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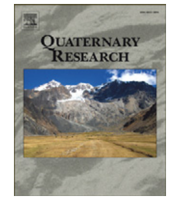

Freshwater control of ice-rafted debris in the last glacial period at Mono Lake, California, USA

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ABSTRACT

The type section silts of the late Pleistocene Wilson Creek Formation at Mono Lake contain outsized clasts, dominantly well-rounded pebbles and cobbles of Sierran lithologies. Lithic grains >425 μm show a similar pattern of variability as the >10 mm clasts visible in the type section, with decreasing absolute abundance in southern and eastern outcrops. The largest concentrations of ice-rafted debris (IRD) occur at 67–57 ka and 46–32 ka, with strong millennial-scale variability, while little IRD is found during the last glacial maximum and deglaciation.

Stratigraphic evidence for high lake level during high IRD intervals, and a lack of geomorphic evidence for coincidence of lake and glaciers, strongly suggests that rafting was by shore ice rather than icebergs. Correspondence of carbonate flux and IRD implies that both were mainly controlled by freshwater input, rather than disparate non-climatic controls. Conversely, the lack of IRD during the last glacial maximum and deglacial highstands may relate to secondary controls such as perennial ice cover or sediment supply. High IRD at Mono Lake corresponds to low glacial flour flux in Owens Lake, both correlative to high warm-season insolation. High-resolution, extra-basinal correlation of the millennial peaks awaits greatly improved age models for both records.

Introduction

Documentation of the nature and timing of paleoclimate change in western North America during the last glacial period is critical to understanding the behavior of the global climate system under different background conditions and during extreme and abrupt events such as Dansgaard–Oeschger and Heinrich events (Heinrich, 1988; Dansgaard et al., 1993). Correlative changes to these North Atlantic events have now been identified in many places around the world (Dansgaard et al., 1993; Cacho et al., 1999; Hendy and Kennett, 2000; Peterson et al., 2000; Burns et al., 2003; Piotrowski et al., 2005), but the effects on the terrestrial landscape and ecosystems of the Great Basin and Sierra Nevada are not as well known.

A great deal has been learned about glacial-era climate in the Great Basin from sediments deposited by the Owens and paleo-Lake Lahontan systems (Davis, 1983; Benson and Thompson, 1987; Hostetler and Benson, 1990; Benson et al., 1996; Lin, 1996; Bischoff et al., 1997; Smith and Bischoff, 1997; Bischoff and Cummins, 2001; Li et al., 2004; Bacon et al., 2006). However, both the Owens and Lahontan systems consisted of multiple basins filling and spilling, adding complexity to the relationship between lake level and climate parameters. In contrast, Mono Lake (Fig. 1) has probably not spilled out of its basin in at least the last glacial cycle, and therefore reconstructed lake levels are almost purely a function of the balance between precipitation and evaporation.

In addition, the lake depocenter sits immediately at the foot of the Sierran canyons, and therefore it was well situated to capture essentially all of the water and sediment generated by the Sierran glaciers in the late Pleistocene (Fig. 1). This direct relationship is rare

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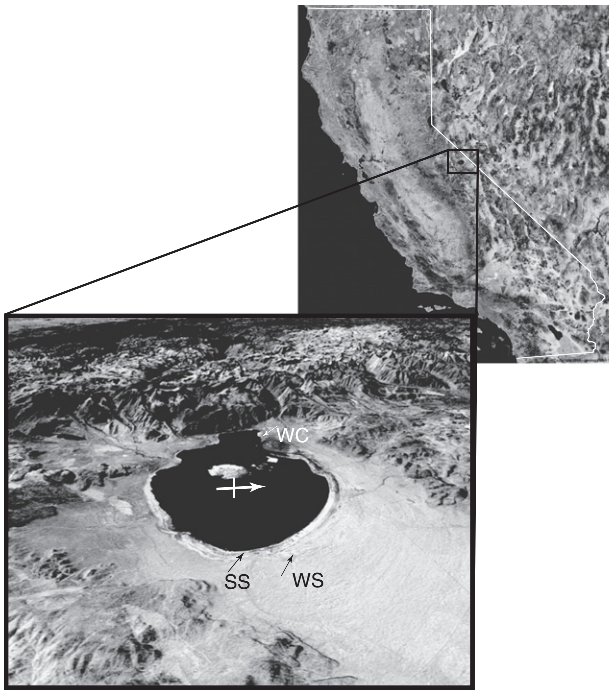

Figure 1. Location map of Mono Lake, California, at the western edge of the Great Basin, and view west across the Mono Basin, into the Sierra Nevada. Outcrops discussed in the text are marked with letters: WC, Wilson Creek type section; WS, Warm Springs section; SS, South Shore cliff. White cross in the lake east of Paoha Island marks 38°N 119°W; arrow points north. Base image of the Mono basin used by permission of Dr. William Bowen.

in the Great Basin, and affords the eventual potential to deconvolve temperature from precipitation. Here we present an examination of out-sized clasts embedded in the silts of the late Pleistocene Wilson Creek Formation type section. Large clasts, some of them decimeter-scale, have long been recognized in the Wilson Creek sediments, and are generally considered to be ice-rafted dropstones (Russell, 1889; Lajoie, 1968; Benson et al., 1998), but have never been studied systematically. Our study aims to quantify the variability of the dropstones through time, and to examine the controlling mechanism(s) and paleoclimatic context of that variability.

The wilson creek formation

Type section

The Wilson Creek Formation was first described and named in the doctoral dissertation of Lajoie (1968), who extensively mapped exposures of time-equivalent sediments all around the Mono Basin. Precise correlation among multiple exposures is facilitated by a sequence of eighteen rhyolitic ashes and one basaltic ash, which form distinctive packages that Lajoie (1968) termed marker sequences A (youngest; Ashes 1–4) through E (oldest; Ashes 18 and 19) (Fig. 2).

At the type section in the Wilson Creek canyon, the Wilson Creek Formation consists of ~7 m of lacustrine silts, which overlie sands and gravels. With the exception of several thin beds of fine sand and inclined silt beds between Ashes 4 and 5, the silts of the type section are generally laminated to finely laminated, indicating deposition under very low-energy conditions. Quiet conditions are also inferred from the boundaries between the ash layers and the surrounding sediment, which are generally horizontal and sharply defined. The dominant component of the Wilson Creek sediments is silt derived from the plutonic and metamorphic bedrock of the Sierra (Lajoie, 1968; Zimmerman, 2006). Fine-grained authigenic carbonate is the major dilutant, with minor authigenic smectite, opal, ostracodes and inorganic carbonate pisoliths (algal ooliths of Lajoie, 1968). The sediments are generally devoid of organic matter (<0.3% in 10 pilot samples).

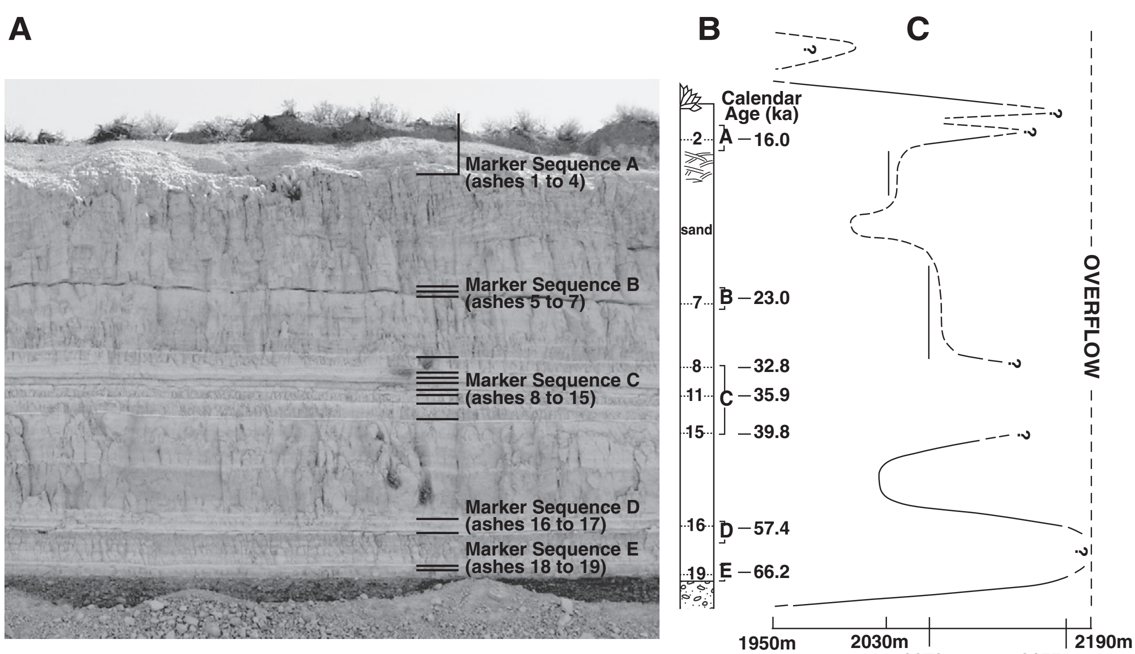

Figure 2. Wilson Creek Formation of Mono Lake. (A) Type section outcrop showing deep lake silts with interbedded ashes, bundled into Marker Sequences by Lajoie (1968). (B) Stratigraphic column showing basal gravels, ash layers with ages from Zimmerman et al. (2006), and occurrence of sand lenses and cross-bedding in the upper part of the type section. (C) Lake-level curve constructed based on stratigraphic relationships at outcrops of the WCF around the Mono Basin (Lajoie, 1968); overflow line indicates spill to the Owens Lake drainage, which may not have occurred in the last 100 ka. Panels B and C modified from Lajoie (1968).

Eastern outcrops

The Wilson Creek Formation is also exposed in a faulted and wave-cut cliff at the South Shore, and in low hills at the Warm Springs location due east of Mono Lake (Fig. 1). Neither exposure contains abundant visible clasts as found at the type section, but at Warm Springs the land surface lies above Ash 1, and is scattered with lag deposits which include abundant Sierran clasts. The bottom of the exposed section at Warm Springs is Ash 15, thus providing stratigraphic overlap with the type section between Ash 15 and Ash 7, and extending to the top of the Wilson Creek Formation. The main cliff at South Shore exposes the interval between Ash 5 and Ash 17, below which lies a layer of dramatic folding due to slumping.

Chronology

The chronology for the Wilson Creek Formation has proven difficult to constrain, despite multiple attempts with radiocarbon and U-series dating of carbonates, $^{40}Ar/^{39}Ar$ on ashes, and relative paleomagnetic intensity (RPI) (Benson et al., 1990; Chen et al., 1996; Kent et al., 2002; Hajdas et al., 2004; Zimmerman et al., 2006; Cassata et al., 2010) (Fig. 3). Here we apply the preliminary chronology suggested by Zimmerman et al. (2006) and discussed at length by Zimmerman et al. (in press). This age model consists of a linear interpolation between the radiocarbon-based age of Ash 1 (14 ka) and ^{14}C–$^{40}Ar/^{39}Ar$ agreement at Ash 7 (23 ka) for the top of the Wilson Creek Formation, and the RPI-based age model of Zimmerman et al. (2006) between Ash 7 and the base of the Wilson Creek type section. This results in an age of 67 ka for the base of the section, indicating that the Wilson Creek sediments record much of Marine Oxygen Isotope Stage 4 (MIS 4), all of MIS 3, and much of MIS 2.

Methods

Dropstones counted in outcrop

The stratigraphic distribution of dropstones in the type section outcrop was quantified by marking all clasts with an exposed diameter of >10 mm, and measuring the distance from each stone's center to the nearest ash bed above and below. Dropstone abundance was quantified along a 20 m stretch of the Wilson Creek canyon, and vertically from the gravels below Ash 19 up to Ash 7. The clast counts were numerically binned into 5-cm-thick stratigraphic intervals and the number of clasts in each interval summed (i.e., total clasts in a 5 cm × 20 m layer). All clasts were removed from the outcrop, numbered, and returned to the lab for further study.

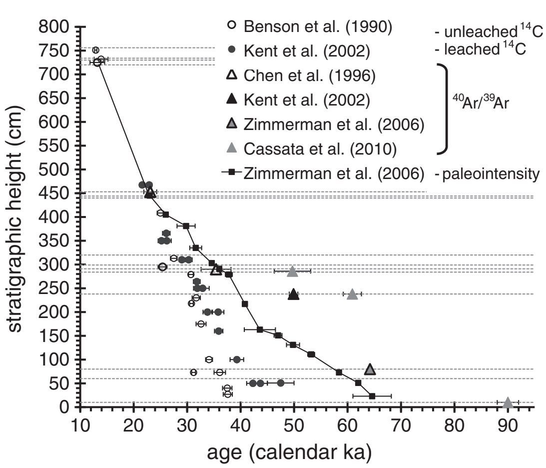

Figure 3. Chronological control on the Wilson Creek Formation. Unleached (Benson et al., 1990) and leached (Kent et al., 2002; Hajdas et al., 2004) radiocarbon ages are minimum estimates; Ar/Ar ages on ashes (Chen et al., 1996; Kent et al., 2002; Zimmerman et al., 2006) are maximum estimates. Within these constraints, Zimmerman et al. (2006) correlated a paleointensity record from the WCF to global reference curves. Age model above Ash 7 is a linear interpolation of the ^{14}C ages. For a more extensive discussion of the Wilson Creek Formation chronology, see Zimmerman et al. (in press).

Lithics counted in sediment samples

Because of the statistically small number of clasts exposed in even 20 m of outcrop, we improved the counting errors by measuring the coarse fraction in a sub-set of a suite of samples that were taken at continuous 2 cm spacing. While counts or weights of lithic grains over fine sand size (~150 μm) are generally accepted to be IRD in the open ocean, the smallest size fraction that unequivocally represents an ice-rafting mechanism in a lake is uncertain. The >425 μm fraction was chosen as the best compromise between the largest possible grain size and that which is represented by a significant number of grains. For each sample, 10 g of bulk sediment was weighed and disaggregated in deionized water, and the >425 μm fraction was separated by wet sieving. To remove carbonate fragments and coatings, the samples were leached in 3 N HCl until no further reaction was detected. The samples were then rinsed, dried, and weighed, and lithic grains (excluding pumice and gypsum) were counted under a microscope. Seventy samples, taken at contiguous 2 cm spacing, were analyzed from the type section. Results are reported here as number of grains per 10 g of bulk sediment (gr/10 g).

As a comparison to the Wilson Creek type section, overlapping intervals of the Warm Springs and South Shore sections were also sampled for >425 μm lithic grains, extending the record through the last glacial maximum into the early deglacial period. Thirty-seven samples from the South Shore locality and 236 samples from the Warm Springs locality were counted, each integrating 2 cm of section. Because both sites are much farther from the source of Sierran debris than Wilson Creek, it was expected that the clasts would be smaller and less abundant due to melting of the ice during transit to the east side of the lake. However, the pattern of variation in the ice-rafted detritus was expected to be similar to that in the type section.

Results

Outcrop vs. sieved populations in the type section

A total of 208 stones were counted in the outcrop, dominantly black, fine-grained clasts (59%), with a secondary population of classic salt-and-pepper granodiorite clasts (17%). Major and trace element chemistry indicates that the source rocks are the metamorphic roof pendants and granitic intrusives of the Sierran canyons (Tamulonis, 2002). The average stone documented by this survey was 15–20 mm in intermediate diameter (maximum = 101 mm), and nearly all were rounded to sub-rounded.

The dropstone (clasts counted in situ) and lithic (sieved >425 μm; collectively, IRD) records of the Wilson Creek type section show a similar four-part variability, despite their fundamental difference in resolution, providing mutual support for the two approaches (Fig. 4). The oldest period of intense rafting, from ~67 to 57 ka, shows the highest concentrations of IRD, with maxima of 18 clasts per 5 cm layer and 535 lithic grains per 10 g of bulk sediment (gr/10 g). This period is also highly variable, with five distinct peaks, each separated by several samples with values <100 gr/10 g. These high-amplitude and high-frequency changes decrease markedly to a second period, characterized by a background of a few tens of grains per sample over the period 57–46 ka. A third period of high IRD concentration, from about 46 to 30 ka, has a similar frequency of variation but lower amplitude

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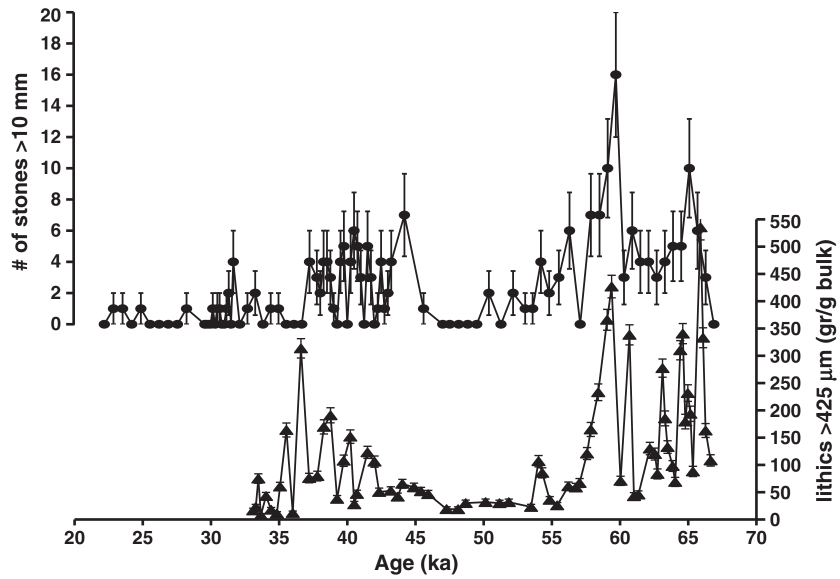

Figure 4. Comparison of the outsized clasts (>10 mm) and counted grains of coarse debris (>425 mm) in the Wilson Creek type section. Despite coarser resolution and larger counting errors of the dropstones compared to the lithics, the same fundamental variability is present in both records.

peaks than the 67 to 57 ka interval. Though this period appears to be shifted younger in the IRD relative to the dropstone record, this is possibly an artifact of the statistical frequency of dropstone occurrence. Finally, ice-rafting appears to be quite low after 30 ka.

Lithic counts in three outcrops

As predicted, the absolute abundance of IRD decreases from west to east (Fig. 5), and the scale of that decrease is approximately a factor of five over ~20 km. On millennial timescales, the peak-to-peak match is good between the South Shore and Warm Springs outcrops, likely because of their proximity to each other. A millennial-scale relationship is more difficult to discern between the type section and South Shore outcrop, with some peak–peak matches (e.g., 36.7 ka, 44.0 ka) and other peak–trough matches (e.g., ~40 ka). This may be a real difference in delivery of IRD on millennial timescales, or the result of different sampling intervals. For example, a distinctive peak in the type section of about 3× background (107 gr/10 g) from 55 to 53.5 ka falls between samples in the South Shore record.

Perhaps surprisingly, the last glacial maximum appears to be a time of very little debris rafting, based on the Warm Springs record. Because the Wilson Creek type section records much larger amounts of IRD than the other outcrops, a last glacial maximum record from that section would be a valuable test of this observation. However, these data are currently not available due to natural stratigraphic complexity in this interval (e.g., Benson et al., 1998). The Warm Springs record terminates with a single peak of 33 gr/10 g between 17 and 15 ka, which is distinctly defined due to a period of near-zero values from 21 to 17 ka.

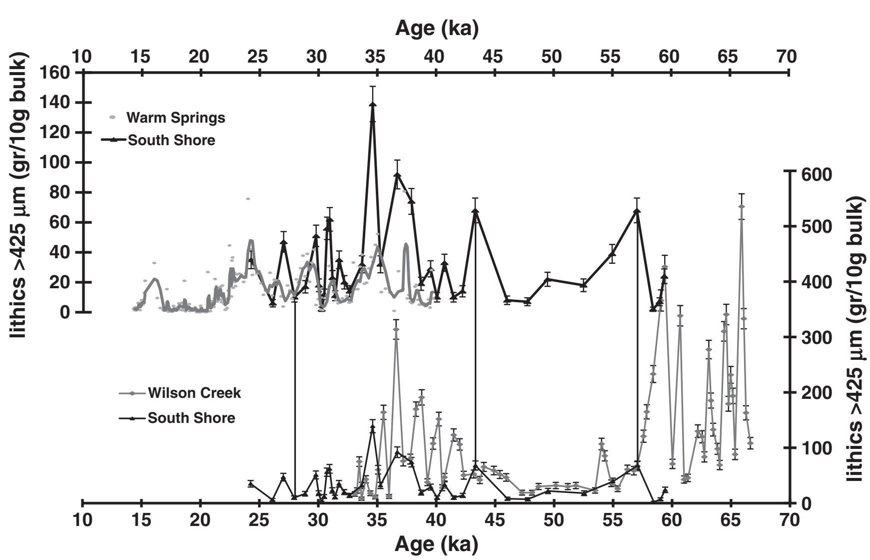

Figure 5. Records of lithic grains per 10 g of bulk sediment, counted in three outcrops of the Wilson Creek Formation. The South Shore and Warm Springs (3-pt. running mean) records are shown together (upper panel), because of their proximity (Fig. 1) and similarity. For comparison, the same South Shore record is plotted with the Wilson Creek record (lower panel); note that the Wilson Creek record here is the same record presented in the lower panel of Fig. 4.

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Discussion

Mechanisms of rafting

In general, several mechanisms may be responsible for depositing coarse debris in deep-water sediments. For example, hyperpycnal freshwater flows from the Truckee River into saline Pyramid Lake, Nevada, have been shown to carry sand-sized sediment as much as 4 km into the lake (Anderson, 2001). This led Anderson (2001) to suggest that this mechanism may also explain the distribution of sand within the deep lake silts of late Pleistocene Lake Estancia. However, while hyperpycnal flows may have contributed to the deposition of the sand-sized fraction in the late Pleistocene Wilson Creek IRD record, the granule, pebble, and cobble-sized material requires another means to be transported into the deep lake.

Rafting by mechanisms such as root mats cannot be absolutely ruled out for the Wilson Creek records, but given the glacial context of the record, we consider rafting by ice to be the most likely explanation for the out-sized clasts. However, the distinction between rafting by icebergs from the Sierran glaciers or by lake ice frozen around the shoreline is significant, since the climatic controls on the two mechanisms may be quite different. Rafting by icebergs from the valley glaciers requires direct contact with the lake at a calving front, and the likelihood of lake–glacier interaction was tested using Digital Elevation Models (DEMs) to compare lake levels known from stratigraphic constraints with moraines as an indicator of glacier extent (Fig. 6).

The best-constrained shorelines and moraines are dated to the Tioga glaciation, between ~14 and 19 ka (Schaefer et al., 2006), and the well-preserved terminal loops on the Tioga moraines clearly indicate that those glaciers did not terminate in the lake. The much longer pre-Tioga moraines are poorly dated, and concurrent lake levels are unknown. However, even supposing that the longer moraines date to early Wilson Creek time, and allowing that the oldest lake highstand (Fig. 3) may have reached the level of the Tioga highstand (2155 masl), the DEM indicates that all of the largest moraines from Lee Vining canyon southward are still above lake level, precluding direct calving of glacial icebergs into the lake.

In Lundy canyon, the DEM suggests that the most extensive moraines preserved would be partially flooded by a lake at 2155 masl; however, mapping of faults in the Mono Basin by Bursik and Sieh (1989) indicates that the toes of the moraines have been down-dropped from their original position by ~21 m. When the eastern ends of the moraines are “restored” up to their original position relative to the canyon, they are no longer in contact with a lake at 2155 masl. This exercise, coupled with the lack of any geomorphic features on the moraines indicating interaction with the lake shore, strongly suggests that the ice rafting was not due to calving glaciers, but rather was a product of lake ice freezing around the shoreline.

Controls on shore-ice rafting

Variability of debris rafting by shore ice may be a function of several components of the shore-ice system: (1) the formation of shore ice (timing, thickness, location); (2) the supply of sediment available to be frozen into the ice; and (3) patterns of melting allowing the movement of sediment-laden ice offshore. In modern mid-latitude lakes, the formation of shore ice is dominantly controlled by patterns of air temperature (Brown and Duguay, 2010). Model and paleoproxy evidence indicate that average annual temperatures in the Great Basin were 5–8°C colder than modern during the last glacial maximum (Bromwich et al., 2004 and references therein), and while less is known about temperatures during the earlier part of the study period and about the seasonal distribution of temperature change, winter shore ice forms in the modern lake, and thus it is likely that air temperature was not the limiting factor in shore-ice formation in late Pleistocene Mono Lake.

In the modern Mono Basin, the main control on the amount and location of shore ice is flux of freshwater from the major Sierran streams. Ice forms first and most frequently in the western embayment, where fresh stream water forms a low-salinity surface layer over the dense, saline lake water, and freezes to form a crust of ice of variable extent and thickness. For example, during the strong El Niño winter of 1982–83, unusually thick and extensive ice covered the lake from the western shore all the way out to Paoha Island (>5 km from the western shore of the lake; Figure 1). Climatic data collected at Cain Ranch in the Mono

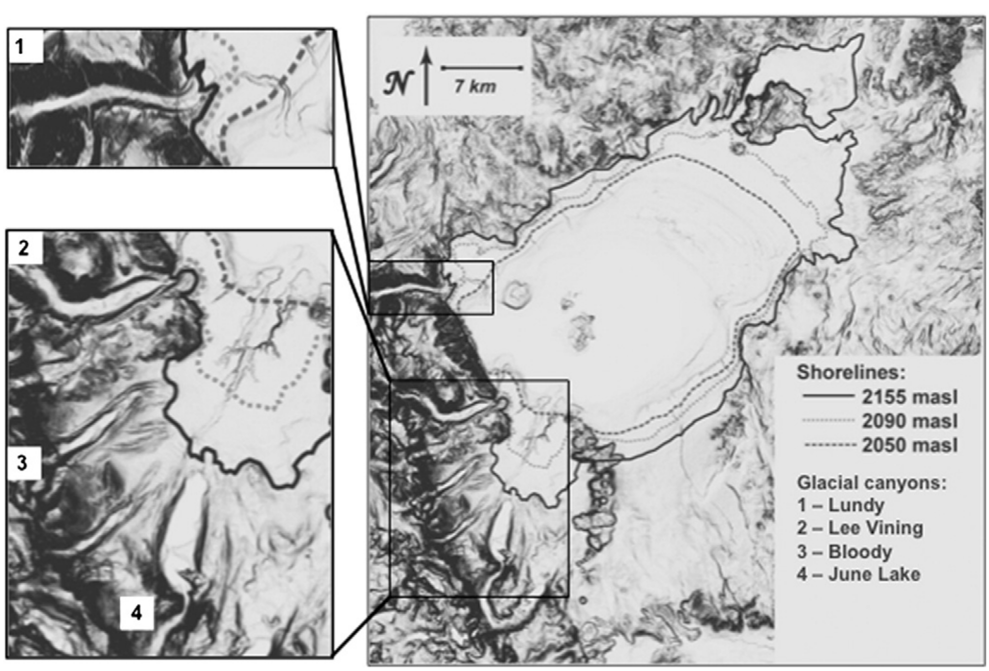

Figure 6. US Geological Survey digital elevation model of the Mono Basin, showing lake levels occupied during the last glacial period long enough to form distinct terraces and major canyons glaciated in the Pleistocene. The shoreline at 2155 m above sea level (masl) was occupied during the final highstand of the lake, at ~14–17 ka (Lajoie, 1968); moraines are mapped and dated in Phillips et al. (1996) and Schaefer et al. (2006).

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Basin from 1931 to 2001 by the Los Angeles Department of Water and Power (LADWP) show that temperatures were within the normal range, but precipitation was 1.5–2.5 times the 1931–2001 average. This precipitation, combined with an unusually large release of water from the Grant Lake Reservoir (~5 times the 1942–1994 average) and an unusual rain-on-snow event in mid-January that melted snowpack at high elevations, resulted in inflow the equivalent of 15% of the lake volume. The strong salinity contrast between the fresh inflow and the 1983 lake (salinity = 99 g/L) promoted stratification (Jellison and Melack, 1993) and the consequent thick ice cover.

Comparison of the IRD record with calcium carbonate flux to the Wilson Creek Formation (Fig. 7), combined with physical stratigraphic and Sr-isotope evidence that calcium carbonate flux is positively correlated to lake level (Zimmerman et al., in press) suggests that freshwater inflow was the major control on the IRD. In the case of the three major highstands indicated by the stratigraphy, a large volume of water was required to raise lake level many tens of meters, too much to be attributed to melting of the mountain glaciers. The correspondence of the peaks in lake level, carbonate, and IRD to the three periods of high spring insolation over the Mono basin probably indicates a general re-organization of the ocean–atmosphere system, resulting in much higher effective wetness. Similar late Pleistocene increases in wetness in eastern (Wang et al., 2004) and southeastern (Cruz et al., 2005) Brazil correlative to insolation peaks were attributed to a larger

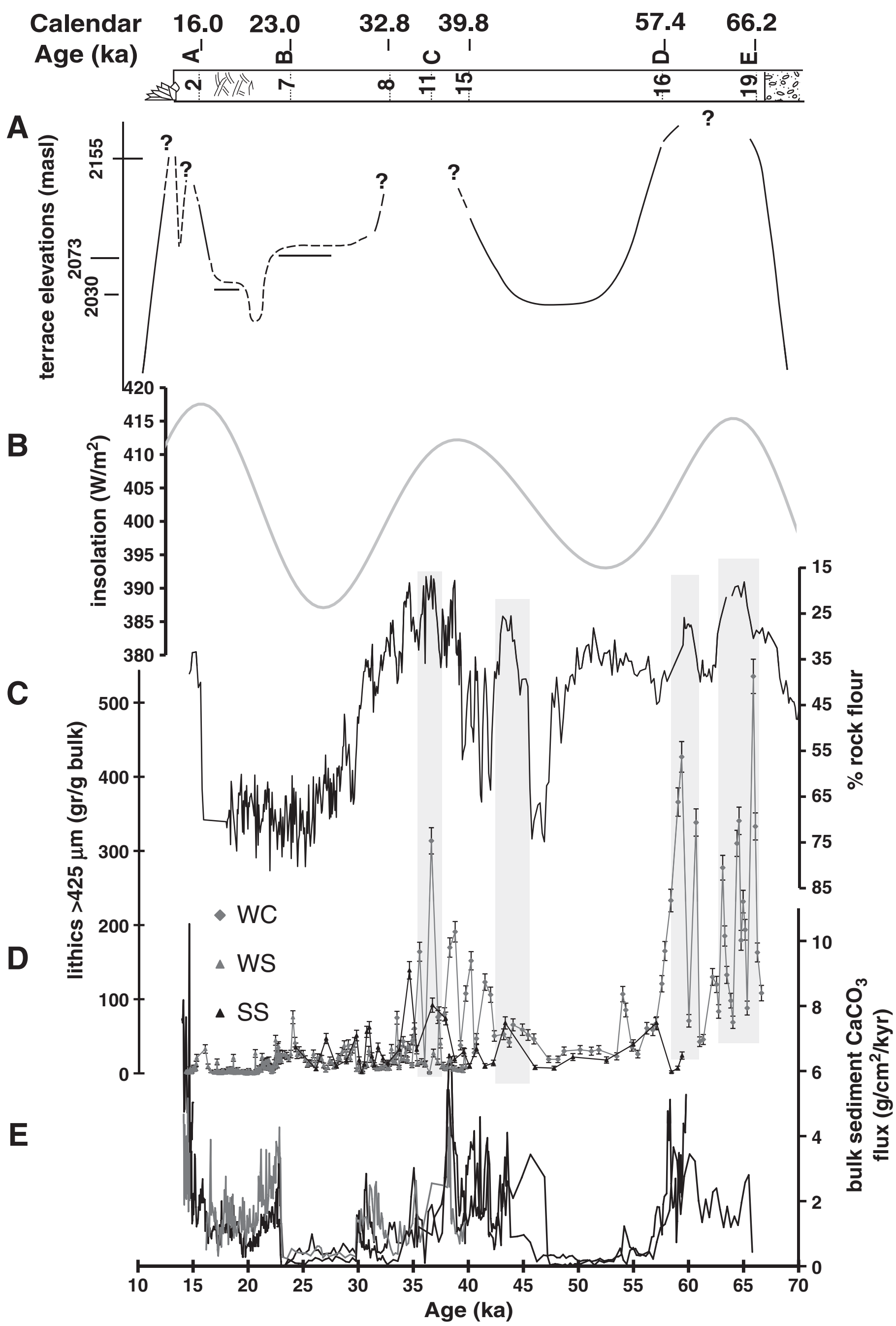

Figure 7. Correlation of ice-rafted debris to lake level and extra-basin climate records. (A) Stratigraphic evidence for lake level compiled by Lajoie (1968) shows the dominance of precession forcing, probably (B) spring insolation (Berger, 1978). In the Owens basin, percent rock flour (C), related to the activity of Sierran glaciers, shows both precessional and millennial variability (Bischoff and Cummins, 2001). The Wilson Creek Formation ice-rafted debris records (D) are very similar to lake level indicated by bulk-sediment carbonate flux (E) to the same sediments, probably because both are controlled by freshwater input to the lake.

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land–sea temperature gradient affecting atmospheric circulation and increasing on-shore moisture transport. The driver of millennial-scale variability within the lake highstands is less clear, and may have been extra-basinal climatic variations in precipitation/evaporation, or possibly internal variability such as meltwater discharge from the Sierran glaciers.

The low abundance of IRD during the last glacial maximum (~25–18 ka), when carbonate flux indicates relatively high lake levels, and during the deglacial period (~18–14 ka), when lake level reached its highest level of Wilson Creek time, requires some additional explanation. During the deglacial highstand, one possibility is a break-down of the freshwater-stratification mechanism. The tremendous volume of water required to raise lake level (~20 times the volume of the modern lake) and the rapidity of the transgression (<1000 years) possibly resulted in a relatively well-mixed, freshwater lake, at least in the shallower portions. In addition, it may be that the supply of stream cobbles along the high shoreline was much less than at more typical late Pleistocene levels, where stream channels and fluvial deposits were better-developed, or that the very rapidity of the rise suppressed the rafting of debris.

On the other hand, during the glacial maximum, stratigraphic evidence suggests that the lake probably stood at levels relatively similar to the two previous highstands, and the paucity of IRD may be due to much colder temperatures. Modern observations and modeling studies indicate that whether a lake ices over completely depends on a balance between the heat stored in the lake and the magnitude and persistence of cold air temperatures. This balance is illustrated by the extent of ice cover in the Laurentian Great Lakes of North America. Lake Superior, although the largest in volume (12,100 km^3) and mean depth (148 m), frequently has >80% ice cover, because it is the northernmost, and thus coldest of the lakes. Lake Ontario, despite its much lower heat storage capacity (1640 km^3 volume and 86 m mean depth), freezes over much less frequently because it is centered ~4° farther south than Superior (Assel et al., 2003). In the case of Mono Lake, very cold temperatures of the glacial maximum may have caused the entire lake surface to freeze. If spring melting began around the shoreline, where the land surface heats before the ice surface, debris-laden shoreline ice would not have the opportunity to raft the debris off-shore. It may be that in full-glacial Mono Lake, much colder mean annual temperatures, and possibly less seasonal variation in temperature, drove different patterns of freezing and melting, suppressing the rafting of debris into the deep lake.

Climatic drivers of freshwater input

The Wilson Creek IRD record presented here shows two timescales of variability, dominated by precession, corresponding to local spring insolation (March–April–May; Figure 7). The few high-resolution lake records in the Great Basin typically show dominantly millennial-scale variability, but the glacial flour record of Bischoff and Cummins (2001) in Owens Lake shows both precessional- and millennial-scale variability. The Owens flour record is interpreted to reflect the production of rock flour by active glaciers, and multi-millennial peaks in flour generally fall during times of low summer insolation. Distinct lows in flour production in the Owens Basin occur at 64 ka, 60 ka, 43 ka, and 36 ka, and match well with peaks, or bundles of peaks, in Wilson Creek IRD, indicating that periods of less glacial activity in the Owens Basin generally coincided with more shore-ice rafting in Mono Lake (Fig. 7).

The correspondence of increased shore ice driven by freshwater pulses at Mono Lake with low glacial activity at Owens Lake appears to support the inference that flour delivery to the lake is a function of production and occurs during peak glacial periods, rather than increased delivery of flour by meltwater from receding glaciers (Bischoff and Cummins, 2001). It may also indicate that glacial advance in the Sierra was more dominated by low insolation and cold temperatures, and less by increased precipitation, which Hostetler and Clark (1997) suggested was equally important to growth of western glaciers.

Globally, millennial-scale variability during MIS 3 is dominated by correlatives to the Dansgaard–Oeschger oscillations first identified in Greenland ice cores (Cacho et al., 1999; Peterson et al., 2000; Wang et al., 2001; Altabet et al., 2002). Recently, evidence has accumulated that the oscillations are due to changes in North Atlantic sea ice and ocean–atmosphere circulation, with cold stadials characterized by extensive sea ice around Greenland, producing extremely cold winters in the North Atlantic, displacement of the Intertropical Convergence Zone (ITCZ) to the south, and a weaker East Asian monsoon Denton et al. (2005). In the Santa Barbara Basin, only a few hundred kilometers to the southwest of Mono Lake, D-O stadials are expressed as sea surface and thermocline cooling, due to a strengthening of the cold California Current (and/or weakening northward transport of subtropical water), related to the strength and position of the North Pacific High (Hendy and Kennett, 1999; 2000). These changes almost certainly affected the Mono and Owens Lake basins, but, as noted by Bischoff and Cummins (2001), neither chronology is yet sufficient to make precise millennial-scale correlations.

Conclusions

DEM and geomorphic evidence together indicate the likelihood that ice-rafted detritus, as represented by the >425 μm and >10 mm sediment fractions in the Wilson Creek Formation, was carried by lake ice formed around the shoreline, rather than rafted by Sierran glacier ice. Shore-ice rafting varied on both precessional and millennial timescales, and correspondence of IRD peaks and peaks in calcium carbonate flux suggests that both were controlled by freshwater flux. Pulses of freshwater likely caused temporary stratification of the lake, and cold-season formation of shore ice. Ice formation and break-up patterns, and possibly supply of debris, were secondary controls, and may explain the little to no ice rafting recorded in the last glacial maximum by the Warm Springs IRD record.

Lake-level increases of up to 100 m during spring insolation peaks preclude melting of Sierran glaciers as a cause of increased lake level and ice rafting during those periods, because the lake rises require a much larger volume of water than can be provided by glacial melting. However, millennial-scale IRD variability during lake highstands may be the effect of glacial melting or of relatively small increases in precipitation. Several peaks in ice-rafting correspond to periods of low glacial flour delivery to Owens Lake, reinforcing the inference that IRD is not due to glacial processes. Unfortunately, precise, robust correlation of the millennial peaks in Mono Lake IRD to canonical MIS 3 records awaits improvement in the Wilson Creek Formation age model.

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