34.1. INTRODUCTION

The Sierra Nevada is a major north–south mountain range in California that separates the internally drained basins and desert ranges to the east from the Central Valley to the west. Although it runs from the Tehachapi Mountains on the northern edge of the Mojave Desert to near Mount Lassen (35°40.5′N), the highest part of the Sierra Nevada (crest elevations of 3400–4300 m) lies between ~36°N and ~38°N, the approximate latitudes of the towns of Olancha (south) and Bridgeport (north). This entire reach was heavily glaciated during the Pleistocene, and some small glaciers still occupy sheltered cirques high in the mountains. Enhanced accumulation and shading from adjacent peaks allow these modern glaciers to exist well below the regional climatic snowline (estimated at ~4500 m elevation at 37°N; Flint, 1957, p. 47). Although the glaciers occur progressively lower altitudes to the north, the topographic crest north of Bridgeport plunges below the average snowline, or equilibrium-line altitude (ELA), for the modern glaciers. During the major Pleistocene glaciations, however, the ELA was ~820 m lower than for modern glaciers (Warhaftig and Birman, 1965; Gillespie, 1991), and then large glaciers occurred in the northern Sierra Nevada also (Fig. 34.1). Remarkably, the terminal moraines of maximum advances of different ages cluster closely together (Fig. 34.2), such that there appears to be a rough maximum limit to the size of Sierran glaciers over a half million years or more.

In the Sierra Nevada, the advance and retreat of glaciers are especially sensitive to changes in winter precipitation and summer temperature. At present, the Sierra Nevada receives moisture mainly from winter low-pressure systems from the Pacific Ocean guided by the jet stream. Mean annual precipitation on the eastern slope of the Sierra Nevada at ~37°N ranges from ~100 cm a⁻¹ at the crest to ~25 cm a⁻¹ 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. There are two main sources of precipitation: northerly, from the Gulf of Alaska; and southerly (the so-called “Pineapple Express”), from tropical latitudes in the Pacific driven by a southern branch of the jet stream. Therefore, precipitation in the Sierra Nevada and the Cascade Mountains to the north is not necessarily in phase on an annual or even a decadal scale.

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. However, modelling by Rupper et al. (2009) has shown that except for arid environments with precipitation less than ~150 mm a⁻¹, there is generally enough snowfall to grow glaciers and summertime temperatures have a strong control on their advance and retreat.

The Sierra Nevada consists of a batholith of Mesozoic plutons of intermediate composition, commonly granodiorite, intruded metamorphic marine sedimentary rocks and island arc volcanic rocks, both now preserved as roof pendants. The range is a large crustal block that has been tilted to the west and broken by extensional basin-and-range faulting on the east. The timing of these tectonic events is controversial, but tilted Miocene lava flows west of the crest, and faulted Pliocene basalt flows in the ranges east of the Sierra Nevada indicate that much of the early tectonic activity started before the Quaternary Period, although faulting continues today.
California in the nineteenth century was a long way from the European centres where geological theory was first developed. Nevertheless, the Sierra Nevada received a surprising amount of attention, and the understanding of mountain glaciation was advanced in no small part there. For example, Josiah Whitney, the California State Geologist, and John Muir, prominent naturalist, debated famously the relative roles of glacial, and tectonic processes in sculpting the spires, ridges, and deep valleys of the Sierra Nevada, with special attention given to Yosemite Valley. LeConte (1873) modified the positions taken earlier and derived an essentially modern view that glaciers had excavated the highlands and widened the upper reaches of river valleys, but that the basic landscape was nevertheless formed largely by fluvial activity. Matthes (1930, 1965) undertook decades of study of the glaciated troughs of the western

34.1.1. Background

California in the nineteenth century was a long way from the European centres where geological theory was first developed. Nevertheless, the Sierra Nevada received a surprising amount of attention, and the understanding of mountain glaciation was advanced in no small part there. For example, Josiah Whitney, the California State Geologist, and John Muir, prominent naturalist, debated famously the relative roles of glacial, and tectonic processes in sculpting the spires, ridges, and deep valleys of the Sierra Nevada, with special attention given to Yosemite Valley. LeConte (1873) modified the positions taken earlier and derived an essentially modern view that glaciers had excavated the highlands and widened the upper reaches of river valleys, but that the basic landscape was nevertheless formed largely by fluvial activity. Matthes (1930, 1965) undertook decades of study of the glaciated troughs of the western

FIGURE 34.1 Extent of Quaternary glaciers in the Sierra Nevada, modified from Warhaftig and Birman (1965) and Clark (1995). Late Pleistocene (Tioga) and older glacial deposits are, in general, so similar in extent that they are difficult to distinguish at this scale; see Figs. 34.2 and 34.3. Base map: USGS NED dataset (3-s resolution, ∼90 m).
slopes of the Sierra Nevada, and Blackwelder (1931) similarly analysed the glacial evidence east of the crest. Blackwelder, in particular, pioneered relative dating in an effort to correlate moraines from valley to valley, and to the glacial stratigraphy developed along the southern margin of the Laurentide Ice Sheet. Matthes and Blackwelder made an early attempt to reconcile their glacial sequences, but in the absence of numerical age control, correlation was
difficult, as successive generations of glacial geologists have confirmed while refining the glacial stratigraphy.

By the 1970s, the modern framework of the Sierra Nevada glaciations was well developed (e.g. Warhaftig and Birman, 1965; Fullerton, 1986), but numerical age control was weak or missing entirely. Recent investigations have improved this glacial history. In particular, a more thorough accounting has been developed for glaciations pre-dating marine oxygen isotope stage (MIS) 6 (>186 ka), and the MIS 6–2 (186–12 ka) and Holocene glacial history has been refined by numerical dating. Most of the research has taken place in the eastern Sierra Nevada, although recently new studies have been made west of the crest also (James et al., 2002). The improvements to the glacial history are based on continued exploration and mapping, improved and new methods of numerical and relative dating and extraction and analysis of sediment cores from lakes and bogs.

Many advances in the past few decades have resulted from the development and application of rigorous dating techniques to glacial drift and landforms. Early studies included K/Ar dating of lava flows interbedded with till (Dalrymple, 1963, 1964) and C dating of latest Pleistocene sediments in bogs that could be related 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 Ar–Ar ages for basalt flows at Sawmill Canyon (Inyo Country), but in the end could only conclude that the Hogsback moraine was less than 119±3 ka and must postdate MIS 6 (186–128 ka), a conclusion already reached by Burke and Birkeland (1979) on the basis of soil development.

Beginning in the 1980s, advances in accelerator mass spectrometry (AMS) led to the measurement of trace concentrations of exotic isotopes created by cosmic-ray bombardment of rocks exposed at the Earth’s surface, and the calculation of exposure ages of these rocks (e.g. Nishizumi et al., 1989; Gosse and Phillips, 2001). From these dates, landform ages could be inferred if the erosion rate of the dated surfaces could be estimated. The glacial chronology worldwide was a logical and early target of this new technology, and convenient samples for analysis were found in boulders exposed on the crests of moraines.

Evidence from the Sierra Nevada and other glaciated mountain ranges is incomplete, due to the overriding of earlier deposits by later glaciers and the high potential for erosion in the steep canyons. Constrained by the limited availability of local numerical ages, correlation to oxygen isotope data from marine sediment cores and/or to ice cores from Greenland or Antarctica has often been used as a proxy chronology for the local glacial history. In this review, we use MISs as a convenient chronological timescale, recognising that improved numerical dating may someday compel revision, especially for the past 50 ka for which soil erosion and boulder exhumation and erosion do not present such major complications as for dating older rocks.

### 34.2. GLACIAL ADVANCES

Blackwelder (1931) recognised four main glaciations in the eastern Sierra Nevada: McGee, Sherwin, Tahoe and Tioga. Subsequently, the glacial history has been refined and revised. The recognised glaciations of the Sierra Nevada are summarised by Fullerton (1986, Chart 1, Table 34.1) and those discussed in this review are listed in Table 34.1. Discussion draws on Kaufman et al. (2004) and Clark et al. (2003). The glacial advances are grouped for discussion below into Pliocene and early Pleistocene (MIS 22–6, ~380–186 ka; MIS 6, 186–128 ka), late Pleistocene (MIS 5–latter 2, 128–14 ka) and Post-Tioga glaciations and advances (latest MIS 2 and MIS 1, 14 ka to present).

ELAs summarised in Table 34.1 were calculated using the accumulation/ablation area ratio (AAR, with a ratio of 0.65 giving the ELA) and the highest-moraine techniques for palaeoglaciers in 70 eastern Sierra Nevada valleys between 36.5 and 39.5°N (Gillespie, 1991). The modern ELA was taken to be 3860 at 37°N (Burbank, 1991), but the “true” value may be 100–200 m higher (e.g. Meierding, 1982) or even 640 m higher (Flint, 1957) since anomalously low cirque glaciers can occur in sheltered locations.

#### 34.2.1. Pliocene and Early Pleistocene Glaciations

The earliest glaciations are represented by deeply weathered erratic boulders and diamictons on highland surfaces. These deposits occur in a wide range of topographic settings: mountaintops, arêtes, beheaded valleys hundreds of metres above modern canyons and benches on the eastern escarpment (Gillespie, 1982). Not all of the diamictons are necessarily glacial drift, but some appear to be (e.g. Brocklehurst et al., 2002). Given the range of sites and elevations of these deposits, it is likely that a number of unnamed glaciations are represented. However, our understanding of glacial chronology, extents and ELA depressions for this time is poor. The oldest identified till, the McGee till, is among the deposits in this category.

The McGee till crops out near the summit of McGee Mountain, a large, broad peak south of the town of Mammoth Lakes (53°57′55.93″N, 118°2′58.23′′′E). Metamorphic rocks and the eroded remnant of a 2.7-Ma basalt flow (Dalrymple, 1963, 1964) here are covered by large, exotic granitic boulders from a source area located on the other side of McGee Canyon. Evidently, the time of transport was long ago (~1.5 Ma; Huber, 1981) because McGee...
Creek has been incised ~800 m since access to the summit of McGee Mountain for the erratic boulders was last possible (e.g. Putnam, 1962; Gillespie et al., 1999).

The next youngest drift deposits occur in the vicinity of the late Pleistocene moraines, suggesting that deposition occurred when the landscape had much its present appearance. Moraines from this period have been largely eroded, but Sharp (1972) identified a degraded Sherwin moraine in the Bridgeport Basin. Two tills have been described: the “old red till” on Lower Rock Creek and the Sherwin till (Sharp, 1968).

Sharp (1968) observed both tills exposed in a road cutting next to Little Rock Creek, just south of Long Valley. The lower till has deeply weathered, disintegrating granitic boulders and a red palaeosol. Birkeland et al. (1980) estimated from relative dating that the palaeosol on this buried...
till represents \( \sim 100 \) ka of development. The till is overlain unconformably by a second deeply weathered till that also contains grusy boulders but lacks the distinctive red palaeosol. **Sharp** (1968) traced this second till \( \sim 125 \) m up the canyon wall to the “type locality” of the Sherwin till, the Big Pumice Cut on U.S. Highway 395. Another till with a distinctive red palaeosol underlies till mapped as Sherwin by Sharp (R. P. Sharp, unpublished data, 1979) near the end of the left-lateral moraine of Big Pine Creek, \( \sim 50 \) km to the south.

**Sharp** (1968) demonstrated that the Sherwin till underlies and therefore pre-dates the Bishop Tuff at the Big Pumice Cut, near the southern end of Long Valley. **Sarna-Wojcicki et al.** (2000) dated sanidine crystals in the Bishop Tuff to \( 759 \pm 2 \) ka \((^{40}\text{Ar/}^{39}\text{Ar})\). R. P. Sharp (personal communication, 1976) estimated that upon burial, the till was weathered about as much as Tahoe till is today, requiring \( \sim 50–100 \) ka. Other studies support this estimate. From the development of the palaeosol on the buried till, **Birkeland et al.** (1980) estimated an age at burial of \( \sim 50 \) ka, and **Nishizumi et al.** (1989) analysed cosmogenic nuclides to yield an estimate of \( \sim 67–53 \) ka. Thus, the Sherwin glaciation probably occurred at \( \sim 820 \) ka (i.e. late Early Pleistocene). It follows that **Sharp’s** (1968) old red till at Lower Rock Creek is \( \sim 920 \) ka.

**Figure 34.3** shows that the Sherwin glaciers of the central Sierra Nevada were more extensive than their successors, extending farther onto the low-angle floors of Bridgeport Basin and down the slopes of the Sherwin Grade at the Big Pumice Cut. Because the topographic gradients are relatively low here (\(<5^\circ\)), a minor additional depression of ELA could account for the larger length of the Sherwin glaciers. In the Bridgeport Basin, an additional ELA depression of as little as \( \sim 100 \) m from the Tahoe ELAs might explain the difference in extent (Clark et al., 2003).

### 34.2.1.1. MIS 22–6 Glaciations

The period between \( \sim 820 \) and \( 186 \) ka, the beginning of MIS 6, is sparsely populated with glacial evidence. However, two glacial or glaciofluvial deposits, one near the Sonora Junction and the other in Mohawk Valley, are dated to this interval by tephras.

The deposit near Sonora Junction is from the West Walker River (Blackwelder, 1931; Clark, 1967, 1968). A roadcut near U.S. highway 395 exposes fluvial gravel of Wheeler Flats that contains a tephra identified as Rockland Ash-Tuff by **Sarna-Wojcicki et al.** (1985), now dated at \( \sim 550 \) ka (A. M. Sarna-Wojcicki, quoted in Clark et al., 2003). If the gravel is glaciofluvial, as seems likely, the tephra may date an unnamed, pre-Tahoe glaciation. **Mathieson and Sarna-Wojcicki** (1982) found the Rockland ash in a similar stratigraphic relation in the Mohawk Valley in the northern Sierra Nevada.

Several other tills appear to date from the MIS 8–6 \((303–186 \) ka\) interval, but the age control is not compelling. **Fullerton** (1986) discussed a till from Reds Meadow, Devils Postpile National Monument. This till overlies the Bishop Tuff and underlies an andesite, the age of which has been very loosely constrained by K/Ar to \( 650 \pm 350 \) ka. **Curry** (1971) and **Sharp** (1972) presented evidence for other tills of this same general period from Rock Creek and the Bridgeport Basin. **Gillespie** (1982) described two moraines outside the Mono Basin moraines at Bloody Canyon (QpMBI and QpMBII in Table 34.1) that appear to postdate the Sherwin till. **Phillips et al.** (1996) presented \(^{36}\text{Cl}\) exposure ages from an “older Tahoe” moraine at Walker Creek (Bloody Canyon) in the \( \sim 200 \) ka range, but other dates from the same moraine were 130 and 150 ka.

The MIS 22–6 interval appears to have been marked by a number of glacier advances, despite the scarcity of widespread evidence. In the absence of accurate and precise numerical dates, correlation of tills and elucidation of the glacial history from this interval remains problematical.

### 34.2.2. MIS 6 Glaciations

The record of Sierra Nevada glaciations becomes more detailed with MIS 6, but remains incomplete compared to the generalised history deduced from lake-sediment cores (e.g. Smith et al., 1991; Bischoff et al., 1997). Tills that probably date from MIS 6 include the Mono Basin, pre-Tahoe and Tahoe I tills of Bloody Canyon (Fig. 34.4), the Casa Diablo till of Mammoth Lakes and the pre-Hogsback till of Sawmill Canyon in Inyo County. Moraines from this period are eroded and commonly broad-crested, with few exposed boulders. Boulders that are exposed may be disintegrated, heavily pitted and split.

The type locality for the Mono Basin moraines is at Bloody Canyon, near Mono Lake (Sharp and Birman, 1963; Figs. 34.4 and 34.5). The degree of weathering and erosion is similar to many Tahoe moraines (Burke and Birkeland, 1979), and it is uncertain how many moraines from the two glaciations may have been misclassified. At the same distance from the range front, the Mono Basin moraines at Bloody Canyon are lower in elevation than the Tahoe moraines, possibly as a result of range-front faulting between glaciations (Clark, 1972). They were preserved because the subsequent Tahoe glaciers extended along a more northerly course. **Phillips et al.** (1990) measured cosmic-ray exposure ages averaging \( \sim 103 \) ka for eight boulders from these moraines (Fig. 34.6). The dates were revised downwards to \( \sim 80–60 \) ka as new estimates for production rates of \(^{36}\text{Cl}\) were made (Phillips et al., 2001; revised as discussed in James et al., 2002). Even these ages are minima, as soil and boulder erosion on the moraines (e.g. Birkeland and Burke, 1988; Hallet and Putkonen, 1994) reduce the exposure ages estimated by this technique.
The Tahoe glaciation is one of the four major Sierra Nevada glaciations recognised by Blackwelder (1931). Gillespie (1982) showed that the “Tahoe” moraine of Sharp and Birman (1963) at Bloody Canyon was composite, with a young till comprising the crest and an older till the right-lateral flank (Figs. 34.4 and 34.5). These two tills were called “Tahoe II” and “Tahoe I,” respectively. However, they are probably from different glaciations. Phillips et al. (1990) obtained cosmogenic ages for the Tahoe II moraine. These ages averaged ~60 ka, later revised to ~50–42 ka. No age estimate for the Tahoe I moraine was obtained.

Phillips et al. (1990) did measure \(^{36}\text{Cl}\) dates for five boulders from the “older Tahoe” moraines, discussed above, that protrude from the right-lateral composite moraine. The stratigraphic relation between this “older Tahoe” moraine and the Mono Basin moraines is unclear, although both are buried by Tahoe I till (see Clark et al., 2003; Kaufman et al., 2004). The \(^{36}\text{Cl}\) dates for the “older Tahoe” till, called “pre-Tahoe I, post-Mono Basin” till in Fig. 34.5, are ~220–140 ka (unrevised).

Although these “older Tahoe” values have not been adjusted downward in accordance with new production
FIGURE 34.4  View west from pre-Tahoe end moraines of Bloody Canyon (Fig. 34.2B), showing important among the younger Tahoe and Mono Basin moraines. The left-lateral Tahoe II moraine comprises the high ridge to the right (north). The older Tahoe I moraine crops out part way down the flank of the moraine. Both Tahoe moraines bury the older Mono Basin left-lateral moraine, seen emerging from the composite Tahoe moraine in left centre. Photograph by D. H. Clark.

FIGURE 34.5  Map of the Bloody Canyon moraines (after Gillespie, 1982). Jl, Ka and Kja are plutonic rocks; Qal is Quaternary alluvium. Qsh is Sherwin till of Sharp and Birman (1963). QpMBI and QpMBII 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); QTaI and QTaII are the Tahoe I and II moraines (Gillespie, 1982). QTe (shaded for clarity) is the Tenaya moraine, and QTi are the undifferentiated Tioga moraines. Topographic contour interval is 24 m (80 ft).
rates, it is clear that they are greater than the $^{36}$Cl ages for the Mono Basin moraines $\sim$1 km away. Phillips et al. (1990) regarded the older Tahoe as pre-dating the Mono Basin glaciation. These findings appear to contradict field relations among the moraines. It is noteworthy that only a small number of boulders were dated, and scatter among dates for each till is large. The dating studies have illuminated the conflicts between stratigraphic and chronologic analyses, and the current strengths and deficiencies in each.

The pre-Tahoe Casa Diablo till, near the town of Mammoth Lakes, is weathered to a similar degree as nearby Tahoe till (Burke and Birkeland, 1979; Birkeland et al., 1980). Given the degree of soil development, the Tahoe till was taken to date from MIS 6 by Burke and Birkeland (1979). Although the Casa Diablo till is interbedded with basalt flows that should afford a good dating opportunity, K/Ar analyses by Curry (1971) and Bailey et al. (1976) disagree, constraining the till to either $\sim$453–288 or 126–62 ka, respectively. On the basis of relative dating techniques, Burke and Birkeland (1979) suggested that the Casa Diablo till was correlated with the older Tahoe and/or Mono Basin tills to the north. Fullerton (1986) pointed out that the absence of 185-ka quartz latite boulders in the Casa Diablo till, and their presence in the nearby Tahoe till, suggests that the Casa Diablo till may predate MIS 6. Only moraines from the largest advances appear to have been preserved near Mono Lake, and at Bishop Creek, Phillips et al. (2009) found a gap in the record until 26 ka (Fig. 34.7). The Tahoe II and Tenaya advances at Mono Lake seem to have occurred during earlier and later parts of MIS 3, respectively. MIS 2 Tioga advances culminated around 19–23 ka and ended by 15 ka with retreat to the Sierra Nevada crest, or even complete disappearance for a brief period. ELAs for maximum Tioga glaciers were 3040/6 $\sim$150 m (Table 34.1), depressed about 820 m relative to modern glaciers and perhaps 900–1500 m below the climatic ELA, depending on how it is estimated. The climatic ELA is above the crest of the Sierra Nevada, and cirque glaciers exist only in sheltered localities.

34.2.3. Late Pleistocene Glaciations

Blackwelder (1931) recognised that there typically were two Tioga moraines in Sierra Nevada valleys. Sharp and Birman (1963) and Birman (1964) recognised a third, “Tenaya” moraine between Tioga and Tahoe in relative age. Lake-core evidence (e.g. Benson et al., 1998b; Fig. 34.7) suggests that a dozen or more short-lived advances occurred between $\sim$50 and 14 ka. Only moraines from the largest advances appear to have been preserved near Mono Lake, and at Bishop Creek, Phillips et al. (2009) found a gap in the record until 26 ka (Fig. 34.7). The Tahoe II and Tenaya advances at Mono Lake seem to have occurred during earlier and later parts of MIS 3, respectively. MIS 2 Tioga advances culminated around 19–23 ka and ended by 15 ka with retreat to the Sierra Nevada crest, or even complete disappearance for a brief period. ELAs for maximum Tioga glaciers were 3040 ± 150 m (Table 34.1), depressed about 820 m relative to modern glaciers and perhaps 900–1500 m below the climatic ELA, depending on how it is estimated. The climatic ELA is above the crest of the Sierra Nevada, and cirque glaciers exist only in sheltered localities.
From $^{36}$Cl cosmogenic exposure ages at Bloody Canyon and other canyons, Phillips et al. (1996) inferred four separate Tioga stades ranging in age from 25 to 14 ka, revised for the changes in production rates as discussed above. Their dates failed to resolve the Tenaya as a separate glaciation at Bloody Canyon. James et al. (2002) measured $^{10}$Be and $^{26}$Al cosmogenic exposure ages in the South Fork of the Yuba River, suggesting that the maximum extent of the Tioga glaciation there occurred $\sim 18.6 \pm 1.2$ ka. Likewise, the record at Bishop Creek gave moraines ranging from 26 to 15.5 ka in age (Phillips et al., 2009), or latest MIS 3–2 (Fig. 34.7). In Humphreys Basin, above the headwaters of Bishop Creek, Phillips et al. (2009) reported $^{36}$Cl cosmic-ray exposure ages of 15.2$\pm$0.7 ka that suggested to them that even the crest of the Sierra Nevada was nearly free of ice by then. It follows that retreat of glaciers from their maximum Tioga extents was rapid, taking only 1000 or 2000 years.

Based on $^{14}$C ages of ostracodes in Mono Lake sediments interbedded with basaltic ash, Bursik and Gillespie (1993) inferred at nearby June Lake an age of $< 25.2 \pm 2.5$ cal. ka BP for the maximum Tioga advance, which overrode a cinder cone. They inferred an age of 31.7 cal. ka BP 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 and Gillespie (1993) regarded the Tenaya as a separate advance.

Other age control for the Tioga glaciation is available from sediment cores collected from bogs and lakes. D. H. Clark cored Grass Lake Bog, south of Lake Tahoe, and dated a sharp transition from Tioga glacial to overlying non-glacial sediments at 21.13–19.85 cal. ka BP. This date may mark the onset of retreat of the Tioga maximum advance, and is consistent with the $^{36}$Cl dates from Bishop Creek (Phillips et al., 2009; Fig. 34.7). Basal lake sediment from the west slope of the Sierra Nevada yielded a minimum date for the beginning of Tioga retreat of 15.57$\pm$0.82 $^{14}$C ka BP (18.84$\pm$0.91 cal. ka BP; Wagner et al., 1982, cited in Fullerton, 1986). The basal age from the Greenstone Lake cores instead demonstrates that the area near Tioga Pass was deglaciated by $\sim 13.1$ $^{14}$C ka BP ($\sim 15.5$ cal. ka BP; Clark, 1997). James et al.’s (2002) cosmogenic data show that the Tioga glaciers retreated rapidly from the middle elevations of the Yuba River 15,000–14,000 years ago. Clark and Gillespie (1997) agreed that the Tioga glaciers vanished entirely or were restricted to cirques during this interval.

### 34.2.3.1. Post-Tioga Advances

The Hilgard advance, proposed by Birman (1964) as a separate post-Tioga glaciation, was considered to be a very late Tioga stade by Birkeland et al. (1976), and a recessional standstill by M. Clark (personal communication, 1988). Thus, the Hilgard glaciation is no longer regarded as a separate stade.

The Recess Peak glaciation is the first 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, constructed within the past 2000–3000 years (Birman, 1964; Curry, 1969; Scudder, 1987). However, soil work by Yount et al. (1982) suggests that Recess Peak deposits are early Holocene or older. Firm numerical constraints on the moraines from sediment coring of nearby lakes demonstrates that the Recess Peak advance began by $\sim 14.2$ cal. ka BP and ended before $\sim 13.1$ cal. ka BP (Clark, 1997; Phillips et al., 2009). Plummer’s (2002) $^{36}$Cl cosmogenic ages of 12.6$\pm$1.3 ka (production rate uncertainties included) overlap Clark’s (1997) age range.

ELA estimates for Recess Peak glaciers were only $\sim 340$ m higher than that for the maximum Tioga glaciers (Table 34.1). This value may probably overestimate the climatic severity during the Recess Peak advance because cirque glaciers can occur at anomalously low elevations.

Curry (1971) recognised two Holocene Neoglacial advances having lichenometric ages equivalent to $\sim 1100$ and $970$ $^{14}$C a BP ($\sim 1015$ and 920 cal. a BP). Coring of the Conness Lakes indicates that Neoglacial began there by $\sim 3.2$ $^{14}$C ka BP (3.4 cal. ka BP, Konrad and Clark, 1998; 3.2 cal. ka BP, Bowerman and Clark, 2011). Curry (1971) dated the Matthes (Little Ice Age) advances at 620$\pm$55 $^{14}$C a BP ($\sim 610$$\pm$ 40 cal. a BP). The absence of a $\sim 700$ $^{14}$C a BP ($\sim 630$ cal. a BP) tephra blanketing Matthes moraines coupled with evidence from dendrochronology (Wood, 1977) indicates that Matthes glaciers reached their maximum positions after that eruption (180 cal. a BP: Bowerman and Clark, 2011). Stine (1994) identified two droughts at about AD 1112–900 and 1350–1250.

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**FIGURE 34.7** (A) $\delta^{18}$O record (left) and total inorganic carbon (TIC) from Mono Lake (right), for 41–12 ka. Low stands L1–L4 have been labelled and shaded. Middle curve shows the $\delta^{18}$O record from the GISP2 ice core, Greenland, with Heinrich events H1–H4 and Dansgaard–Oeschger events D2–D8 labelled for reference. From Benson et al. (1998b). $^{10}$Be cosmic-ray exposure ages for Bishop Creek compared to three nearby drainages, Walker Creek (Fig. 34.2B), Little McGee Creek and the South Fork of the Yuba River, on the west side of the Sierra Nevada are shown on the far right. Error bars are 1$\sigma$ and the integer by each indicates the number of samples dated. (B) Dates for the same drainages over an expanded time range (250–0 ka) compared to the SPECMAP marine $\delta^{18}$O record (Imbrie et al., 1984; data from Imbrie and McIntyre, 2006). Marine oxygen isotope stages are labelled and shaded for reference. Dating references: $^a$Phillips et al. (2009); $^b$Phillips et al. (1996); $^c$James et al. (2002); $^d$Porter and Swanson (2008); $^e$Bierman et al. (1995); $^f$Dünningforth et al. (2007).
just before the onset of the Matthes advances in the Sierra Nevada. ELAs for Matthes glaciers were ~480 m higher than ELAs for the maximum Tioga glaciers.

The absence of moraines between the Recess Peak and Matthes moraines, and the absence of outwash deposits between 13.1 and 3.4 cal. ka BP, suggests that no significant glacial advances in the Sierra Nevada occurred during that time, including during the Younger Dryas interval (Clark and Gillespie, 1997). If Younger Dryas glaciers were present in the Sierra Nevada, they must have been smaller than both the Recess Peak and Matthes glaciers and restricted to cirques.

34.3. DISCUSSION

34.3.1. Younger Dryas

The absence of any moraines between the Recess Peak moraines and the Matthes moraines, as well as the absence of any periods of outwash between 13,100 and 3400 cal. a BP, indicates that no significant glacial advances in the Sierra Nevada occurred during that time, which includes during the Younger Dryas interval (Clark and Gillespie, 1997), although alluvial fans have experienced limited Holocene aggradation (e.g. Bierman et al., 1995; Zehfuss et al., 2001). This finding, combined with evidence favouring Younger Dryas advances in the Rocky Mountains and potentially the North Cascades (e.g. Reasoner et al., 1994; Kovanen and Easterbrook, 2001) suggest a complex regional climate during the late-glacial period in western North America. It also indicates that the climate during the Little Ice Age was the coldest and/or wettest (i.e. most glacial) in the Sierra Nevada of the past 13,000 years.

34.3.2. Comparison with the Cascade Range

Porter and Swanson (2008) reported 76 $^{36}$Cl ages for a moraine sequence from Icicle Creek, in the Cascade Range. The dates cluster at $12.5 \pm 0.5$, $13.3 \pm 0.8$, $16.1 \pm 1.1$, $19.1 \pm 3$, $70.9 \pm 1.5$, $93.1 \pm 2.6$ and $105.4 \pm 2.2$ ka (Fig. 34.7). The younger, Tioga-age dates are in good agreement with those from the Sierra Nevada. However, the agreement is less clear for MIS 4 and 5 moraines. It is possible that this is due to incomplete preservation, or due to the noted problems with dating older, eroded deposits, but it is also possible that the glaciations themselves were more synchronous up and down the Pacific coast of North America at the MIS 2 LGM than before.

34.3.3. Lake Records

Direct glacial deposits and landforms present an incomplete record of mountain glaciations. This record has been be fleshed out by analysis of lake-sediment cores (e.g. Bischoff et al., 1997; Fig. 34.7). Core data can establish the duration of glaciations, information that is difficult to acquire from moraines and drift alone. The findings of Benson et al. (1996) at Mono Lake suggest that the average duration of glacial advance and retreat during MIS 3–2, period including the Tioga glaciation, was on the order of 3 ka. In fact, the fluctuation of Sierra Nevada glaciers inferred from Owens Lake (Bischoff et al., 1997; Bischoff and Cummins, 2001) and Mono Lake (Benson et al., 1996, 1998a,b) cores seems to show the same three scales of climatic oscillation as the marine/global system: Milankovitch, Heinrich and Dansgaard–Oesger (Benson et al., 1996, 1998a,b). Benson et al. (1998a) interpreted the data to show that glacier activity in the Sierra Nevada was synchronous with cold periods in the North Atlantic.

34.3.4. Reliability of “Older” Cosmic-Ray Exposure Dates

Figure 34.7 suggests that, especially for glacial deposits older than ~50 ka, there may be “geologic” scatter in the dates in excess of analytic and systematic measurement errors and in excess of what might be expected from geologic mapping and relative dating, possibly due to unaccounted-for effects of soil and boulder burial and erosion. It is also possible that our ability to “read” the landscape and correlate landforms on the basis of relative weathering is less than we have thought and hoped; thus, preservation of moraines may have been more erratic than we have assumed. Nevertheless, the spatial richness of the record from glacial deposits and landforms supplies information difficult to glean from a limited number of cores alone, especially in the latest Pleistocene.

34.3.5. Dating Paraglacial Deposits

For a time, it seemed that the record of glaciation might be better read from alluvial or outwash fans downvalley from the glaciers than from the moraines themselves. Gillespie (1982) suspected that paraglacial deposition accounted for much of the Sierran Bajada, and Whipple and Dunne (1992) elaborated a process-based explanation for this synchrony. Bierman et al. (1995) measured pairs of $^{10}$Be and $^{26}$Al of cosmic-ray exposure dates that seemed to confirm the hypothesis. Dünnforth et al. (2007) added further dates for the glaciated Shepherd Creek fan, and the adjacent unglaciated Symmes Creek fan, finding more Holocene aggradation in the unglaciated drainage. Nevertheless, comparison of fan and moraine dates (Fig. 34.7) suggests that the glacial record is not much better preserved in the fans than in the moraines. It may be that fan-resurfacing floods that do occur occasionally beneath glaciated canyons.
34.3.6. ELA Depression

ELA depressions for the different Pleistocene Sierra Nevada glacier advances represented in the land record increase with age but show a remarkable consistency. Figure 34.8A shows the trend in Tioga ELAs from North to South for the Sierra Nevada. In Fig. 34.8B, the nearly parallel trend for the youngest Tahoe glaciers is shown. From the Tioga to the Sherwin glaciation, the ELA depression of the maximum advances was within a range of ~200 m.

That ELA depressions should be increasingly greater for older glaciations is expected because moraines for smaller, older glaciers were obliterated by younger glaciers. What is surprising is that the ELAs dropped time and again to within 10% or 20% of their MIS 2 values, even though the pattern of sea-level depression inferred from marine cores suggests that the high-latitude ice sheets were much larger during MIS 2 (Tioga) than, for example, during MIS 4–3 (Tenaya, Tahoe II; e.g. Martinson et al., 1987).

**FIGURE 34.8** Equilibrium-line altitudes (ELAs) along the eastern front of the Sierra Nevada. (A) Tioga glaciers. (B) ΔELA for Tioga (Ti) and late Tahoe (Ta) moraines (ELA_{Ti}−ELA_{T_0}). ELA_{Ti} descends almost linearly from south to north. The cause of the deviation of up to 300 m above the regression line near 37.5°N is unknown. ELA_{Ta} rose slightly higher to the north than ELA_{Ti}; the cause for this trend, if real, is also unknown. After Gillespie (1991).
Gillespie and Molnar (1995) emphasised 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 and Molnar (1995) suspected. Nevertheless, there does appear to some fundamental limit to maximum ELA depressions, at least over the past ~800 ka. This in turn implies a fundamental limit to climatic extremes on the western coast of North America.

34.4. SUMMARY

The Sierra Nevada was repeatedly glaciated during the Quaternary Period. The glacial record on the eastern side of the range includes at least eight Pleistocene glaciations, and multiple stades are known for some of them. Lake-sediment core data suggest that this record is incomplete and that there have been many more advances than have been recognised, no doubt in part due to obliteration of evidence from smaller, older glaciers by larger, younger ones.

The last Pleistocene glacier advance, the Recess Peak advance, pre-dated the Younger Dryas event in the Sierra Nevada, and any Younger Dryas glaciers there must have been restricted to the cirques. Because there is evidence elsewhere in western North America supporting the presence of Younger Dryas glaciers, it appears that there may have been considerable local variability in the regional response to a “global” climatic event. Nevertheless, the available lake-core data have been interpreted to show a general synchronism of glacier advances in the Sierra Nevada to cold periods in the North Atlantic.

ELA depressions of the largest glaciers were the same within 20%, independent of age. This suggests a remarkable consistency in the extreme climate in California over a time span of 800 ka or more.

Recent efforts to date glacial deposits numerically have added detail to our understanding of Sierra Nevada glacial chronology, and have facilitated correlation with the lake-core records. However, except for results for the late Pleistocene advances, results may serve only as limits to the age of the glaciations, because of erosion and other geological complexities. Further numerical dating will probably be required in order to refine the glacial history, particularly for older glaciations for which great uncertainties remain.

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REFERENCES


