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Mountain glaciers, because of their small size, are usually close to equilibrium with the local climate and thus should provide a test of whether temperature oscillations in Greenland late in the last glacial period are part of global-scale climate variability or are restricted to the North Atlantic region. Correlation of cosmogenic chlorine-36 dates on Sierra Nevada moraines with a continuous radiocarbon-dated sediment record from nearby Owens Lake shows that Sierra Nevada glacial advances were associated with Heinrich events 5, 3, 2, and 1.

During the last glacial period, the climate in the North Atlantic region was characterized by a sequence of quasi-cyclical fluctuations (*1*). Combined ice core and marine sediment core evidence indicates that during periods ranging in duration from about 500 to 2000 years the climate became progressively colder. The maxima of these Dansgaard-Oeschger cycles were often marked by the expulsion of large numbers of icebergs from the ice caps surrounding the North Atlantic (Heinrich events) (*2*). The iceberg expulsions were rapidly followed by abrupt warming. The cold episodes culminating in Heinrich events have been postulated to be the cause of mountain glacier advances in western North America (*3*) and elsewhere (*4*).

This hypothesis has proved difficult to test, in large part because of the difficulties in dating moraines by ^{14}C and other conventional approaches. Cosmogenic nuclide methods (*5*) can be used to directly date moraines (*6*, *7*), but various uncertainties (*8*, *9*) render tenuous direct chronological comparisons with millennial-scale events such as iceberg discharges.

An alternative approach that circumvents these difficulties is to investigate continuous and datable sedimentary records in environments associated with mountain glaciers. Although the sediment-based approach provides a nearly continuous record, it must use indirect proxies for glacial extent. Here we test glacial proxies in a sediment record from Owens Lake, California (*10*), by comparing the ^{14}C chronology of the proxies with direct ^{36}Cl ages of Sierra Nevada moraines.

The Owens River drains the eastern flank of the Sierra Nevada (Fig. 1). All of the major valleys originating from the Sierra Nevada contain late Pleistocene moraine complexes showing that the altitude of the equilibrium line was ~1000 m lower (*11*). The characteristics of sedimentation in Owens Lake should therefore have been sensitive to changes in the magnitude of discharge and type of sediment load produced by glaciation, particularly the release of large amounts of rock flour by glacial meltwater. Benson *et al.* (*10*) used increases in magnetic susceptibility and decreases in inorganic carbon, organic carbon, and carbonate δ^{18}O as indicators of glacial advance.

We have used cosmogenic ^{36}Cl buildup (*12*) to date late Pleistocene moraines in four drainages (Fig. 1). Two of the drainages, Bishop Creek and Little McGee Creek, are tributary to the Owens River. Bloody Canyon drains into Mono Lake and is about 20 km north of the headwa-

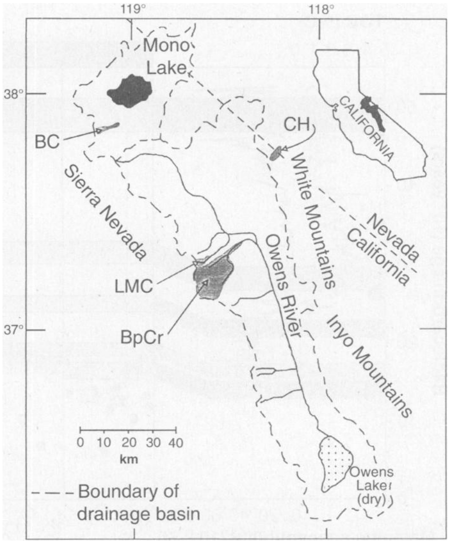

Fig. 1. Location of Owens River drainage basin and valleys where moraines were dated with the use of cosmogenic ^{36}Cl. CH = Chiatovich Creek, BC = Bloody Canyon, LMC = Little McGee Creek, and BpCr = Bishop Creek.

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ters of the Owens River. Chiatovich Creek is on the eastern side of the White Mountains, the range immediately east of the Sierra Nevada. All four drainages contain complex sequences of late Pleistocene moraines (Fig. 2).

The largest boulders available on the crest of each moraine (Fig. 2) were sampled by hammer and chisel close to the center of their top surfaces. The samples were processed and analyzed for ^{36}Cl by standard methods (*13*). Ages were calculated for rock-surface erosion rates of 0 and 5 mm/ka (Fig. 2 and Table 1) (*14*).

If all of the boulders sampled on a single moraine had the same history, except for variable rock erosion rates, then all samples should show mutual overlap within some part of the age range indicated by the erosion calculations. Instead, boulders from a single moraine usually show scatter toward young ages because soil erosion progressively exposes boulders after moraine deposition (*8*). We have therefore interpreted the overlapping range of ages that cluster at the maximum end of the range for each moraine as the depositional age (*15*).

The data (Fig. 2) show that the younger moraines in the Sierra Nevada yield ^{36}Cl ages for major advances at 49 ± 2, 31 ± 1, 25 ± 1, 19 ± 1, and 16 ± 1 ka. Comparison of this chronology, after conversion to the radiocarbon time scale (*16*), with the magnetic susceptibility and organic carbon content curves from Owens Lake demonstrates that the proxy indicators for glaciation accurately record glacial advances (*17*). Furthermore, the advances for which moraines are preserved are those having the strongest signals in the sedimentary record. The Tioga 2 advance at 22 ± 1 ^{14}C kyr has the lowest equilibrium line altitude (ELA) of any Tioga advance and correlates with the maximum magnetic susceptibility (χ) signal in Owens Lake. The advance having the next lowest ELA, Tioga 3, corresponds to the second largest peak in χ. The moraine position shows that the Tioga 1 advance was relatively minor and was probably preserved at Little McGee Creek only because of faulting. The core evidence from Owens Lake is consistent with a relatively minor advance. This correspondence supports the inference from the Owens core data that there were a series of minor glacial advances between 40 and 25 ^{14}C kyr that are not recorded by moraines, presumably because the moraines were overridden by the later, more extensive advances.

These glacial events in the Sierra Nevada appear to be temporally related to climatic cycles in the North Atlantic and elsewhere. The earliest advance, at 49 ± 2 ka, was close to the time of Heinrich event 5 (H5) [43 ka on the GRIP time scale (*18*) and about 47 ka on the GISP2 scale (*19*)], although uncertainties in both ^{36}Cl and ice core chronologies at this age range do not permit any close correlations. No moraines correlative to H4 were dated. The Owens Lake core (Fig. 2) indicates that this was an extended interval of limited glacial extent in the Sierra Nevada, and any moraines associated with H4 were probably destroyed by subsequent, more extensive advances. The Tioga 1 advance at 28 ± 1.5 ^{14}C kyr appears to have slightly preceded H3, and the Tioga 2 advance seems to have slightly preceded H2, although the ^{14}C chronologies of neither the marine nor the Owens Lake cores are sufficiently precise to permit unambiguous distinction of phase relations. The Tioga 2 advance appears to have been a critical transition point in the climate system. After this advance, the climate did not return to the previous oscillatory pattern but rather locked into a full glacial mode. This pattern of rapid increase in glacial extent beginning at about 23 ^{14}C kyr strongly resembles that inferred for global ice volume from Huon Peninsula terraces (*20*) and ^{18}O in tropical ocean cores (*21*). The Tioga 3 advance clearly immediately preceded H1, and the Tioga 4 advance at ~14.5 to 13 ^{14}C kyr probably included at least the latter half of H1. The extent of both lakes and glaciers was apparently large, but not maximum, during the time preceding H1. At close to the initiation of H1 (15 to 14.5 ^{14}C kyr), the glaciers retreated suddenly, and Owens Lake shrank to near desiccation [less than half of the modern (*22*) surface area], but by the end of H1, the glaciers had readvanced and the Owens River lacustrine system rapidly refilled to peak late Pleistocene levels (*23*) (more than five times the modern surface area). The peak in both glacial and lacustrine extent was apparently brief.

The above summary indicates that although expansions of Sierra Nevada glaciers were apparently related to Heinrich events, the relation was probably not one of simple synchronicity. Rather, Sierra Nevada glacial advances, in the case of H1 at least and possibly the other events, slightly preceded the Heinrich events, and during the events, the water balance may have oscillated strongly. The Owens Lake record (*10*) may also indicate a similar pattern for the smaller iceberg discharge events (*1*) between H5 and

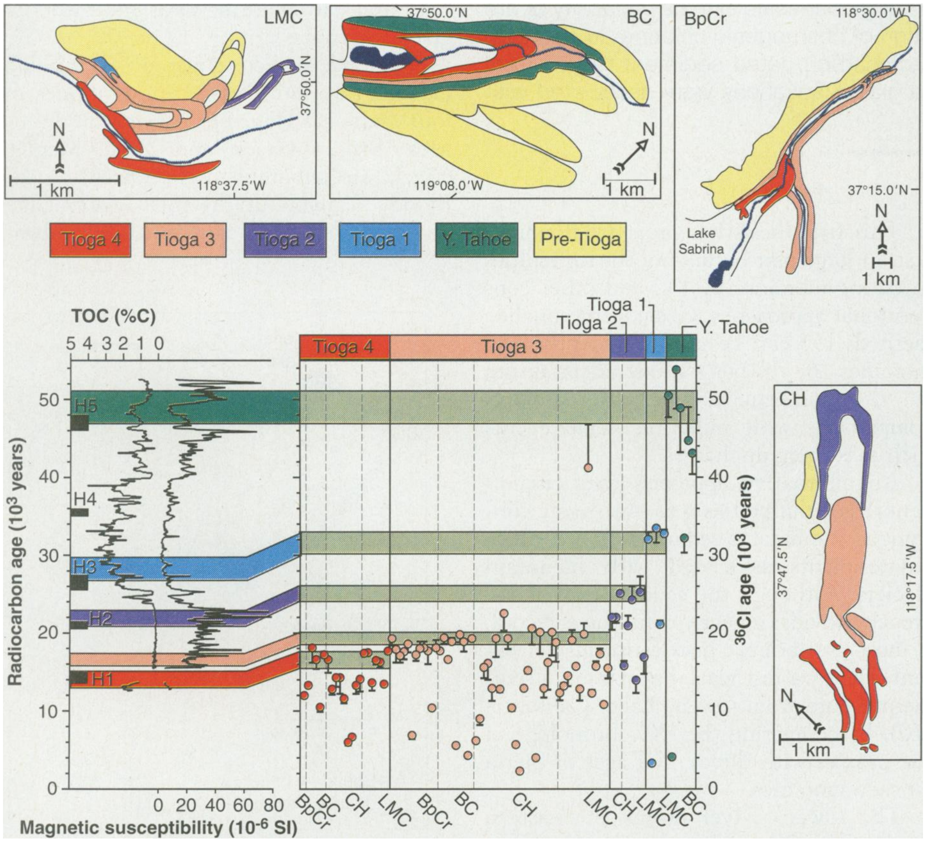

Fig. 2. Chlorine-36 age distributions compared with proxies for glacial extent from Owens Lake sediments from (*9*). Peaks in the proxy records are interpreted as indicating extensive glaciation. Moraine maps and corresponding ^{36}Cl ages are color coded. Bloody Canyon (BC) map modified from (*6*), Bishop Creek (BpCr) from (*26*), and Chiatovich (CH) from (*27*). Dots indicate ^{36}Cl ages assuming zero rock erosion rate, and bars indicate the ages assuming a 5-mm/ka erosion rate.

Table 1. Chlorine-36 ages for boulders on Sierra Nevada moraines, for assumed rock erosion rates varying from 0 to 5 mm/ka.

Sample	^{36}Cl age (ka)	
	0 mm/ka	5 mm/ka
Bishop Creek: Tioga 3		
91-11	20.3	19.8
90-22	18.1	19.1
90-23	10.4	10.5
90-24	17.7	16.0
90-25	18.1	18.9
90-26	18.8	18.9
91-1	17.2	16.4
91-2	6.9	6.4
91-3	18.6	17.5
91-4	17.6	16.6
90-73	17.1	16.2
90-74	17.9	16.2
90-75	19.3	18.4
91-5	14.9	14.2
91-6	19.8	18.2
91-7	29.7	24.6
91-8	22.4	24.3
90-19	19.7	20.6
90-20	18.8	19.6
90-21	15.9	16.6
Chiatovich Creek: Tioga 4		
C87-1	14.1	12.5
C87-2	13.3	12.2
C87-3	6.7	6.4
C87-4	6.0	5.6
C287-5	11.6	11.0
C287-6	14.3	12.2
C387-1	14.3	13.1
C387-2	12.8	12.1
C387-3	16.6	14.9
Chiatovich Creek: Tioga 3		
C587-1	18.8	16.3
C587-2	20.1	17.1
C587-3	16.2	12.7
C787-1	12.9	11.7
C787-2	20.1	17.3
C787-3	4.0	3.9
C7b87-1	20.6	18.5
CH89-P12	15.2	14.8
CH89-P12-1	12.9	12.8
CH89-P22-1	2.3	2.2
CH89-P22-2	5.7	5.6
CH89-P22-3	10.4	10.0
CH89-P23-1	19.3	17.9
CH89-P23-2	22.5	20.3
CH89-P23-3	12.8	12.4
C1187-1	19.3	16.9
C1187-2	12.9	11.3
C1187-3AW	16.1	14.0
C1287-1AW	15.6	14.2
C1287-2	9.0	8.2
C1287-3	6.2	6.0
Chiatovich Creek: Tioga 2		
CH89-P8-1	25.1	25.1
CH89-P8-2	22.0	21.3
CH89-P8-3	22.0	20.4
Little McGee: Tioga 4		
LMC88-6	16.7	16.8
LMC88-7	16.7	16.9
LMC86-1	13.0	12.1
LMC86-2	15.8	15.3
LMC86-3	15.6	15.0
LMC86-4	12.9	13.0
LMC86-5	16.9	16.6
Little McGee: Tioga 3		
LMC90-12	11.9	11.0
LMC90-13	12.6	12.9
LMC90-14	14.1	12.8
LMC90-15	10.4	10.5
LMC90-16	15.0	15.3
LMC90-17	12.4	11.0
LMC90-19	15.0	13.8
LMC90-21	39.3	44.3
LMC90-23	11.7	12.1
LMC90-24	15.0	15.6
LMC90-25	16.5	17.1
LMC90-26	18.1	19.3
LMC90-27	18.9	20.1
Little McGee: Tioga 2		
LMC91-3	15.1	15.6
LMC91-4	20.0	21.2
LMC91-5c	23.1	24.7
LMC91-6	13.5	11.9
LMC91-7	24.1	25.9
LMC91-8	16.4	14.3
Little McGee: Tioga 1		
LMC86-6	30.6	31.4
LMC86-7	3.2	3.2
LMC86-8	32.0	30.3
LMC86-9	20.2	20.6
LMC86-10	31.3	31.8
Bloody Canyon: Tioga 4		
BC86-1	17.2	17.6
BC86-2	10.5	9.9
BC87-3	16.6	15.4
BC86-5	18.1	16.2
BC90-5	13.3	13.6
Bloody Canyon: Tioga 3		
BC86-6	19.3	19.2
BC86-7	4.3	4.2
BC86-8	18.9	17.6
BC86-9	19.8	18.8
BC86-10	5.6	5.6
BC86-11	18.9	19.4
BC90-1	16.6	16.5
BC90-2	19.4	18.6
BC90-3	17.7	17.5
Younger Tahoe		
BC87-1	43.1	40.8
BC87-2	44.7	49.0
BC87-3	32.2	30.3
BC87-4	48.9	43.3
BC87-5	53.8	49.5
BC88-1	4.1	4.0
BC88-5	50.5	49.0

H3. Although the nature of the climatic linkages remains to be explained, the close association of both glacial and lacustrine fluctuations in western North America with these events supports the hypothesis that they were of global scale.

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13. The samples were leached in deionized water to remove meteoric ^{36}Cl and were dissolved in hydrofluoric acid; the Cl precipitated as AgCl. Detailed methods and sample location maps are given in (*24*). The rocks were also analyzed by standard methods for major elements: Cl, Gd, and B, and in some cases U and Th. Complete data are given in (*24*). Data for the Bloody Canyon moraines were published previously (*6*). Chlorine-36 was analyzed by accelerator mass spectrometry [D. Elmore *et al.*, *Nature* **277**, 22 (1979)] at the Purdue Rare Isotope Measurement Laboratory, Purdue University. Exposure ages were calculated with ^{36}Cl production constants determined by F. M. Phillips, M. G. Zreda, M. R. Flinsch, D. Elmore, and P. Sharma [*Geophys. Res. Lett.* **23**, 949 (1996)]. Production rates were assumed to be constant with time. Production by thermal neutrons was calculated using the approach of B. Liu, F. M. Phillips, J. T. Fabryka-Martin, M. M. Fowler, and W. D. Stone [*Water Resour. Res.* **30**, 3115 (1994)], and epithermal neutron production was also incorporated with an analogous approach. Background ^{36}Cl production by neutrons from U and Th in the rock was calculated using the approach of J. T. Fabryka-Martin [thesis, University of Arizona (1988)].
14. Here we use the convention of "ka" to refer to ages on the ^{36}Cl and ice core time scales (1 ka = 1000 years) and "^{14}C kyr" to refer to the ^{14}C time scale (1 ^{14}C kyr = 1000 carbon-14 years).
15. Modeling [M. G. Zreda, F. M. Phillips, D. Elmore, *Water Resour. Res.* **30**, 3127 (1994)] has shown that, in the age range considered here, effects of thermal neutron production will not cause significant overestimation of maximum ages. Hallet and Putkonen (*25*) have argued that moraine and rock-surface erosion may produce anomalously young moraine ages. Their analysis is not applicable for the samples reported here because (i) they did not account for production of ^{36}Cl by thermal neutrons, which counters age bias due to rock weathering; (ii) the average size of boulders we sampled (1 to 4 m) was much larger than they assumed (0.5 m); and (iii) even if their analysis were correct, the effects would be small in the age range considered here [figure 2B of (*25*)].
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