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## Correlation of Late-Pleistocene Lake-Level Oscillations in Mono Lake, California, with North Atlantic Climate Events

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# Correlation of Late-Pleistocene Lake-Level Oscillations in Mono Lake, California, with North Atlantic Climate Events

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Oxygen-18 ( $^{18}\text{O}$ ) values of sediment from the Wilson Creek Formation, Mono Basin, California, indicate three scales of temporal variation (Dansgaard–Oeschger, Heinrich, and Milankovitch) in the hydrologic balance of Mono Lake between 35,400 and 12,900  $^{14}\text{C}$  yr B.P. During this interval, Mono Lake experienced four lowstands each lasting from 1000 to 2000 yr. The youngest lowstand, which occurred between 15,500 and 14,000  $^{14}\text{C}$  yr B.P., was nearly synchronous with a desiccation of Owens Lake, California. Paleomagnetic secular variation (PSV) data indicate that three of four persistent lowstands occurred at the same times as Heinrich events H1, H2, and H4.  $^{18}\text{O}$  data indicate the two highest lake levels occurred  $\sim 18,000$  and  $\sim 13,100$   $^{14}\text{C}$  yr B.P., corresponding to passages of the mean position of the polar jet stream over the Mono Basin. Extremely low values of total inorganic carbon between 26,000 and 14,000  $^{14}\text{C}$  yr B.P. indicate glacial activity, corresponding to a time when summer insolation was much reduced. © 1998 University of Washington.

## INTRODUCTION

During the last glacial age, ice-core and marine records indicate that the climate of the North Atlantic region was characterized by alternating cool–warm intervals (Dans-

gaard–Oeschger cycles) that lasted between 500 and 2000 yr (Bond *et al.*, 1993; Bond and Lotti, 1995). The strongest of the cool intervals were often terminated by the massive discharge of icebergs (Heinrich events) from ice sheets surrounding the North Atlantic (Bond *et al.*, 1992; Broecker, 1994). Abrupt warming followed the Heinrich events. In recent papers (Benson *et al.*, 1996a, 1997a) it was shown that Owens Basin, California, was relatively dry during the occurrence of the North Atlantic region Younger Dryas (Heinrich event H0), Older Dryas, Oldest Dryas, and Heinrich H1 and H2 events.

Chemical records from sediment cores taken in Owens Lake, California, indicate that major advances of Sierran glaciers occurred between 52,500 and 12,500  $^{14}\text{C}$  yr B.P. (Fig. 1). The glacial advances appear to have been accompanied by decreases in the amount of water entering Owens Lake (Benson *et al.*, 1996a). These data indicate that the Owens Basin was cold and dry when the North Atlantic region was cold.<sup>1</sup> Unfortunately,  $^{14}\text{C}$  age controls for the

<sup>1</sup> During glacial advances, the total organic carbon content of Owens Lake decreased, indicating that productivity decreased in response to decreases in air and water temperatures and to decreases in light penetration that accompanied the input of turbid melt water. During some advances,  $\delta^{18}\text{O}$

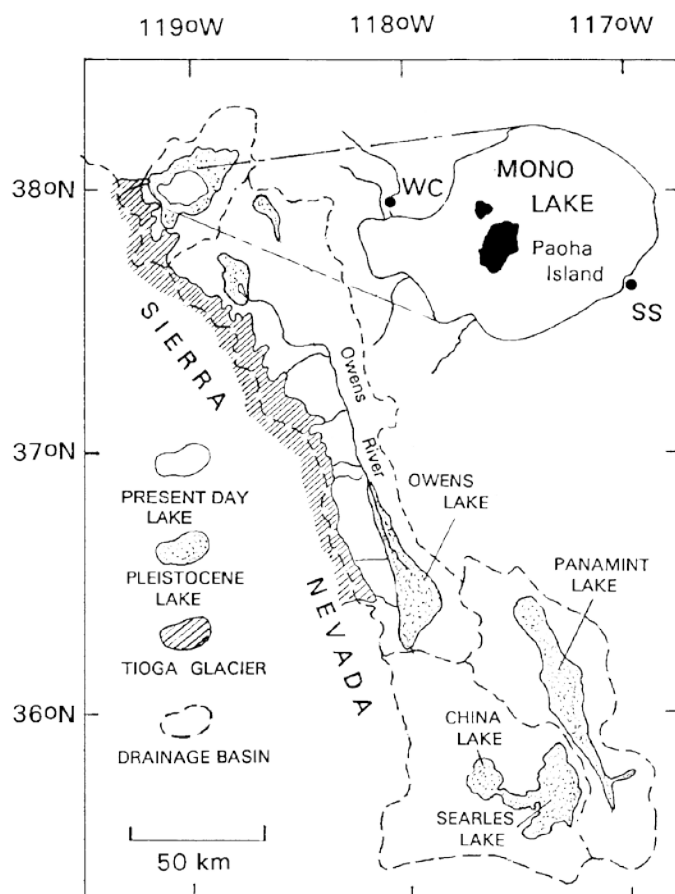


FIG. 1. Map showing location of the Mono and Owens Lake basins. WC refers to the location of the Wilson Creek type section and SS refers to the South Shore site from which samples between Ashes 4 and 5 were obtained. The South Shore site is 17 m lower in elevation than the type section and appears to have remained submerged during shallow-water reworking of sediments at the type section. Generalized area of Tioga valley glaciers and ice caps was modified from Wahrhaftig and Birman (1965).

Owens Lake and North Atlantic records are not sufficiently accurate to allow objective comparison of millennial-scale climatic oscillations prior to 20,000  $^{14}\text{C}$  yr B.P.

In this study, we have employed paleomagnetic secular variation (PSV) data obtained on North Atlantic and Mono Lake sediments as well as  $^{18}\text{O}$  and total inorganic carbon (TIC) measurements of Mono Lake sediments to show that lowstands of Mono Lake occurred during Heinrich events H1, H2, and H4. These results enforce the concept that relatively dry–wet oscillations in the climate of the Great Basin of the western United States occurred at approximately the same times as cold–warm oscillations in the climate of the North Atlantic region.

values increased, indicating that spill from Owens Lake decreased or even ceased. Note that we use the word “dry” in a relative sense as some of the dry intervals in the late Pleistocene were not as dry as today’s climate.

## STUDY AREA

Mono Lake is located in a structural depression at the western edge of the Great Basin, directly north of the Owens Lake Basin (Fig. 1). This closed-basin lake lies in the rain shadow of the Sierra Nevada which receives most of its precipitation in the cool season when the mean position of the polar jet stream lies between 37 and 39°N (Starrett, 1949; Pyke, 1972).

The last lake-level maximum (highstand) of Mono Lake<sup>2</sup> occurred  $\sim 13,000$   $^{14}\text{C}$  yr B.P. (Fig. 2). Variations in lake size prior to 15,000  $^{14}\text{C}$  yr B.P. have proven difficult to document using surficial materials, although (Lajoie *et al.*, 1982) have argued that brief highstands of Mono Lake also occurred at  $\sim 34,000$  and  $\sim 26,000$   $^{14}\text{C}$  yr B.P. (Benson *et al.*, 1990, Fig. 14).

To obtain a high-resolution record of lake-level change in the Mono Basin, we sampled the late Pleistocene Wilson Creek Formation which crops out along the periphery of Mono Lake. The Wilson Creek Formation, which consists of 6 to 15 m of finely laminated muds and silts, contains 19 tephra layers (ashes) that provide stratigraphic control throughout the basin (Plates 2 and 3, Lajoie, 1968). The sediments and volcanic tephra layers of the Wilson Creek Formation are described in Lajoie (1968). With the exception of Ash 2, a 3- to 6-m-thick basaltic tephra layer derived from Black Point, the other tephra layers are rhyolitic. In its type section (Fig. 1), the Wilson Creek Formation contains  $\sim 7$  m of lacustrine sediments that overlie fluvial gravel, containing small lenses of sand. With the exception of a few sand units located between Ashes 4 and 5, the sediments of the Wilson Creek Formation have the same style, consisting of laminated and structureless muddy silts. Little or no expandable clays have been found in Wilson Creek sediments and the carbonate fraction consists solely of calcite. Ostracodes usually compose  $\leq 15\%$  of the carbonate fraction (L. Benson and M. Weimer, unpublished data).

In the type section, the Ash 4 to 5 interval is characterized by contorted and deformed bedding (Fig. 3; Lajoie, 1968, Fig. 14A, Plates 2 and 3). A series of imbricate thrusts that repeat parts of the section in this interval are believed to have formed in response to loading by Ash 2. Ash 2 is itself irregularly bedded and contorted in the Wilson and Mill Creek areas (Lajoie, 1968, Photo no. 22). At its South Shore site (Lajoie, 1968, Plate 13; Fig. 1), the Wilson Creek Formation is thicker than the type section and 17 m lower in elevation. At this site, the sediments between Ash 4 and 5 are neither contorted nor deformed. Comparison of paleomagnetic-field directions (inclination and declination) obtained from the Wilson Creek Formation at its type and

<sup>2</sup> Although the lake that occupied the Mono Basin in the late Pleistocene has often been referred to as Lake Russell in honor of I. C. Russell (Russell, 1889), in this paper, we will refer to the lake that has intermittently occupied the Mono Basin during the Quaternary by its modern name—Mono Lake.

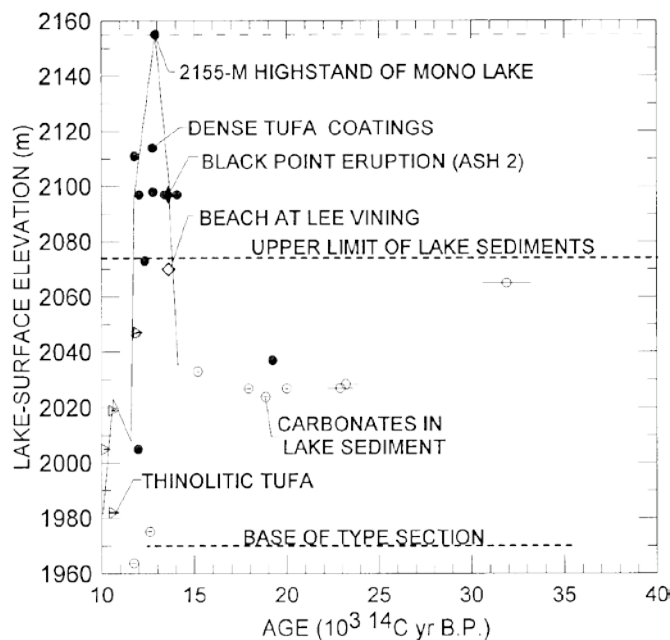


FIG. 2. Elevation-age plot of selected carbonates (tufas) from the Mono Lake basin. Solid circles indicate relatively dense tufas; open circles indicate carbonates found in lake sediments above the elevation of the Wilson Creek type section. Lake-surface elevation at time of Black Point eruption (13,610 <sup>14</sup>C yr B.P., Table 1) was determined from a bathtub ring of basaltic pumice (Ash 2) deposited in Mono Lake basin. The carbonate data indicate that Mono Lake (Pleistocene Lake Russell) achieved a highstand at ~13,000 <sup>14</sup>C yr B.P. Thinolitic tufa often yields unreliable <sup>14</sup>C ages; i.e., it is thought to have formed as the metastable hexahydrate of CaCO<sub>3</sub>. It is plotted here because it may have recrystallized soon after subaerial exposure and therefore may date a decline of Mono Lake.

South Shore sites indicates that sediment is missing between Ashes 4 and 5 at the type section (J. C. Liddicoat and S. P. Lund, unpublished data).

## METHODS

To rectify the problem of missing and repeated intervals of sedimentation between Ashes 4 and 5, we obtained a nearly continuous set of 2-cm-thick samples from the South Shore site (Fig. 1). Samples also were taken several cm above and below Ashes 4 and 5 at the South Shore site to ensure data overlap with the Wilson Creek isotope site. At the South Shore site, the Ash 4–5 interval (3.66 m) is much thicker than the same interval at the type locality, implying that the South Shore site may have escaped erosion during the time interval that separated ash deposition.

At the Wilson Creek isotope site, a continuous set of 2-cm-thick samples each weighing ~200 g and integrating ≤70 yr were analyzed for  $\delta^{18}\text{O}$ . Samples from both sites were washed in deionized water, freeze dried, and homogenized prior to analysis.  $^{18}\text{O}$  values obtained on the total inorganic fraction (low-magnesium calcite) are reported relative

to the VSMOW standard. Analytical procedures are discussed in Benson *et al.* (1996a).

## AGE CONTROL

Radiocarbon ages of carbonate samples from the Wilson Creek Formation, as well as the distances of the samples above and below tephra layers (Benson *et al.*, 1990, Table IV), were used to construct an age model for the Wilson Creek type section. Linear regression of data between Ashes 1 and 4 and between Ashes 5 and 19 (Fig. 4a) was used to estimate the <sup>14</sup>C ages of individual tephra layers (Table 1). Age estimates for the tephra layers (Table 1), together with two new AMS <sup>14</sup>C determinations on unaltered ostracode valves, were then used to set the chronology for samples obtained in this study from our main isotope sampling site (Fig. 4b). Given the fit of our linear age–depth models, we consider its accuracy to be no better than a thousand years.

Our main 6.94-m-thick isotope sampling site was located near exposures originally used to construct the 7.17-m type section and contains a sequence of sediments deposited between 35,400 and 12,900 yr B.P. A linear fit using the ages of and depth interval between Ashes 4 and 5 was used to estimate the ages of samples taken from the South Shore site.

## RESULTS AND DISCUSSION

### *Correlations of Lake-Size Changes with Climate Change in the North Atlantic Region*

In a hydrologically closed lake, increases in lake volume resulting from input of isotopically light streamflow discharge and on-lake precipitation are reflected in decreased values of  $\delta^{18}\text{O}$ . The greater the change in volume the more abrupt the change in  $\delta^{18}\text{O}$  (Benson *et al.*, 1996b; Gat, 1981).  $^{18}\text{O}$  data from the Wilson Creek Formation (Fig. 5) indicate the existence of three scales of temporal variation in the hydrologic balance.

The 10<sup>3</sup>-year scale in hydrologic variability is evidenced by 500- to 1500-yr oscillations in the size ( $\delta^{18}\text{O}$  value) of Mono Lake. The oscillations are most clearly displayed in the plot that represents the running mean of three successive measurements of  $\delta^{18}\text{O}$  (Fig. 5). This scale of hydrologic variance is similar to the scale but not amplitude of variance in air temperature recorded in Greenland ice core GISP2. The  $\delta^{18}\text{O}$  data from the GISP2 core (Groote *et al.*, 1993; Stuiver *et al.*, 1995) depicted in Figure 5 was converted from its “absolute” chronology (Meese *et al.*, 1994) to a <sup>14</sup>C chronology using the data of (Bard *et al.*, 1993). The <sup>14</sup>C chronology was then “stretched” to place the Heinrich events that matched to Dansgaard–Oeschger cycles at 14,000, 21,000, 27,000, and 35,500 yr B.P.

The multimillennial (Heinrich) scale in hydrologic variance is evidenced by persistent lowstands (L1 through L4) of Mono Lake (high values of  $\delta^{18}\text{O}$ ) that occurred every

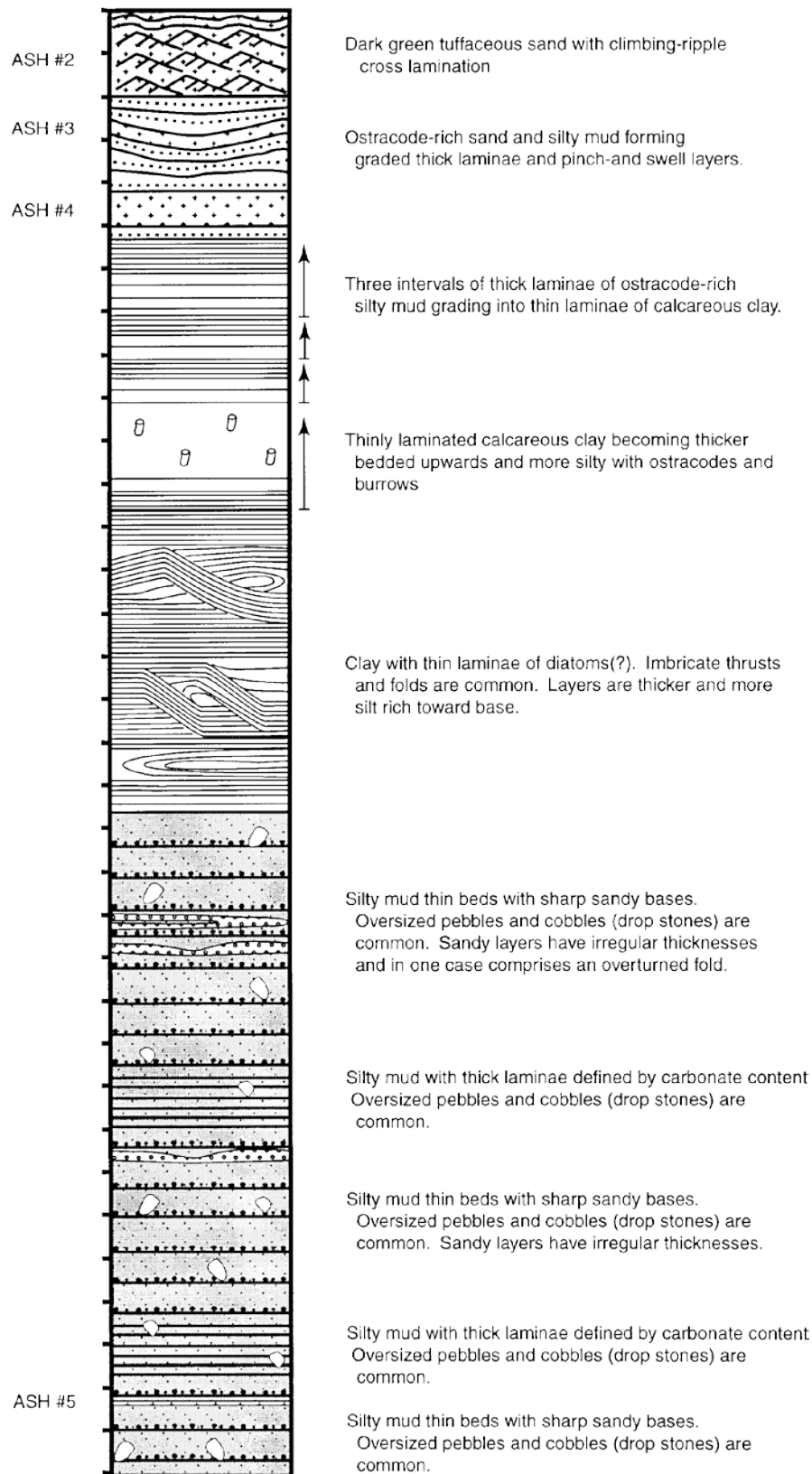


FIG. 3. Partial stratigraphic section of sediments exposed along Wilson Creek at the type locality of the Wilson Creek Formation. Ash unit numbers from Lajoie (1968). Tick marks define 10-cm intervals. The clay unit with imbricate thrusts is probably a glide plane for a slump caused by deposition of Ash 2.

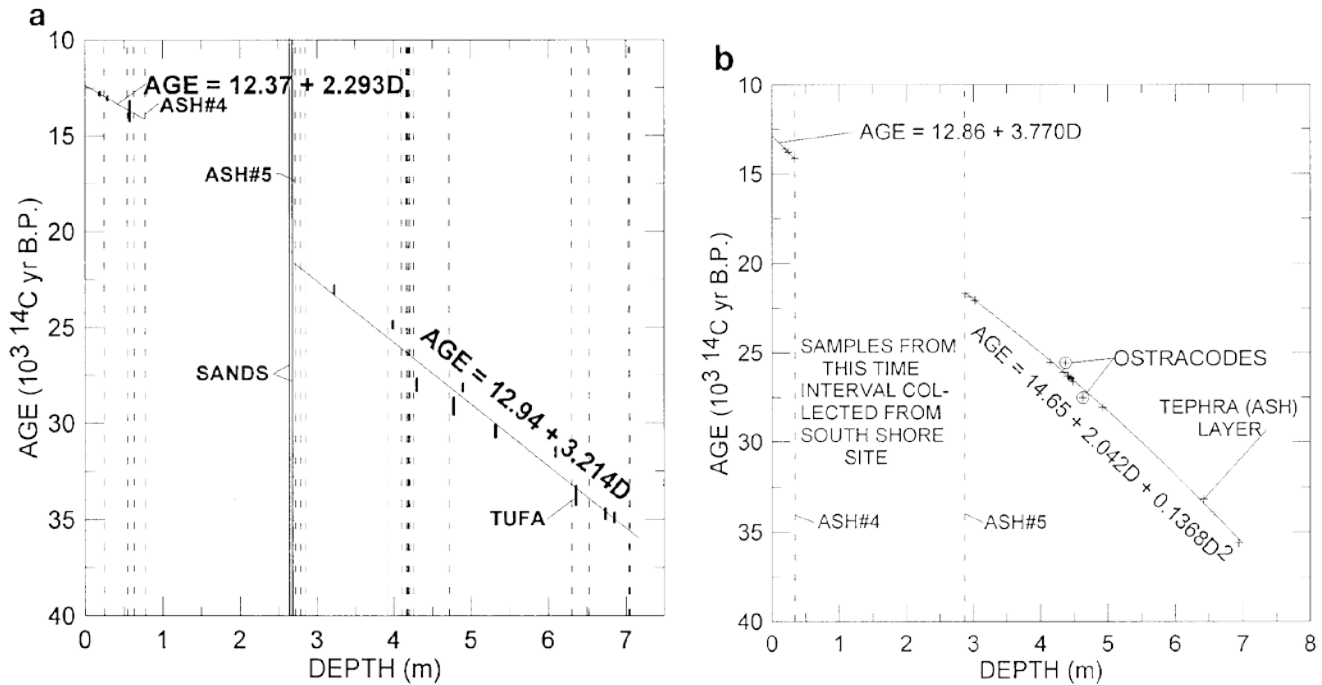


FIG. 4. (a) Radiocarbon ages and depths of carbonates in the Wilson Creek area used to estimate the ages of 19 tephra layers (ashes) exposed in the Wilson Creek Formation along Wilson Creek. Ashes are depicted as vertical dashed lines. Data used in this figure were taken from Wilson Creek type section listing in Table IV in Benson *et al.* (1990). In the regression equations,  $D$  refers to depth in meters (m). In constructing the two regression lines, some samples from Table IV were rejected. Sample USGS-1435 came from the reworked Ash 4–5 interval. Radiocarbon ages of samples USGS-1436 and L-1167C were splits from the same collection of ostracode valves whose radiocarbon ages are anomalously young ( $\sim 23,000$  instead of  $\sim 26,000$   $^{14}\text{C}$  yr). We expect that modern carbon was added to many of the thin-walled ostracode valves. The radiocarbon age of sample USGS-362, a nodular tufa with carbonate coatings from the base of the Wilson Creek Formation, was also clearly too young ( $28,600$  instead of  $\sim 36,000$   $^{14}\text{C}$  yr). Sample USGS-276 was rejected because its  $^{14}\text{C}$  age was infinite ( $39,600$   $^{14}\text{C}$  yr). (b) Radiocarbon age control for Wilson Creek isotope section. Age control is based on estimated ages of 18 tephra layers (Table 1). The two ostracode AMS  $^{14}\text{C}$  ages provide a check on the reliability of the tephra-derived age model for the interval  $25,000$  to  $27,500$   $^{14}\text{C}$  yr B.P.

6000 to 7000 years. Given the  $^{14}\text{C}$ -based chronologies for the marine and lacustrine data sets, it appears that the youngest prominent lowstands of Mono Lake occurred during Heinrich events H1 through H3 (Fig. 5).

Radiocarbon reservoir effects, however, are neither constant nor easily quantified in marine and lacustrine environments; e.g., modern tufas in Mono Lake have  $^{14}\text{C}$  ages ranging from 1100 to 2100  $^{14}\text{C}$  years (Benson *et al.*, 1990). Because much of the reservoir effect in Mono Lake may have resulted from inputs of  $^{14}\text{C}$ -free carbon accompanying subsurface volcanism, the pre-Holocene value of the reservoir effect may have at times been of the same magnitude as the modern effect, given the history of volcanism evidenced by the 19 tephra layers contained within Wilson Creek sediments.

Porous lacustrine carbonates typical of the Mono Basin, however, do not remain closed systems with respect to carbon. Such carbonates tend to acquire  $^{14}\text{C}$  when exposed to the subaerial environment by a dissolution–reprecipitation process that occurs when low-pH rain comes in contact with the carbonate. This process can decrease the apparent  $^{14}\text{C}$  age of porous carbonates by more than 1000 years (Thompson *et al.*, 1986). Because carbonates can acquire modern carbon

during their entire tenure in the subaerial environment, the apparent  $^{14}\text{C}$  ages of the oldest Mono Lake tufas may be much younger than the events they appear to date. For these reasons, we turned to another method of comparison to test the hypothesis that Mono Lake lowstands accompanied periods of intense ice rafting in the North Atlantic Ocean.

Recently Lund (1996) has shown that distinctive magnetic-field features in Holocene records of paleomagnetic secular variation (PSV) can be traced across North America for more than 4000 km without change in pattern. In this paper, we have applied this concept, which assumes nearly synchronous (within  $\pm 100$  to 200 years) field variability, to PSV records from Mono Lake and the North Atlantic Ocean. The likelihood that lowstands of Mono Lake were synchronous with Heinrich events was tested using data from two deep-sea sediment cores from the western North Atlantic (P-094 located at  $50.2^\circ\text{N}$ ,  $45.7^\circ\text{W}$  and CH88-10P located at  $29.6^\circ\text{N}$ ,  $73.3^\circ\text{W}$ ; Haskell *et al.*, 1991; Stoner *et al.*, 1995; Stoner *et al.*, 1996). Four detrital carbonate intervals (DC1 through DC4) identified in P-094 are considered equivalent to Heinrich events H1 through H4 (Stoner *et al.*, 1995; Stoner *et al.*, 1996). The carbonate and oxygen-isotope stra-

TABLE 1  
Radiocarbon Ages for the Wilson Creek Formation

Ostracode sample	CAMS no. <sup>a</sup>	Depth in isotope section (m)	Radiocarbon age (uncalibrated) <sup>14</sup> C yr B.P. $\pm$ 1 std. dev.
OST:436-438	20031	4.37	25,570 $\pm$ 260
OST:461-463	20032	4.63	27,520 $\pm$ 270

Tephra layer	Depth in isotope section (m)	Estimated age <sup>14</sup> C yr B.P. <sup>b</sup>	Depth in type section (m)
Ash #1	0.00	12,920	0.24
Ash #2	0.20	13,610	0.54
Ash #3	0.24	13,790	0.62
Ash #4	0.34	14,140	0.77
Ash #5	2.88	21,680	2.72
Ash #6	2.96	21,870	2.78
Ash #7	3.02	22,070	2.84
Ash #8	4.14	25,540	3.92
Ash #9	4.34	26,090	4.09
Ash #10	4.40	26,310	4.16
Ash #11	4.42	26,340	4.17
Ash #12	4.44	26,410	4.19
Ash #13	4.46	26,470	4.21
Ash #14	4.48	26,600	4.25
Ash #15	4.92	28,080	4.71
Ash #16	6.42	33,160	6.29
Ash #17	6.57	33,900	6.52
Ash #18	—	35,530	7.03
Ash #19	6.94	35,600	7.05

<sup>a</sup> CAMS, Samples analyzed by Center for Accelerator Mass Spectrometry (CAMS) facility at Lawrence Livermore National Laboratory.

<sup>b</sup> Radiocarbon ages estimated by interpolation using the age model of Figure 4a. Ages of Ashes #1–#14 are probably accurate within 500 yr. After 27,000 <sup>14</sup>C yr B.P., paleomagnetic secular variation data for the Wilson Creek type section and deep-sea core records (see text for discussion) indicate that Wilson Creek tufa based <sup>14</sup>C age estimates of Ashes #15–#19 are too young. The marine-based <sup>14</sup>C age model indicates the following <sup>14</sup>C ages for Ashes #15–#19: 31,500, 37,000, 38,000, >40,000, and >40,000 <sup>14</sup>C yr B.P.

tigraphies of CH88-10P were then used to estimate the locations of Heinrich events H1 through H4 in this core, using previously developed correlations between these stratigraphies and Heinrich events (Bond *et al.*, 1993; Keigwin and Jones, 1994; Bond and Lotti, 1995).

Paleomagnetic field directional and intensity variations recorded in CH88-10P sediments (Lund, 1993; Schwartz *et al.*, 1996a) and P-094 (Stoner *et al.*, 1995; Stoner *et al.*, 1996) were used to create a magnetic chronostratigraphy in which each Heinrich event was associated with directional features of the magnetic records. We then correlated intensity records for P-094 and CH88-10P (Lund *et al.*, 1988; Schwartz *et al.*, 1996b) and directional records (both inclination and declination) for CH88-10P with Wilson Creek PSV features to determine what Mono Lake  $\delta^{18}\text{O}$  features were associated with Heinrich events (Fig. 6).

From the PSV data, it is apparent that Heinrich events H1, H2, and H4 and Mono Lake lowstands L1, L2, and L4 are nearly synchronous; however, H3 does not correlate with any Mono Lake lowstand. Lowstand L1 is of particular interest because it occurred at very nearly the same time (15,500 to 14,000 <sup>14</sup>C yr B.P.) as a drying of Owens Lake (15,500 to

~13,300 <sup>14</sup>C yr B.P.). A sediment core taken from Pyramid Lake in the Lahontan Basin also indicates a maximum in  $\delta^{18}\text{O}$  values at 14,500 <sup>14</sup>C yr B.P. (L. V. Benson, unpublished data).

Negrini (1997) has associated the Wono tephra layer dated at 27,300  $\pm$  300 <sup>14</sup>C yr B.P. (Benson *et al.*, 1997b) with paleomagnetic inclination features of Lake Chewaucan sediments that can be correlated with inclination features in the Wilson Creek Formation (Fig. 6). The correlation indicates that our Wilson Creek age model is correct back to 27,000 <sup>14</sup>C yr B.P. If our PSV approach is correct, it implies that lake and marine <sup>14</sup>C time scales began to diverge at  $\geq$ 27,000 <sup>14</sup>C yr B.P. and that by 35,000 <sup>14</sup>C yr B.P. (Mono Lake time scale) <sup>14</sup>C ages of Mono Lake carbonates are ~3000 yr too young relative to the marine time scale. This suggests that either the marine reservoir effect has been underestimated or, more likely, that the addition of 0.3% modern carbon has shifted the ages of the oldest Mono Lake tufas. This also implies that the ages of Wilson Creek Ashes 15–19 (Table 1) have been underestimated with our age model.

The fact that H3 is not associated with any persistent lowstand of Mono Lake is of particular interest because H3 is considered to mostly have originated from sources other



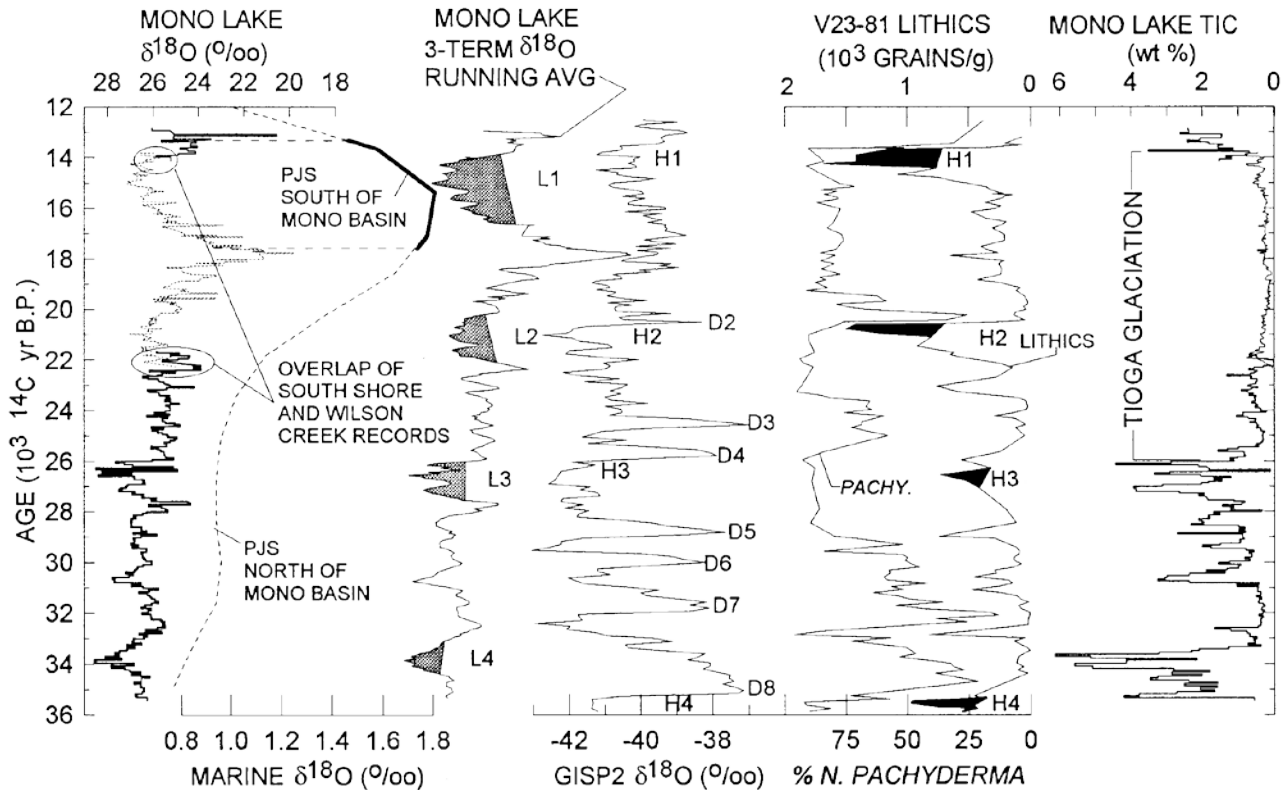


FIG. 5.  $\delta^{18}\text{O}$  and TIC records from Wilson Creek sediments compared with the lithic and *Neogloboquadrina pachyderma* (left-coiling) records from North Atlantic core V23-81, the SPECMAP stacked marine  $\delta^{18}\text{O}$  record (Imbrie *et al.*, 1984), and the  $\delta^{18}\text{O}$  record from GISP2 ice core, Greenland (Grootes *et al.*, 1993; Stuiver *et al.*, 1995). H1 to H4 refer to North Atlantic Heinrich (Heinrich, 1988) events; L1 to L4 refer to principal lowstands of Mono Lake, D2 to D8 refers to Dansgaard-Oeschger interstadies. Placement of Heinrich events on the GISP2 record follows Bond and Lotti (1995).

than the Laurentide ice sheet (Grousset *et al.*, 1993; Gwiazda *et al.*, 1996). This implies that only massive ice rafting events, originating in the Laurentide ice sheet, were capable of perturbing the climate of the Mono Lake area, possibly through the effect of the ice sheet on the trajectory of the polar jet stream. This also lends support to the hypothesis of MacAyeal (1993) that surging of the Hudson Bay lobe of the Laurentide ice sheet caused Heinrich events.

Clark and Bartlein (1995) have recently suggested that late Pleistocene alpine glaciers in the western United States advanced to their terminal areas up to several thousand years before a Heinrich event and retreated shortly thereafter. The data presented in Clark and Bartlein (1995), though of low resolution, are consistent with the data presented herein which indicate that H1, H2, and H4 occurred during cold and relatively dry periods.

The  $10^4$ -yr (Milankovitch) scale of climate variability is evidenced by parallelism between the overall trend in the Wilson Creek and marine  $\delta^{18}\text{O}$  records from 35,500 to 18,000  $^{14}\text{C}$  yr B.P. (Fig. 5).<sup>3</sup> This parallelism is inter-

preted to indicate the gradual southward movement of the mean position of the polar jet stream in response to increasing size of the Laurentide ice sheet (Antevs, 1948; Benson and Thompson, 1987; Kutzbach and Guetter, 1986). The lack of parallelism between 18,000 and 13,000  $^{14}\text{C}$  yr B.P. is interpreted to indicate that the polar jet stream was forced south of the Mono Basin ( $38^\circ\text{N}$ ) as the ice sheet expanded. The two lake-level maxima ( $\delta^{18}\text{O}$  minima), centered at 18,000 and 13,100  $^{14}\text{C}$  yr B.P., therefore, correspond to two passages of the polar jet stream core over the Mono Basin.<sup>4</sup>

The 13,100  $^{14}\text{C}$  yr B.P. sediment-based highstand occurs at essentially the same time as the tufa-based highstand, previously dated at 13,000  $^{14}\text{C}$  yr B.P. (Fig. 2). The highstand at 18,000  $^{14}\text{C}$  yr B.P. was not recorded in the tufa-based lake-level record (Fig. 2). This probably reflects the erodable nature of the substrate (silts and sands) on which carbonates were deposited; i.e., the transgression to the 13,100  $^{14}\text{C}$  yr B.P. highstand effectively removed most of the older surficial carbonates deposited during previous highstands.

<sup>3</sup> The stacked marine  $\delta^{18}\text{O}$  record (PDB standard) is assumed to be a proxy for the size of the Laurentide Ice Sheet during the last glacial (Imbrie *et al.*, 1984).

<sup>4</sup> Benson *et al.* (1995) previously suggested this mechanism for the large and abrupt increases in the level of Lake Lahontan that occurred at  $\sim 21,000$  and  $\sim 14,500$   $^{14}\text{C}$  yr B.P.

### Glaciation of the Mono Basin

In the Owens Basin, the Tioga glaciation occurred between  $\sim 25,000$  and  $\sim 15,000$   $^{14}\text{C}$  yr B.P. as indicated by

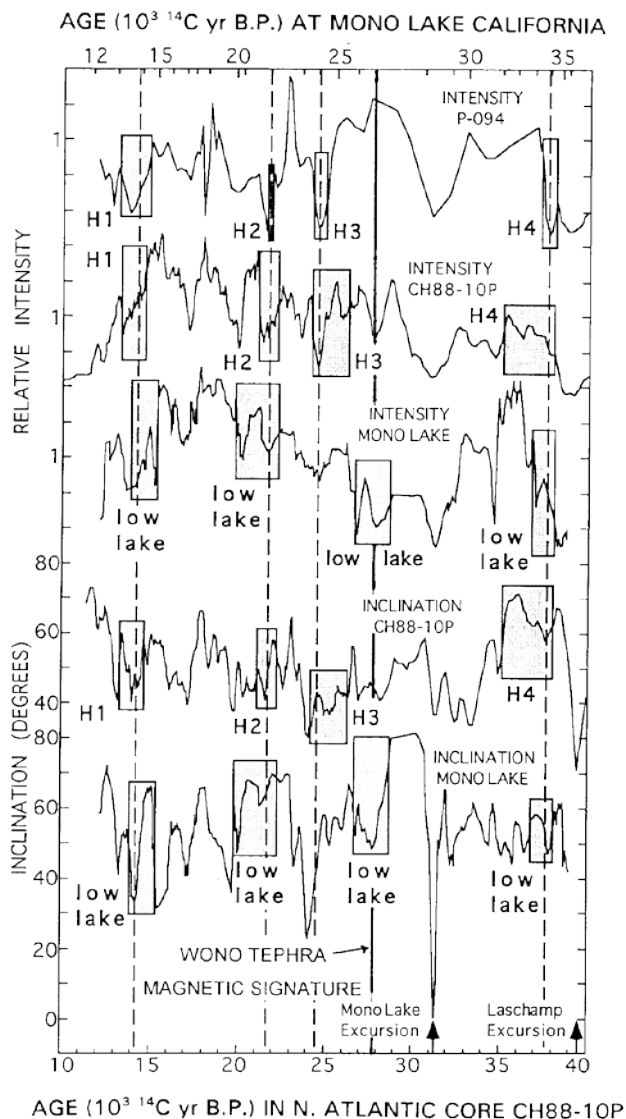


FIG. 6. Comparison of Heinrich event and Mono Lake lowstand ages using paleomagnetic field variability (intensity and inclination) for chronostratigraphic control. Methodology for placement of the Heinrich events on the paleomagnetic waveforms is discussed in the text. The stratigraphic locations of Heinrich events in North Atlantic cores CH88-10P, and P-094 are indicated by gray boxes labeled H1 through H4. Mono Lake lowstands are shown as gray boxes labeled "low lake." The paleomagnetic data indicate that Heinrich events H1, H2, and H4 occurred during Mono low-lake intervals, whereas, Heinrich event H3 did not. Note that the intensity record of Mono Lake is sufficient to show the correlation between L4 and H4 but the inclination record is equivocal. The  $^{14}\text{C}$  chronology for CH88-10P (Keigwin and Jones, 1989; Keigwin and Jones, 1994) was used to develop a common time scale for the marine records (Fig. 6). Radiocarbon ages of Mono Lake sediments are shown in the upper abscissa and radiocarbon ages of marine sediments are shown in the lower abscissa. The location of the inclination feature associated with the 27,300  $^{14}\text{C}$  yr old Wono tephra layer is indicated by a solid vertical line.

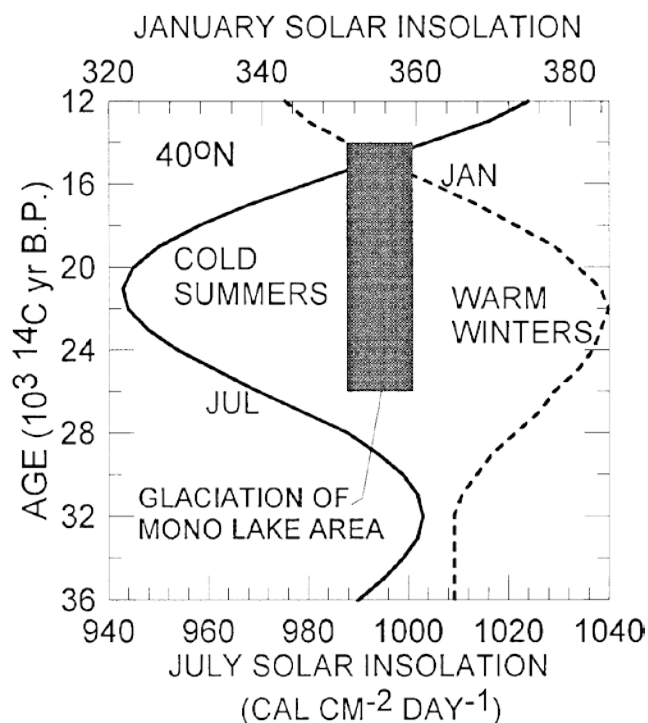


FIG. 7. Values of January and July insolation at  $40^\circ\text{N}$  for the period 36,000 to 12,000  $^{14}\text{C}$  yr B.P. The period of intense glaciation recorded by the TIC fraction of Mono Lake sediments occurred during a time characterized by cold summers and warm winters.

increased magnetic susceptibility and decreased TIC and total organic carbon (TOC) concentrations in cored sediments (Benson *et al.*, 1996a).

In a closed basin lake, such as Mono Lake, changes in TIC are expected to parallel changes in  $\delta^{18}\text{O}$  unless the influx of detrital silicates masks the TIC signal (Benson *et al.*, 1996a). Though the amplitude of the variations differ in the two data sets, such a parallelism does occur in the Mono Lake record between 35,400 and 26,000  $^{14}\text{C}$  yr B.P. (Fig. 5). Between 26,000 and 14,000  $^{14}\text{C}$  yr B.P., however, TIC values are markedly reduced and the TIC and  $\delta^{18}\text{O}$  records are unrelated. We attribute the reduction and loss of variability in TIC between 26,000 and 14,000  $^{14}\text{C}$  yr B.P. to the influx of detrital rock flour that accompanied Tioga glaciation of the Mono Basin (Fig. 5). The Tioga glaciation may have, in part, been the result of reduced summer insolation; e.g., a plot of July insolation at  $40^\circ\text{N}$  (Fig. 7) indicates extremely low values during the period of interest.

### CONCLUSIONS

Most of the major dry (and probably cool)<sup>5</sup> periods in the Mono Basin between 35,900 and 12,900  $^{14}\text{C}$  yr B.P. appear

<sup>5</sup> The 2 to 3 ‰ increase in  $\delta^{18}\text{O}$  that occurred during the transition to Mono Lake lowstands can also partly be attributed to decreases in water temperature; i.e., fractionation of  $^{18}\text{O}$  into calcium carbonate increases by  $\sim 0.25$  ‰ per  $^\circ\text{C}$  reduction in water temperature (O'Neil *et al.*, 1969).

to have occurred at nearly the same time as cool periods in the North Atlantic. Cold–warm oscillations in the North Atlantic region have previously been attributed to abrupt changes in the rate and location of thermohaline overturn (Broecker *et al.*, 1990; Broecker and Denton, 1989; Lehman and Keigwin, 1992; Rind *et al.*, 1986). To the extent that the dry–wet transitions in the Mono Basin are synchronous with cold–warm transitions in the North Atlantic region, our data support the hypothesis that cooling of the North Atlantic caused a downstream cooling of the atmosphere and the North Pacific. This in turn led to a decrease in the amount of moisture reaching the western United States of America.

Age controls for both lacustrine and marine records, however, remain inadequate to demonstrate the absolute synchronicity of climate change across the Northern Hemisphere and it is possible that there are substantial offsets in the timing of climate transitions in both regions. In any case, we envision the polar jet stream as a principal component of the atmospheric teleconnection that linked climate change across the upper part of the Northern Hemisphere (Clark and Bartlein, 1995). Similar high-resolution data from lower latitudes (e.g., 20°N) would help answer the question whether climate change was synchronous and unidirectional across the entire Northern Hemisphere.

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