was defined by the length times the width. Total length covered by the PGFs is ~500 km. Width, the distance from the fault, 10 km on the footwall side and 50 km on the hanging wall side, was based on mislocation uncertainty of 10 km [R. Arvidsson and R. Wahlström, *Swedish Nuclear Fuel Waste Manage. Tech. Rep. 93-13* (1993)] and surface projection of a 45° dipping fault in a 40-km-deep crust. The area covered by postglacial earthquakes, about 6% of the area east of the dotted line in Fig. 1, contains 48 out of 99 earthquakes, of the investigated area. The statistical probability of this occurrence, estimated as a Poisson process, is almost zero.

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Climatic and Hydrologic Oscillations in the Owens Lake Basin and Adjacent Sierra Nevada, California

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Oxygen isotope and total inorganic carbon values of cored sediments from the Owens Lake basin, California, indicate that Owens Lake overflowed most of the time between 52,500 and 12,500 carbon-14 (^{14}C) years before present (B.P.). Owens Lake desiccated during or after Heinrich event H1 and was hydrologically closed during Heinrich event H2. The magnetic susceptibility and organic carbon content of cored sediments indicate that about 19 Sierra Nevada glaciations occurred between 52,500 and 23,500 ^{14}C years B.P. Most of the glacial advances were accompanied by decreases in the amount of discharge reaching Owens Lake. Comparison of the timing of glaciation with the lithic record of North Atlantic core V23-81 indicates that the number of mountain glacial cycles and the number of North Atlantic lithic events were about equal between 39,000 and 23,500 ^{14}C years B.P.

Evidence of rapid oscillations in air and sea surface temperatures during the last glacial period have been recognized in ice cores from Greenland (*1*) and sediment cores from the North Atlantic (*2, 3*). Layers of lithic fragments rich in carbonate debris (Heinrich layers) have been found in sediment cores from the temperate North Atlantic and appear to be linked to the dynamics of the Laurentide Ice Sheet and other Northern Hemisphere ice sheets by the discharge of icebergs into the North Atlantic (*3–5*). The last four Heinrich events occurred at the end of progressive decreases in sea surface and air temperatures (Dansgaard-Oeschger cycles) and were followed by rapid warmings.

Several authors have attempted to link proxy records of climate change from other areas of the world to Dansgaard-Oeschger cycles and Heinrich events (*6*). In particular, it has been suggested that alpine glaciers in the Rocky Mountains advanced to their terminal areas up to several thousand years before a Heinrich event and retreated soon thereafter (*7*). However, limitations in chronology and sampling resolution have made it difficult to demonstrate that North Atlantic climatic oscillations were synchronous with climatic and hydrologic oscillations in other regions. Here we present continuous, well-dated, high-resolution proxy records of climate change in the Owens Lake basin and compare them with the North Atlantic lithic record documented in core V23-81 (*8*).

Owens Lake is located in the Great Basin of the western United States between the central Sierra Nevada and Inyo-White mountain ranges (Fig. 1). Cool-season orographic precipitation in the Sierra Nevada, mostly from North Pacific sources, supplies >99% of the runoff reaching Owens basin (*9*).

Sediment cores OL90-1 (length, 32.75 m) and OL90-2 (28.20 m) were obtained from the Owens Lake basin in 1990 (Fig. 1) (*10*). Age control for OL90-2 was based on 26 accelerator mass spectrometry (AMS) ^{14}C determinations made on the total organic carbon (TOC) fraction of the cored sediment (Fig. 2) (*11*). Age control for OL90-1 was obtained by matching 30 magnetic susceptibility (χ) features common to both cores. The OL90-2 ^{14}C age–depth polynomial was then applied to OL90-1. A continuous set of sediment samples, 5 to 6 cm in length, was taken from the two cores. Total carbon (TC), total inorganic carbon (TIC), and $\delta^{18}O$ values were determined on each sample (*12*).

To determine if abrupt changes in climate affected the hydrologic balance of the Owens Lake basin, we examined the $\delta^{18}O$ and TIC records (Fig. 3). The $\delta^{18}O$ value (*13*) of a lake represents a balance between amounts and $\delta^{18}O$ values of water input to and lost from a lake. When Owens Lake

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overflowed, $\delta^{18}O$ was primarily a function of the outflow:inflow ratio. When the residence time of water in the Owens Lake basin approached zero, the $\delta^{18}O$ of Owens Lake approached the $\delta^{18}O$ value of inflow (calcite precipitated from a 15°C lake in which the outflow:inflow ratio approaches unity would have a $\delta^{18}O$ value of ~15 per mil). Under steady-state conditions, the $\delta^{18}O$ value of a hydrologically closed Great Basin lake would be highly enriched (calcite precipitated from a 15°C lake would have an $\delta^{18}O$ value of ~30 per mil) (*14*).

Between 52,500 and 15,500 years before present (B.P.), $\delta^{18}O$ values determined on the TIC fraction of Owens Lake sediment are generally low (<22 per mil) (Fig. 3), indicating that Owens Lake overflowed most of this time (*15*). Isotopic values are relatively low between 40,000 and 30,000 years B.P., reflecting a climate that was extremely wet (low values also occur at 28,500 and 26,500 years B.P.). Before and after the interval characterized by extremes in $\delta^{18}O$ minima, $\delta^{18}O$ values reflect drier climates: For example, between 52,500 and 40,000 years B.P. there are several $\delta^{18}O$ maxima that denote brief periods of intermittent closure (C_1 to C_8). Owens Lake receded below the elevation of the core site and may have desiccated between <15,500 and 13,700 years B.P. (*16*). An abrupt decrease in $\delta^{18}O$ at 13,300 years B.P. culminated in extremely low $\delta^{18}O$ values at 13,000 years B.P., indicating a profound increase in wetness.

Chemical weathering of granitic Sierran rocks results in an Owens River composition dominated by Na, Ca, and HCO_3^- (*9*). When Owens Lake was closed, all dissolved Ca (and an equal amount of CO_3^{2-}) entering Owens Lake precipitated as $CaCO_3$. During overflow, some Ca and HCO_3^- were lost from the basin; the greater the outflow:inflow ratio, the greater the loss of Ca. If influx of detrital silicates remained constant, increases in the fraction of $CaCO_3$ (TIC) should have paralleled increases in $\delta^{18}O$. Thus, comparison of TIC and $\delta^{18}O$ records should allow us to determine times of uneven accumulation of detrital silicates.

First-order trends in TIC and $\delta^{18}O$ parallel each other between 40,000 and 26,000 years B.P., but only a few TIC and $\delta^{18}O$ maxima are coeval. Between 52,500 to 40,000 and 26,000 to 15,500 years B.P., variations in TIC and $\delta^{18}O$ are not synchronous, and the percentage of TIC is typically low, indicating that detrital sediments have obscured the TIC signal (Fig. 3). A combination of scanning electron microscopy, x-ray diffraction, and grain-size data indicates that the detrital material is rock flour (fine silt) mainly transported to the Owens basin by glacial meltwater (*17*).

Magnetic susceptibility (χ) provides evidence for the timing of glaciation. The χ of Owens Lake sediment derives from the postdepositional alteration of detrital iron-bearing minerals (for example, magnetite and biotite) to greigite (Fe_3S_4) in anoxic

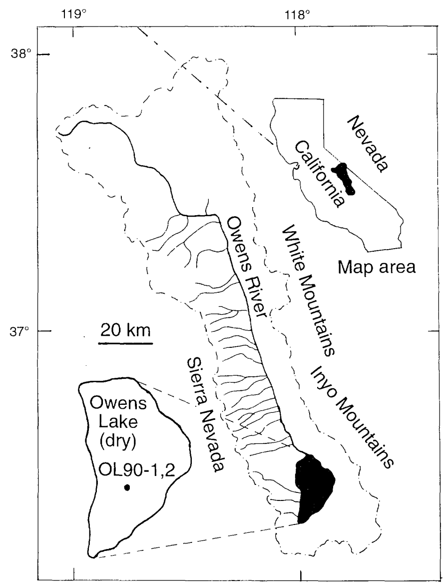

Fig. 1. Location map of the Owens Lake basin (dash-dotted line). Cores OL90-1 and -2 were taken within 200 m of each other.

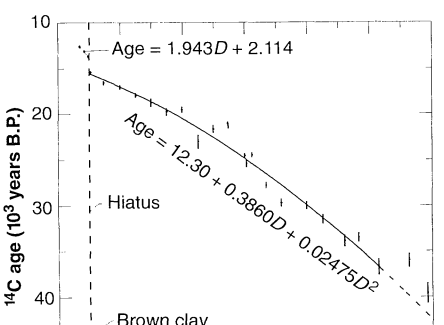

Fig. 2. AMS ^{14}C age control for core OL90-2. The ^{14}C age polynomial was not fit to ^{14}C ages of samples from depths $D > 25$ m. A hiatus in the sediment record (dashed line) occurs at a depth of 6 m. Ages have not been calibrated and are reported in ^{14}C years B.P.

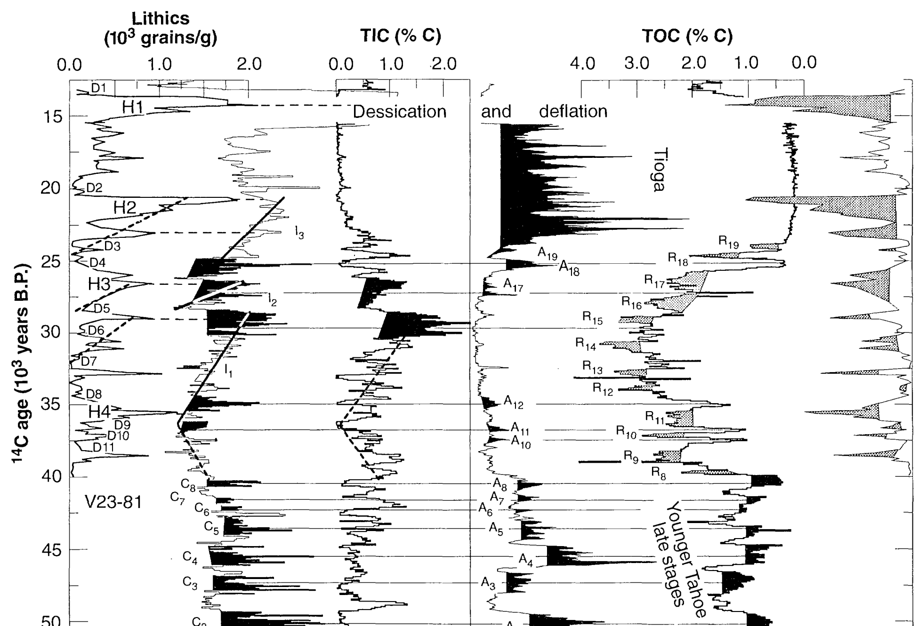

Fig. 3. The $\delta^{18}O$, TIC, TOC, and χ records from cores OL90-1 and -2 compared with the lithic record from North Atlantic core V23-81 for the period 52,500 to 12,500 years B.P. Greenland Dansgaard-Oeschger (D) warm events and Heinrich (H) events are indicated. Selected maxima in $\delta^{18}O$, TIC, χ, and minima in TOC are shown in black; maxima in TOC and lithics (from V23-81) are indicated in gray. Lithics are measured in number of grains >150 μm in size per gram of sediment. Trends in increasing $\delta^{18}O$ (decreases in wetness of the Owens Lake basin) are indicated by lines I_1 to I_3; Sierran glacial advances (peaks in χ) are labeled A_1 to A_{19}; Sierran glacial recessions (peaks in TOC) between 39,000 and 24,000 ^{14}C years B.P. are labeled R_8 to R_{19}. Periods of hydrologic closure of Owens Lake before 40,000 years B.P. are labeled C_1 to C_8. Correlations among the OL90-1 and -2 records are indicated by thin solid lines. Dashed lines indicate possible correlations between lake size minima and lithic events.

pore waters of Owens Lake (*18*); χ, therefore, should act as an indicator of the intensity of glacial erosion in the central Sierra Nevada. New cosmogenic ^{36}Cl age estimates of Sierra Nevada moraines (*19*), together with other age estimates of Tioga glaciations (*20, 21*), demonstrate that maxima in χ occur during advances of Sierran glaciers.

The oldest series of χ events (between 52,500 and 40,000 years B.P.) may indicate late-stage advances of the Younger Tahoe glaciation (*21, 22*). The eight oldest glacial advances (A_1 to A_8) occurred when relatively heavy $\delta^{18}O$ values indicate that the lake was intermittently closed (C_1 to C_8), suggesting that the climate was cold and relatively dry (Fig. 3). Between 40,000 and 23,500 years B.P., Owens Lake also experienced closure during glacial advances A_{10} to A_{12}, A_{17}, and A_{18}. The Tioga glaciation also occurred during a relatively dry period (23,500 to 15,500 years B.P.). There are moderate peaks in χ between 40,000 and 27,500 years B.P. that indicate the advance of an as-yet-unnamed series of minor glaciers during a relatively wet interval (*23*). The moraines resulting from these minor glacial advances were probably overridden during subsequent intense periods of early Tioga glaciation between 23,500 and 21,500 years B.P.

Between 52,500 and 23,500 years B.P., maxima in χ are coincident with minima in TOC (Fig. 3). The TOC minima likely resulted from decreases in biological productivity and dilution of the TOC fraction with glacially derived silt (*24*). For example, TOC concentrations were reduced to <0.3% during the Tioga glaciation. Maxima in TOC mark the occurrence of 11 glacial recessions (R_9 through R_{19}) between 39,000 and 24,000 years B.P. (Fig. 3).

One of our purposes was to determine whether records of climate change from the Owens basin could be objectively linked to North Atlantic climate events. At least 9 of the 11 glacial recessions discussed above appear to have occurred at the same time as lithic events recorded in V23-81 (Fig. 3). In addition, H2 occurred immediately after the most intense period of Tioga glaciation, and H1 may have occurred near the end of the Tioga. It is tempting to conclude that Sierran glacial recessions were coeval with periods of accelerated iceberg discharge to the North Atlantic; however, ^{14}C age controls for OL90-2 (Fig. 2) and V23-81 do not permit this conclusion (*25*).

What can be said is that the number of advances and retreats of Sierran glaciers is almost identical to the number of iceberg discharge events. Air temperature strongly affects the size of alpine glaciers. Lithic and foraminiferal records from V23-81 indicate that periods of increased iceberg discharge occurred near the ends of cooling cycles (*5*). It is, therefore, plausible to suggest that variability in air temperature over the Northern Hemisphere may have linked Sierran glacier cycles with iceberg discharge cycles in the North Atlantic. Whether different regions in the Northern Hemisphere experienced synchronous changes in air temperature remains an unanswered question.

A comparison of the Owens Lake hydrologic-balance proxy ($\delta^{18}O$) with the North Atlantic lithic record does not indicate a high degree of correlation (Fig. 3) (*26*). A dry period occurred during or after H1, and the Owens Lake basin was relatively dry during H2. Between 37,000 and 21,000 years B.P., there are three intervals (I_1 = 36,500 to 28,500; I_2 = 28,000 to 26,500; and I_3 = 25,000 to 20,500 years B.P.) where $\delta^{18}O$ values increase in a more or less regular manner, indicating progressive decreases in the frequencies and amounts of overflow. Increases in lithic deposition in the North Atlantic paralleled $\delta^{18}O$ increases during I_1, I_2, and the last half of I_3, but increase in iceberg discharge was a more discontinuous process than decrease in wetness of the Owens Lake basin. Only a few lithic maxima occur at the same time as $\delta^{18}O$ maxima, and there are numerous millennial-scale oscillations in the $\delta^{18}O$ record that have no corollary in the lithic record.

The results of this study indicate that before the Tioga glaciation, about 19 glacial cycles occurred with an average frequency of about 1500 years (*27*) and that glacial advances and retreats within the Tioga occurred with a frequency of <1000 years. Oxygen-18 and χ data suggest that the oldest part of the Owens Lake record (52,500 to 40,000 years B.P.) was characterized by relatively intense periods of glaciation that were accompanied by reductions in discharge to Owens Lake.

During the middle part of the record (40,000 to 28,000 years B.P.), χ maxima are relatively small, indicating that glacial advances were confined to high elevations. Oxygen-18 and χ data suggest that glacial advances in this part of the record also were accompanied by reductions in discharge to Owens Lake. The Tioga glaciation, which occurred during the most recent part of the record (28,000 to 15,500 years B.P.), was terminated by a severe drought that occurred during or immediately after H1. Comparison of the timing of glaciation with the lithic record of North Atlantic core V23-81 indicates that the number of mountain glacial cycles and the number of North Atlantic lithic events were about equal between 39,000 and 24,000 years B.P.

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10. Sediments from OL90-1 and -2 are mostly fine silts made up of quartz, feldspar, and biotite fragments. Some authigenic calcite is also present.
11. The AMS ^{14}C dates were determined at the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry; before analysis, all samples were pre-treated with dilute HCl to remove inorganic carbon.
12. Each sample (which integrates ~75 years of record) was repeatedly suspended in 40 ml of water and centrifuged, and the supernatant was decanted until its conductivity was less than three times that of tap water. The samples were then freeze-dried and homogenized. Magnetic susceptibility was measured every 2 cm with the use of a whole-core measurement sensor. The Inyo-White Mountains contain dolomite. If this dolomite was transported to Owens Lake, the measured TIC and $\delta^{18}O$ values would not be entirely representative of Owens Lake water; however, x-ray diffraction of several OL90-2 samples failed to indicate the presence of dolomite.
13. All $\delta^{18}O$ values are reported relative to the Vienna standard mean ocean water (VSMOW) standard.
14. Today the mean value of precipitation falling in the central Sierra Nevada is ~−14.5 per mil [L. V. Benson, *Limnol. Oceanogr.* **39**, 344 (1994)], and the $\delta^{18}O$ value of water evaporated from Pyramid Lake (~350 km north of the Owens basin) is ~−14 per mil (______ and J. W. C. White, *ibid.*, p. 1945). Thus, the steady-state $\delta^{18}O$ value of a closed lake that receives water from the central Sierra Nevada should be −0.5 per mil. The ^{18}O fractionation factor between calcite and water is ~30.5 at 15°C [J. R. O'Neil *et al.*, *J. Chem. Phys.* **51**, 5547 (1969)]; therefore, the $\delta^{18}O$ value of calcite precipitated from a closed lake would be ~30 per mil. When a lake overflows, its $\delta^{18}O$ value is primarily a function of the outflow:inflow ratio; an increase in this ratio causes a decrease in the $\delta^{18}O$ value of lake water. When this ratio approaches unity, the $\delta^{18}O$ value of lake water approaches the $\delta^{18}O$ value of precipitation (~−14.5 per mil). Calcite precipitated from this water would have a $\delta^{18}O$ value of ~16 per mil.

15. Overflow of Owens Lake occurs when wetness exceeds ~2.4 times the historical mean [H. S. Gale, *U.S. Geol. Surv. Bull.* **580-L**, 251 (1914)].
16. Discontinuities in the depth-age distribution of OL90-2 indicate a sediment hiatus between ~15,500 and 13,700 ^{14}C years B.P. Sediments at the base of the hiatus are characterized by features that indicate desiccation, including a 1- to 3-mm-thick lag deposit of frosted quartz grains. Removal of sediments by wave reworking or deflation implies that the 15,500-year age represents a maximum estimate of the initiation of desiccation.
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23. Values of $\delta^{18}O$ from 40,000 to 30,000 years B.P. are generally low, indicating a period in which precipitation fell as snow. The lack of pronounced glaciation during this interval is probably the result of relatively high warm-season (May through August) insolation [A. Berger and M. F. Loutre, *Quat. Sci. Rev.* **10**, 297 (1991)].
24. The introduction of glacially derived clay increased lake turbidity, decreasing photosynthetic production of organic carbon. Seasonal ice cover and decreased water temperatures also decreased productivity.
25. Radiocarbon age control for OL90-2 and V23-81 is no better than 500 to 1000 years. Thus, the time between maxima and minima in both records is of the same order as the composite ^{14}C error, implying that North Atlantic lithic events cannot be uniquely matched with advances or retreats of Sierran glaciers.
26. The lack of correlation between high-frequency events in the lithic and $\delta^{18}O$ records may derive from the fact that North Atlantic climate variability mainly depended on changes in air temperature (Dansgaard-Oeschger cycles), whereas the hydrologic balance of Owens Lake depended not only on air temperature but also on cloud cover, humidity, and precipitation [L. V. Benson, *U.S. Geol. Surv. Water Resour. Invest. Rep. 86-4148* (1986)]. The poor correlation may also result from the timing of carbonate precipitation. Precipitation is favored by warm water temperature and high concentrations of Ca^{2+} and CO_3^{2-}. These conditions occur in the late autumn when overflow is at a minimum and $\delta^{18}O$ values are high and not necessarily representative of average overflow conditions.
27. There are about 19 glacial cycles between 52,500 and 23,500 years B.P.; however, some of the older Tahoe advances (for example, A_2) may consist of more than one glacial cycle.
28. We thank J. Andrews, G. Bond, and S. Lehman for their excellent reviews and suggestions. W. C. McClung of Lake Minerals Corporation allowed us access to the coring sites. Support was provided by the U.S. Geological Survey Global Change Program, NSF, and a University of Southern California Faculty Research Innovation Fund grant. The work was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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Chronology for Fluctuations in Late Pleistocene Sierra Nevada Glaciers and Lakes

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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 $\delta^{18}O$ 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-

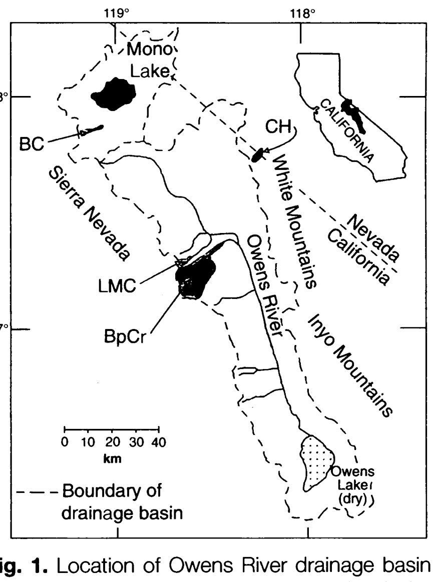

Fig. 1. Location of Owens River drainage basin and valleys where moraines were dated with the use of cosmogenic ^{36}Cl. CH = Chiatovich Creek, BC = Bloody Canyon, LMC = Little McGee Creek, and BpCr = Bishop Creek.

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