier advances in the Sierra Nevada occurred during that timespan, including during the Younger Dryas interval (Clark & Gillespie, 1997). If glaciers were present in the Sierra Nevada during Younger Dryas time, they must have been smaller than Recess Peak glaciers and largely restricted to cirques.

Numerical Dating of Glaciations

Rigorous dating in the Sierra began with K/Ar dating of lava flows interbedded with till (Dalrymple, 1963, 1964) and \(^{14}\)C dating of latest Pleistocene sediments in bogs that could be correlated stratigraphically to glacial deposits (Adam, 1966, 1967). K/Ar dating, however, was problematic and opportunistic, because the glacial deposits and landforms themselves could not be dated. For example, Gillespie et al. (1984) obtained high-precision \(^{40}\)Ar and \(^{39}\)Ar dates for basalt flows at Sawmill Canyon (Inyo Country), but in the end could only conclude that the Hogsback moraine was less than 119,000 ± 3000 years old and must postdate MIS 6, a conclusion already reached by Burke & Birkeland (1979) on the basis of soil development.

The Sierra Nevada provided an early opportunity to estimate production rates for cosmogenic \(^{10}\)Be and \(^{26}\)Al, based on analyses of bedrock exposed by retreat of the Tioga glaciers, assumed to have been 11,000 years ago (Nishiizumi et al., 1989). Later, \(^{14}\)C dates from lake cores demonstrated that the area actually was deglaciated by \( \sim 15,500 \) cal yr B.P. (Clark, 1997). As a result of this and similar findings elsewhere, estimated production rates for these isotopes were reduced and now give ages compatible with those obtained using other techniques.

Phillips et al. (1990, 1996) are the primary researchers responsible for the effort to obtain cosmogenic ages for Sierra Nevada moraines. Their most notable work has been in Bloody Canyon, where \(^{36}\)Cl ages for Tenaya and Tioga agree closely with \(^{14}\)C ages, as discussed above. Their ages are consistent with field observations that the latest Pleistocene moraines and boulders appear little eroded. The cosmogenic ages for the older Tahoe and Mono Basin moraines present a significant challenge to the field stratigraphy, however.

The Mono Basin moraines at Bloody Canyon appear to be buried by both Tahoe I and Tahoe II moraines (Fig. 8), and thus must be older. Figure 9 clearly shows that the dates...
for Tahoe II are indeed younger than Mono Basin. However, Phillips et al.’s (1990) “older Tahoe” appears to be older than Mono Basin, not younger. This finding appears to violate the stratigraphic order and, if correct, requires that the Bloody Canyon glaciers changed paths several times in order to explain the positions of the moraines.

The “older Tahoe” moraine dated by Phillips et al. (1990) is not demonstrably the same as the Tahoe I till, seen to bury the Mono Basin moraine in Fig. 8. Re-examination of field relations shows that the Tahoe I moraine buries the “older Tahoe” moraines. Thus, it is possible that Phillips et al. are correct in their dating and geologic interpretation. However, this requires that the large difference in soil characteristics between the Tahoe I and Tahoe II moraines (Birkeland & Burke, 1988) represent only a few thousand years during MIS 3, which appears unlikely.

A more likely possibility is that the age of the sharp-crested Mono Basin moraines is underestimated. Hallet & Putkonen (1994) showed by modeling that cosmogenic exposure ages for old, eroded moraines underestimate landform ages. They further concluded that even apparent age reversals, such as observed at Bloody Canyon, were possible if boulder erosion was also considered.

Although the ages, and even the relative age relations, among the older moraines of Bloody Canyon remain unresolved, direct dating of landforms less than ~50,000 years old seems to be a reality. This remarkable ability will surely yield important discoveries in the near future. It seems prudent, however, to regard cosmogenic ages for older landforms with skepticism until further developments explain the observed discrepancies.

Lake-Sediment Cores

Runoff and sediment from Sierra Nevada glaciers enter lakes fed by rivers draining the mountains. Sediment cores extracted from these lakes record climate and erosion, integrated over the watershed. Given the eroded nature of many older glacial deposits in the steep mountains, and the absence of deposits of small glaciers that were overridden by younger, larger ones, it is reasonable to turn to lake-sediment cores for a more complete record. Smith (1983) analyzed a core from Sealeys Lake, which intermittently received water from Owens River. Smith’s study established the periods of major overflow from Owens Valley, upriver, and showed the promise of sediment cores for analyzing the eastern Sierra Nevada glacial history. Owens Lake and Mono Lake, which received runoff from the Sierra Nevada during all or most of the Quaternary Period, offer a more complete record, and soon attracted attention.

During times of decreased water flow, Owens Lake was closed, saline, alkaline, and biologically productive. During times of increased water flow, it was fresh and biologically unproductive. During glaciations, rock flour in the lacustrine sediment increased, total organic carbon decreased, and magnetic susceptibility peaked (Bischoff et al., 1997). Therefore, oscillations in the chemical, mineralogical, and magnetic attributes of sediment cores from Owens Lake can provide clues to the climate and glacier response in the Sierra Nevada headwaters.

Detailed analysis of Owens Lake Core OL-92 focused on upper part of the core containing the Tahoe and Tioga record (MIS 6 to MIS 2). Bischoff et al. (1997) analyzed oscillations of lake salinity and rock flour content back to 155,000 years ago with a 1500-year resolution. They discovered evidence for two glacier advances during MIS 6 and three during MIS 4–2. The two MIS-6 stades occurred 155,000–146,000 and 140,000–120,000 years ago.

Rock-flour influx during the later MIS-6 stade terminated abruptly 118,000 years ago, which Bischoff et al. (1997) interpreted as marking the onset of the last interglaciation. However, δ18O data from the same core show a gradual transition after ~140,000 years ago, parallel with isotopic evidence from carbonate deposited by groundwater near Death Valley (Winograd et al., 1992).

The global glacial-interglacial transition occurred about 128,000 years ago, according to orbitally tuned data from North Atlantic marine sediment cores (Martinson et al., 1987). Thus, large glaciers in the Sierra appear to have remained active for thousands of years after the regional climate began to change, and even after strong changes in the global climate and shrinking of the high-latitude ice sheets. Bischoff & Cummins (2001) found evidence in the rock-flour data for four brief periods of glacier activity during the interval 80,000–53,000 years ago. Thus, from the end of MIS-5 and throughout MIS 4 there were brief glacier advances. The carbonate and rock-flour records are not perfectly correlated. Bischoff & Cummins (2001) concluded that at least some glacier advances began during dry, cold conditions. However, the activity of the glaciers increased during wet periods. For example, the MIS-2 LGM was a time of enhanced precipitation, as well as low temperatures.

Dates for the MIS 4–2 stades correspond well to the 39Cl cosmogenic dates of Phillips et al. (1996) for boulders from Sierra Nevada moraines. Based on rock-flour data, Bischoff & Cummins (2001) suggested that brief glacier advances occurred ~47,000 and 41,000 years ago, and a longer one (the Tioga glaciation) from 30,500 to 15,500 years ago. High-resolution magnetic susceptibility data of Benson et al. (1998a) for Mono Lake indicate that the Tioga glaciation was characterized by four stades, and did not begin in earnest until 24,500 years ago (Fig. 10). The magnetic susceptibility and total organic carbon data revealed an additional 12 stades in the interval 52,500–31,000 years ago, at the base of the studied core section. Many of these stadial advances must have occurred in the vicinity of the Sierra Nevada crest, where moraine or drift preservation would be unlikely.

High-frequency fluctuation of Sierra Nevada glaciers is strongly supported by data from Mono Lake. Mono Lake δ18O data for 35,400–12,900 14C yr B.P. show the same three scales of climatic oscillation as the Owens Lake data: Milankovitch, Heinrich, and Dansgaard-Oeschger (Benson et al., 1996, 1998a, b). Benson et al. (1998a) interpreted their data to show that glacier activity in the Sierra Nevada, which peaked at times of low summer insolation, was synchronous with cold periods in the North Atlantic.
Fig. 10. Magnetic susceptibility (MS) and total organic carbon (TOC) from Owens Lake core OL-90. MS increases and TOC decreases with glacier activity (note that TOC values increase from right to left). The core shows evidence of 17 stades (S-1 through S-17) between 52,500 and 18,500 14C yr B.P., the start of the Tioga Glaciation (after Benson et al., 1998a, Fig. 10).

Equilibrium-Line Altitude

ELAs calculated using the accumulation area ratio (AAR) method and the highest-lateral moraine technique for paleoglaciers in 70 eastern Sierra Nevada valleys between 36.5° and 39.5°N are summarized in Table 2 (Gillespie, 1991). The modern ELA is taken to be 3860 m at 37°N (Burbank, 1991) based on selected glaciers, but the “true” value may be 100–200 m (e.g. Meierding, 1982) higher. If Flint’s (1957) estimated climatic snowline is accepted, the difference would be even greater. Because firm limits rise to the east, the ELAs obtained with the AAR method are higher than they would be if there was no precipitation gradient.

At 37°N, the Tioga ELAs were ~820 m lower than for modern, sheltered cirque glaciers, or 920–1020 m (or even 1360 m) below the modern climatological ELA. They rose, on average, 3.1 ± 0.2 m/km toward the south. ELAs for earlier late Pleistocene glaciers were 45–195 m lower than for the Tioga glaciers. Tenaya ELAs were 45 m lower than Tioga, and Tahoe II were 95 m lower. Even for Sherwin glaciers, where evidence is best preserved in Bridgeport Basin (Sharp, 1972), ELAs were perhaps no more than 100 m below those of the Tahoe glaciers (Gillespie et al., 2003).

The overall spatial pattern of ELA depression is consistent with the generalized regional patterns for cirque elevations reported by Porter et al. (1983).

That ELA depressions should be increasingly greater for those older glaciations for which moraines were not obliterated by younger glaciers is not surprising. What is surprising is that the ELAs dropped time and again to within 10–20% of their MIS-2 values, even though the pattern of sea-level variation inferred from marine cores suggests that the high-latitude ice sheets were much larger during MIS 2 (Tioga) than during MIS 3–4 (Tenaya, Tahoe II) (e.g. Martinson et al., 1987). Gillespie & Molnar (1995) emphasized this discrepancy, but Shackleton (2000) pointed out that the sawtooth history of ice volume inferred from the marine cores was due, more than previously suspected, to effects of cold water. Consequently, James et al. (2002) suggested that the record of mountain and high-latitude glaciations was more similar than Gillespie & Molnar (1995) suspected. Nevertheless, there does appear to be some fundamental, possibly climatic, limit to maximum ELA depressions over the last 800,000 years.

Glaciation of Hawaii

In the chain of volcanoes that comprise the Hawaiian Islands, only Mauna Kea (4206 m) on the island of Hawaii has an unequivocal record of multiple glaciation (Porter, 1979a) (Fig. 11). Haleakala volcano (3052 m) on Maui probably was glaciated repeatedly during the middle Pleistocene (Moore...
et al., 1993), but details of its glacial history have yet to be elaborated. Mauna Loa (4169 m), Hawaii’s second-highest summit, likely had a small ice cap during the last glacial maximum, but if so, the record lies buried beneath Holocene lavas that mantle the upper slopes.

The limit of the last (Makanaka) ice cap (ca. 70 km$^2$) on Mauna Kea is marked by a discontinuous terminal moraine or moraine complex as well as the upper limits of erratic boulders on cinder cones that lie within the glacial limit (Porter, 1979b) (Fig. 12). Upslope from the lobate outer moraines, striated bedrock surfaces are interspersed with loose bouldery drift.

Beyond the Makanaka drift limit, and below pre-Makanaka lava flows, remnants of an older moraine system are found on the southern flank of the volcano (Fig. 1). Although the area of this (Waifu) ice cap was greater than the Makanaka ice cap, its extent can only be estimated (ca.
Two Makanaka moraine boulders have 36Cl ages of 18,900 on K/Ar dates of associated lava flows, 36Cl surface-exposure pre-Waihu lavas. Several gullies on the southern slope of the mountain beneath MIS 4, and Makanaka drift with MIS 2 (Wolfe younger alkalic lavas are smaller. The dates indicate that lavas, K/Ar dates have large error ranges, but those for radiocarbon ages. Due to the low K content of sub-Pohakuloa ages of several moraine boulders, and several limiting (Holocene) radiocarbon dates and/or tephra layers. Limiting criteria offer poor resolution for these old degraded deposits, and dating them by cosmogenic isotope dating methods have yet to be applied widely, but holds considerable promise for dating and corelating Late Pleistocene moraines throughout the western mountains.

The stratigraphic resolution and dating of Middle and Early Pleistocene glaciations also remain a major problem. In many drainages, multiple pre-Late Pleistocene moraines exist, but they are poorly studied and none are closely dated. Relative-age criteria offer poor resolution for these old degraded deposits, and dating them by cosmogenic isotope methods at present seems problematic. The best hope for accurate age estimates and limits, especially for drift older than ca. 50,000 years, is further dating of till-bracketing lava flows, which are known from a few localities in Washington, the Sierra Nevada, Alaska, and Hawaii. Dated studies of Holocene moraines have been carried out in a few key areas in Alaska and west of the Rocky Mountains, but in many areas the existing chronology is tentative and incomplete. Without more data, it will not be possible to assess whether Neoglacial advances were synchronous along the crests of the Cascades and the Sierra Nevada.

Because climate of the Cordillera varies both latitudinally and longitudinally, alpine glaciers may have responded more to local climate than to average regional climate.

References

The chronology of Mauna Kea glaciation is based largely on K/Ar dates of associated lava flows, 36Cl surface-exposure ages of several moraine boulders, and several limiting radiocarbon ages. Due to the low K content of sub-Pohakuloa lavas, K/Ar dates have large error ranges, but those for younger alkalic lavas are smaller. The dates indicate that Pohakuloa drift likely correlates with MIS 6, Waihu drift with MIS 4, and Makanaka drift with MIS 2 (Wolfe et al., 1997). Two Makanaka moraine boulders have 36Cl ages of 18,900 and 20,300 years (Dorn et al., 1997). A 36Cl date of 14,700 years near the summit of the mountain and radiocarbon dates from the base of a lacustrine section in Lake Waihu (3968 m) provide minimum ages of close to 15,000 years for deglaciation of the summit.

The Makanaka ELA sloped gently toward the SSE and lies, on average, ca. 470 m lower than the present summit (corrected for isostatic subsidence; Porter, 1979b) (Fig. 13). The Waihu ELA can be reconstructed only on the southern flank of the volcano, where it lay ca. 675 m below the summit during that glaciation. The volcano is now too low to sustain a glacier. If the ELA of the last glacial maximum lay close to the modern July freezing isotherm (ca. 4715 m), then full-glacial ELA depression was about 935 ± 135 m.

Challenges for the Future
Whereas the extent of Late Quaternary glaciers is now reasonably well known in much of the western Cordillera, some major gaps and uncertainties remain. Extensive detailed mapping and study of glacial deposits in many Alaskan ranges, the Oregon Cascades, and the western Sierra Nevada remain to be done. Most extant chronologies still rely on minimum limiting (Holocene) radiocarbon dates and/or tephra layers. Cosmogenic isotope dating methods have yet to be applied widely, but holds considerable promise for dating and correlating Late Pleistocene moraines throughout the western mountains.

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