Extreme southwestern margin of late Quaternary glaciation in North America: Timing and controls

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ABSTRACT

Well-preserved latero-frontal moraines in the eastern San Bernardino Mountains of southern California provide evidence for several glacial advances during the late Quaternary and mark the southwesternmost limit of glaciation in the Western Cordillera. Using geomorphology and ^{10}Be cosmogenic radionuclide dating, a succession of moraines from three glaciated valleys is dated to 18–20 ka (Last Glacial Maximum), 15–16 ka (Heinrich Event 1), 12–13 ka (Younger Dryas Stade), and 5–9 ka (early-middle Holocene). These ages substantiate the view that glaciation throughout the American Cordilleras was synchronous during the late Quaternary. Furthermore, these data show that glacial advances in southern California occur when a significant decrease in summer temperature is coupled with an increase in moisture flux producing high winter snowfall. This allows for perennial snow accumulation that may, under appropriate conditions, persist to form glacial ice.

Keywords: cosmogenic radionuclide dating, glaciation, San Bernardino Mountains, Last Glacial Maximum, Younger Dryas.

INTRODUCTION

Successions of well-preserved moraines are present on the northern slopes of San Gorgonio Mountain in the eastern San Bernardino Mountains of southern California (Fairbanks and Carey, 1910; Sharp et al., 1959; Herd and Cox, 1980; Fig. 1). These represent the southwesternmost glaciated area in the Western Cordillera of North America and they have the potential to provide important paleoenvironmental and paleoclimatic information on the region for the late Quaternary. This study area provides a model for examining glacial processes and chronologies at the extreme margins of glaciation.

Sharp et al. (1959) identified 10 glaciated valleys and cirques on San Bernardino Ridge and San Gorgonio Mountain, all on north- and northeast-facing slopes. On the basis of relative weathering studies, they suggested that the moraines represented two distinct glacial advances that occurred during the early and late Wisconsin. The scarcity of organic material within and associated with the glacial landforms, however, inhibited them from dating the moraines using radiocarbon methods, the only geochronologic technique available in the 1950s and one that was in its early stages of development. On the basis of weathering criteria and soil development, Herd and Cox (1980) correlated these moraines with the global Last Glacial Maximum (LGM) and what they referred to as the last Pleistocene ice advance at 10–12 ka. Cosmogenic radionuclide (CRN) surface-exposure dating now provides a method to directly date the moraines to define the timing of glacial advances in this region and to test the assumption of Sharp et al. (1959) and Herd and Cox (1980) that these formed during the Wisconsin glaciation. Using ^{10}Be, we dated a succession of moraines from three glaciated valleys. This enabled us to define the timing of each glacial advance and to examine relationships between glaciation and climate change, and to test whether glaciation on San Gorgonio Mountain is synchronous with other glaciated regions of the American Cordilleras and the climatic record from the Northern Hemisphere ice sheets and oceans.

GEOMORPHIC SETTING AND CONTEXT

The San Bernardino Mountains are part of the Transverse Ranges, 120 km east of Los Angeles, and reach a maximum elevation of ~3500 m above sea level (asl) at San Gorgonio Mountain (Fig. 1). Currently there are no glaciers in the Transverse Ranges. The bedrock in the glaciated terrain comprises monzogranites and gneisses (Morton et al., 2003). The climate is Mediterranean with winter precipitation and summer drought. During summer, the westerly jet stream is poleward of California, resulting in warm, cloudless air masses with ambient temperatures ranging on average from 10 to 12 °C. During winter, the jet stream migrates equatorward toward California, and cyclones bring moist Pacific air masses into southern California from the North Pacific Ocean (Minnich, 1984). The winter temperatures coupled with the orographic lifting of the moist air result in an annual precipitation of 70–100 cm. Nearly all of the precipitation above 3000 m asl falls as snow (Minnich, 1986). Winds at summit levels during storms are predominantly southwesterly, with speeds between 20 and 40 ms^{-1}. The high winds transport snow from southwest-facing exposures onto north- and northeast-facing exposures, where there is development of cornices along ridgelines and avalanching of powder down leeward slopes, especially into cirque headwalls (Minnich, 1984). Minnich (1984) showed that perennial snowfields exist in about one-third of the years that have exceptional snowfall (Fig. DR1[1]).

FIELD METHODS

Field work was undertaken on the northern slopes of San Gorgonio Mountain, Jepson Peak and Charlton Peak (Fig. 1), including the catchments of Dollar Lake, Dry Lake region (Big Draw and Little Draw), and North Fork of the Whitewater River. The mapping and relative chronology of Sharp et al. (1959) were examined in the field, aided by aerial photographic interpretation. We broadly agree with their relative chronology, but on the basis of moraine morphology we subdivided the succession into four stages, I, II, III, and IV.

Sampling for ^{10}Be CRN dating was undertaken on the least eroded moraine ridges for each glacial stage. Samples were collected from boulders located on the crests of the moraines. Detailed sampling methods are described in Appendix 1 (see footnote 1). Several samples were collected from each individual moraine to test the reproducibility of the CRN results, in particular whether boulders inherited any significant CRNs (boulders that had been recently exhumed or had toppled, or were significantly weathered would produce CRN ages that are significantly younger than the general population). To further

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[1] GSA Data Repository item 2003103, Figure DR1, Appendices 1 and 2, and Tables 1 and 2, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

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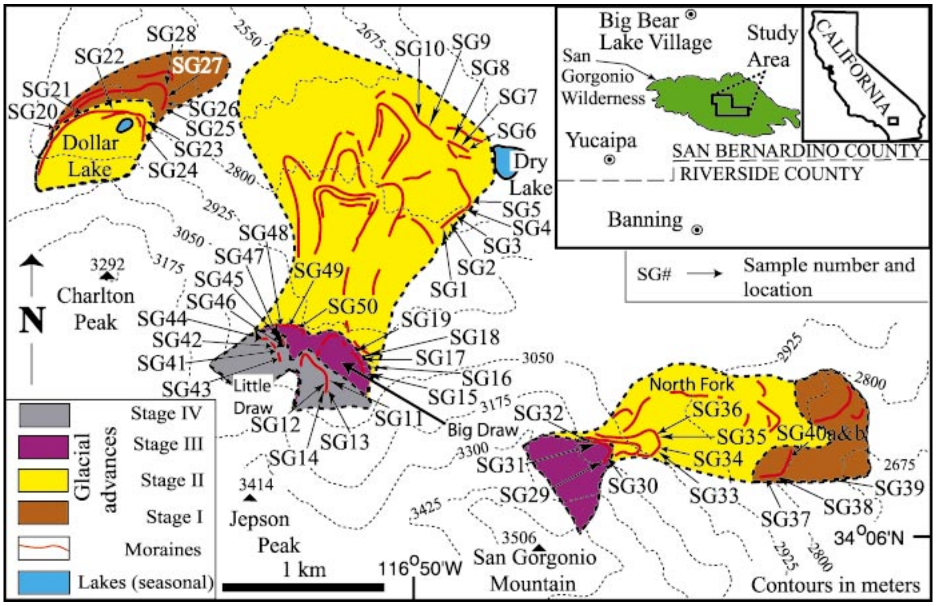

Figure 1. Moraines and sampling locations along north flank of San Gorgonio Mountain. Locations of moraines are taken mainly from Sharp et al. (1959).

minimize the likelihood of spurious ages, we only sampled boulders that appeared to have little evidence of erosion and exfoliation and were not covered with large amounts of vegetation. To estimate the possibility that snow cover may be important in shielding boulders, we examined the boulders that were sampled for ^{10}Be CRN dating after heavy snowfall events in February and April 2001. Although the snow packs were as thick as 2 m, none of the boulders that we sampled was covered with >10 cm of snow. Most boulders were essentially clean of snow because they were in exposed settings where snow was rapidly removed by wind.

LABORATORY METHODS

Samples for ^{10}Be CRN dating were prepared at Lawrence Livermore National Laboratory. Full details of the analytical methods and age calculations are described in Appendix 1 and listed in Table 1 (see footnote 1).

MORAINES

The lowest moraines within each study area comprise high (>50 m) latero-frontal moraines that have steep (>20°) outer faces and include meter-size boulders. These represent stage I and II glacial advances. Lateral glaciofluvial outwash channels and fans are present beyond and adjacent to the moraines that define the former ice limits. A series of subparallel moraine ridges and hummocks is present within the outer moraines. Depressions within stage I and II moraines are filled with sands and silts. These probably represent small ponds that developed within moraine depressions and areas of stagnant ice. The glacial landforms in this region are similar to those associated with debris-mantled glaciers described by Benn and Owen (2002).

Smaller (20 m high), more subdued moraine ridges are present at elevations of ~3000 m asl. These are assigned to stage III. Above stage III moraines small bouldery ridges are found within a few hundred meters of the head of each valley at an elevation of 3050 m asl. Using a reconstruction of the ice and/or snow thickness at these headward sites based on our geomorphic mapping, we calculated a basal shear stress of ~50–60 kPa beneath the former ice and/or snow accumulation. Because shear stresses at the base of glaciers range from 40 to 120 kPa (Paterson, 1994), it is likely that these landforms are moraines rather than boulder accumulations at the toes of thickened snow packs. These landforms are therefore interpreted as small moraines that formed during a minor glacial advance that we call stage IV.

COSMOGENIC RADIONUCLIDE EXPOSURE AGES

The CRN dates are listed in Table 1 (see footnote 1) and plotted in Figure 2. There is strong agreement between ages of boulders within individual moraines. The dates cluster into four groups: stage I, 18–20 ka; stage II, 15–16 ka; stage III, 12–13 ka; and stage IV, 5–9 ka. With the exception of stage IV moraines, the tight clustering of CRN ages suggests that inheritance is not a significant prob-

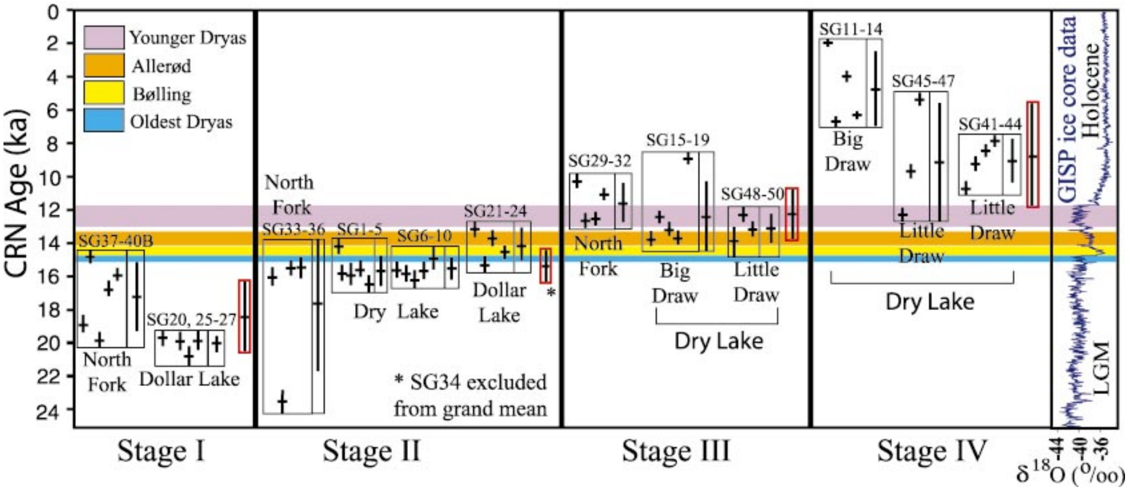

Figure 2. Cosmogenic radionuclide dates (CRN) plotted for each glacial stage. Boulders dated from individual moraines are enclosed within box. Attached box to right of each box shows mean values and standard deviation. Red boxes enclose grand mean and standard deviations for all boulders dated from each glacial stage. GISP—Greenland Ice Sheet Project; LGM—Last Glacial Maximum.

lem in this data set. One notable exception, however, is boulder SG28, which has an age of 32 ka, and has not been included in calculations shown in Figure 1. Furthermore, these data also suggest that weathering, toppling, and/or exhumation are not significant.

DISCUSSION

We follow the view of Zreda and Phillips (1995) that CRN ages on boulders on the crests of moraines define the timing of millennial-scale glaciation. However, the boulders that we sampled were from the crests of large latero-frontal moraines that may represent significant periods (many millennia) of formation and may even represent several glacial advances (cf. Benn and Owen, 2002). This view is partially supported by the absence of stage I dates on the outermost moraines in the Dry Lake region. We believe that the tight clustering of ages (ca. 16 ka) on this moraine shows that a glacier advanced over the stage I moraines during stage II in this valley. This view is supported by the impressive ~80-m-high latero-frontal moraine. In other valleys stage I moraines are present and are morphostratigraphically distinct from stage II moraines; this suggests that stage II represents a distinct glacial advance.

The stage I glacial advance dated as 18–20 ka was coincident with the global LGM and was the most extensive advance in the region with glaciers extending for $\leq$4 km. However, the presence of stage II ages of 15–16 ka on the latero-frontal moraine in the Dry Lake region suggests that stage II was similar in magnitude to stage I. Apparently progressive glacial advances of debris-mantled glaciers resulted in later glaciers impinging on previously deposited moraines to form complex landforms. Stage II moraines dated to 15–16 ka indicate the presence of glaciers $\leq$3 km in length and correlate broadly with latter part of the LGM. Stage III moraines, 12–13 ka exposure age, represent a glacial episode that correlates broadly with the Younger Dryas Stade (11.6–12.9 ka), with glaciers advancing $\leq$1 km. The stage IV moraines, 5–9 ka, represent an early to middle Holocene glaciation, with glaciers $<$0.5 km in length.

The glacial advances on San Gorgonio Mountain are coincident with glacial advances in other regions of the American Cordilleras (Clark and Bartlein, 1995; Lowell et al., 1995; Clapperton, 2000). This supports the view of interhemispheric synchroneity of glacier fluctuations and provides an important link between the glacial chronologies of the Western Cordillera of North America and the mountains of Central and South America. Bradley (1999) summarized literature showing that mountain glaciers at temperate latitudes reached their greatest extent slightly after the LGM (ca. 15–16 ka), essentially coincident with Heinrich Event 1. The glacial chronology of the San Bernardino Mountains glacial record appears to reflect this, particularly the deposits of stage II, which are dated as ca. 15–16 ka.

Our conclusion that the stage III advance on San Gorgonio Mountain occurred partly during the Younger Dryas Stade can be compared with CRN dates of Younger Dryas age for moraines in Alaskan Ranges and Wind River Mountains of Wyoming (Gosse et al., 1995; Briner et al., 2002). However, it contrasts with the Sierra Nevada, where unequivocal evidence for an advance during the Younger Dryas Stade has not been found (Clark and Gillespie, 1996).

The broader spread of ages on stage IV moraines might reflect multiple Holocene global events. For example, this glacial advance might overlap with the ca. 8.5 ka cooling event, evident in the Greenland ice cores (Alley et al., 1997), caused by catastrophic drainage of the Laurentide lakes into the North Atlantic at 8.47 ka (Barber et al., 1999). It might also include younger deposits from the Neoglacial (4–5 ka).

In other regions of the American Cordillera, glaciation was most extensive during the early part of the last glacial cycle (Phillips et al., 1996), but our study found no evidence of a more extensive glacial advance before the LGM, e.g., during the solar minimum of marine oxygen isotope stage 4. This might be due to the lack of preservation of landforms and/or sediments. Alternatively, ongoing Quaternary uplift rates in the transverse ranges (Spotila et al., 1998; Blythe et al., 2000; Cox et al., 2003) might not have raised these mountains high enough to support large glaciers before the LGM. Given that glaciation after the LGM occurred synchronously on the San Bernardino Mountains and distant regions along the American Cordilleras, it seems unlikely that glaciogenic climates were latitudinally any less widespread earlier in the last glacial.

PALEOCLIMATE IMPLICATIONS

Small mountain glaciers are particularly sensitive to climatic change, and hence the timing and extent of former alpine glaciation can be used as proxies for estimating paleoclimate (Bradley, 1999; Porter, 2001). The usual procedure is to use former glacier extent to reconstruct equilibrium-line altitudes (ELAs). Clark et al. (1994) and Benn and Lehmkuhl (2000), however, highlighted the problems associated with reconstructing former ELAs for debris-mantled glaciers in high mountain regios. Nevertheless, we calculated former ELAs for each glacial stage in an attempt to examine the nature of paleoclimatic change in the region (Table 2; see footnote 1). The calculated ranges of ELA depressions (ΔELA) (and changing mean July temperature) are 1200–1980 m (8.3–13.8 °C), 955–1925 m (6.6–13.3 °C), 900–1710 m (6.0–11.1 °C), and 950–1660 m (6.5–10.6 °C) for stages I, II, III, and IV, respectively.

Our modeled ΔELA and resulting past temperature differences are both unexpectedly large. For example, a July temperature reduction of 8–14 °C on San Gorgonio Mountain during the LGM (stage I) is on the high side of estimates based on packrat middens in the Sonoran Desert that suggest cooling of only 8 °C (Van Devender, 1990). Our estimate is likewise inconsistent with packrat data indicating that mean annual temperature decreased by only 6 °C in the Mojave Desert during the LGM (Spaulding, 1990). Furthermore, our ΔELA for stage I contrasts with measurements in the Sierra Nevada that suggest that the ΔELA was ~800 m (Burbank, 1991). The temperature depressions for the other stages are also large and, in particular, an early to middle Holocene temperature difference of 6–10 °C seems highly unrealistic.

The untenably large ΔELAs we determined may indicate that effects other than cooling influenced glacial extent in the study area. In particular, the large lateral transport of snow by southwesterly winds and by avalanching on the north- and northeast-facing slopes of San Gorgonio Mountain (Minnich, 1984) may have amplified the effects of lower temperature. It is important to note, in this respect, that winter storms in these mountains are always accompanied by high winds of the jet stream, and by oblique to horizontal snowfall on the exposed ridgelines and summits. Furthermore, windward slopes, down to the tree line, are virtually snow free all winter. The amount of snow on leeward slopes during recent time was partially quantified by Minnich (1984, 1986). During the above-normal precipitation years of 1969, 1978, 1980, and 1993, the snow-water content on May 1 at 3000 m asl on Big Draw snowcourse, where there is little snow transport, was 150 cm, with final snow melt about July 15. The melt rate from May 1 to July 14 was thus ~2.0 cm/day. Cornice and/or avalanche snows also persisted throughout the summer during those years, until late September. At 2.0 cm melt per day, the water content of perennial snowfields was a minimum of 300 cm. From a paleoclimatic perspective, if we hypothesize that LGM mean precipitation was 150% of the present amount (Spaulding, 1990), there would likely have been a significant increase in snow transport and perennial snow because the increase in precipitation is coupled with an increased seasonal presence of the jet stream above southern California. High winds would be more frequent and stronger due to steeper latitudinal temperature gradients. From modern observations, we know that a wet year (150% of a normal current normal year with mean of 150 cm) will yield perennial snow, even with today's mean July temperatures of 10–12 °C. However, during glacial times, lateral redistribution of an equivalent amount of precipitation would produce 225 cm of water content on north- and northeast-facing slopes and 450 cm in cornice and/or avalanche zones. Extreme wet years would have correspondingly significant increases in snow deposition, with possible repercussions on glacier mass balance continuing for years or decades.

Perennial snow patches after wet winters on the north and northeastern slopes of San Gorgonio Mountain support this view (Fig. DR1; see footnote 1). Snow transport was vital to the maintenance of glaciers because north-facing slopes receive about as much sun in the melt season (May to August) as south-facing slopes. In addition, the mean summer temperature of air masses above modern Sierra Nevada glaciers, all of which are north and northeast facing and have sizes similar to those on San Gorgonio Mountain during the LGM, is 6–8 °C, or ∼5 °C warmer than estimates from a regression of annual precipitation and summer temperature (Ohmura et al., 1992). The regression also predicts that the annual precipitation necessary to support Sierra Nevada glaciers at 6–8 °C is 250–300 cm. Because the mean annual precipitation on Sierra Nevada glaciers is only 75–100 cm (California Department of Water Resources, 1980), these glaciers must be sustained by an additional 150–200 cm of snow deposited via wind transport and/or avalanching. A regression estimate of 300 cm for perennial snowfields on San Gorgonio Mountain is consistent with mean summer temperatures of 10–12 °C. These data and calculations show that it is inappropriate to use ΔELA to reconstruct past temperatures. Furthermore, they support the view that lateral snow transport is vital in sustaining marginal glaciers.

The increased precipitation, and hence glaciation, on San Gorgonio Mountain is likely the result of a southward migration of the midlatitude westerly jet stream, which is controlled by fluctuations in the Northern Hemisphere ice sheets and oceans. This link between the cryosphere, hydrosphere, and atmosphere helps explain the synchroneity of glaciation in the San Bernardino Mountains with other places in the American Cordilleras.

CONCLUSION

This study presents the first CRN dates to define the timing of glaciation in the southwesternmost glaciated area (San Gorgonio Mountain) of the Western Cordillera of North America, and fills an important gap in the glacial chronologies within the central region of the American Cordilleras. Four glacial advances are correlated with the global LGM (18–20 ka, stage I), the Late Glacial (15–16 ka, stage II), the Younger Dryas (12–13 ka, stage III), and early-middle Holocene (5–9 ka, stage IV). These glacial advances are synchronous with glaciation elsewhere in the American Cordilleras, which supports the view that mountain glaciation was synchronous between the Northern and Southern Hemispheres. Glaciation on San Gorgonio Mountain was strongly controlled by topography and precipitation, and shows the importance of high snow advection rates and snow transport in sustaining glaciers in marginal glaciated regions.

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