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Antiphasing between Rainfall in Africa's Rift Valley and North America's Great Basin

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The beginning of the Bølling-Allerød warm period was marked in Greenland ice by an abrupt rise in δ^{18}O, an abrupt drop in dust rain, and an abrupt increase in atmospheric methane content. The surface waters in the Norwegian Sea underwent a simultaneous abrupt warming. At about this time, a major change in the pattern of global rainfall occurred. Lake Victoria (latitude 0°), which prior to this time was dry, was rejuvenated. The Red Sea, which prior to this time was hypersaline, freshened. Lake Lahontan, which prior to this time had achieved its largest size, desiccated. Whereas the chronologic support for the abruptness of the hydrologic changes is firm only for the Red Sea, in keeping with evidence obtained well away from the northern Atlantic in the Santa Barbara Basin and the Cariaco Trench, the onset and end of the millennial-duration climate events were globally abrupt. If so, the proposed linkage between the size of African closed basin lakes and insolation cycles must be reexamined. © 1998 University of Washington.

Key Words: **Africa; Great Basin; paleoclimate; Lake Victoria; Lake Lahontan; ^{14}Cages; abrupt climate change.**

Johnson *et al.* (1996) reported an astounding phenomenon. Based on sediment cores and seismic profiles across the deep portion of equatorial Africa's Lake Victoria, they concluded that prior to about 12,800 ^{14}C yr ago, this lake was dry. The evidence comes from a soil encountered in piston cores at the base of the late-glacial Holocene limnic sequence. The sound reflection from the sediment–soil interface allows its extent to be traced across the entire deep portion of the Lake Victoria basin. Whereas it has long been known that the rift valley lakes experienced dry conditions during peak glacial time (Haberyan and Hecky, 1987; Gasse *et al.*, 1989; Taylor, 1990), the Victoria results provide a means of quantifying the magnitude of this drying.

We say astounding because in order to dry out this lake, an enormous change in climate is required. To see this, we must consider today's water budget (Table 1). Currently, the amount of water entering the lake from the rivers that feed it is comparable to the amount overflowing into the White Nile from Lake Victoria (Piper *et al.*, 1986). Based on rainfall at stations around the lake (Fig. 1), it is estimated that four times as much water is added to the lake by direct rainfall as from rivers. Taken together, these three sets of measurements suggest that evaporation from the lake surface must nearly match rainfall onto the lake (i.e., ca. 1.6 m/yr). Indeed, independent estimates of evaporation rate are consistent with this conclusion (Crul, 1995). The central 20% of the lake's basin is deeper than 60 m. It is in this portion that the coring and seismic surveys conducted by Johnson *et al.* (1996) were concentrated (Fig. 1). Clearly, in order to dry the lake, its size would have to be reduced by at least a factor of ten. Assuming no change in evaporation rate, this would require that the input of water to the lake be reduced tenfold. However, as today only 9% of the rainwater

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TABLE 1
Vital Statistics and Water Budget for Lake Victoria[a]

Lake area	0.69×10^5 km^2
Dry drainage area	1.94×10^5 km^2
Total area	2.63×10^5 km^2
Lake volume	2.76×10^3 km^3
Mean depth	40 m
Maximum depth	79 m
Inputs to lake	
Rain	1.66 m/yr
River	0.42 m/yr
Total	2.08 m/yr
Losses from lake	
Evaporation	1.59 m/yr
Outflow	0.49 m/yr
Total	2.08 m/yr
H_2O residence time	~20 yr

[a] Based on Crul (1995).

falling onto the land portion of the Victoria drainage basin is discharged into the lake, the fractional reduction in rainfall need not be nearly as large as the reduction in lake size. For example, at the −60 m level, 80% of the former lake area would have become land. This complicates the problem of estimating the paleo-rainfall rate. The relationship between the steady-state size of the lake (A), the rate of rainfall (R), and the rate of evaporation (E) over the lake is given by the following equation:

$$EA = fR(D - A) + RA,$$

where D is the area of the drainage basin and f is the fraction of rain falling onto the land portion of the drainage basin that runs off into the lake. Solving for R, this equation becomes

$$R = \frac{E(A/D)}{f + (1 - f)(A/D)}.$$

Assuming that the evaporation rate over the lake and the fraction of runoff from the land portion of the drainage basin were equal to their present day values (i.e., 1.6 and 0.09 m/yr, respectively), then this equation becomes

$$R = \frac{0.42(A/A°)}{0.09 + 0.24(A/A°)},$$

where $A°$ is the present size of the lake (i.e., 0.26 D). This relationship is displayed graphically in Figure 2. As can be seen, in order for the lake to dry up, the rainfall rate would have to be reduced by at least a factor of four (i.e., to no more than 0.4 m/yr). Of course, with drier conditions, it might be expected that the evaporation rate over the lake would rise and that the fraction of runoff from the land portion of the basin would fall. However, to the extent that the tropics cooled during glacial time, evaporation rates would have been reduced. Unfortunately, there is no way to assess how large these changes would be. Nevertheless, it is clear that in order to dry up the lake, the rainfall in the Victoria drainage basin must have been far lower than at present.

The documentation by Johnson *et al.* (1996) of dry conditions in the equatorial portion of the African rift zone prior to 12,800 yr ago is consistent with previous studies (Table 2). Taylor (1990) and Bonnefille *et al.* (1990) provided pollen evidence for dry conditions during the period 21,000 to ca. 12,000 ^{14}C yr ago. Roberts *et al.* (1993) presented evidence for dry conditions prior to 12,700 yr B.P. in the Lake Magadi basin (2°S). Gasse *et al.* (1989) documented low stands of Lake Tanganyika (3° to 9°S) from 22,000 to 13,000 ^{14}C yr ago, with a wet phase following 13,000 ^{14}C yr ago. Although we would like to believe that the studies by Johnson *et al.* (1996) and Gasse *et al.* (1989) indicate that the transition from wet to dry conditions close to 12,800 years ago was abrupt, we must admit that firm supporting evidence is lacking. Radiocarbon dates are needed for terrestrial macrofossils from basal sediments at various water depths in Lake Victoria. Only if all these ages group close to 12,800 ^{14}C yr B.P. could it be stated with confidence that conditions went from dry to comparable to today's in a short interval of time. Such a series of dates would also firm up the apparent tie between the timing of this wetting and that of the onset of the Bølling-Allerød interval in northern Europe about 12,550 ^{14}C yr ago (Table 3).

The dry interval in Africa's equatorial rift valley corresponds to that during which hypersaline conditions prevailed

TABLE 2
Radiocarbon Dates Related to the Boundary between the Late-Glacial, Cold–Dry Interval, and the Succeeding Wet–Warm Period in Equatorial Africa

Location	Radiocarbon age (yr B.P.)	Reference
Lake Kivu	13,700–12,500	Hecky and Degens, 1973
Lake Victoria	13,750 ± 200	Kendall, 1969
Lake Albert	13,340 ± 190	Livingstone, 1975
Kawasenkoko Swamp	13,835 ± 120	Hamilton, 1982
Kaisungor Swamp	12,650 ± 100	Coetzee, 1967
Sacred Lake	14,050 ± 360	Coetzee, 1967
Laboot Swamp	13,776 ± 80	Hamilton, 1976
Lake Mahoma	12,700 ± 120	Hamilton, 1982
Muchoya Swamp	12,890 ± 130	Morrison, 1968
Muchoya Swamp	13,900 ± 130	Taylor, 1990
Kamiranzovu Swamp	13,575 ± 130	Hamilton, 1982
Lake Tanganyika	12,710 ± 120	Gasse *et al.*, 1989
Kashiru Swamp	13,250 ± 200	Bonnefille *et al.*, 1990
Lake Magadi	12,840 ± 120	Roberts *et al.*, 1993

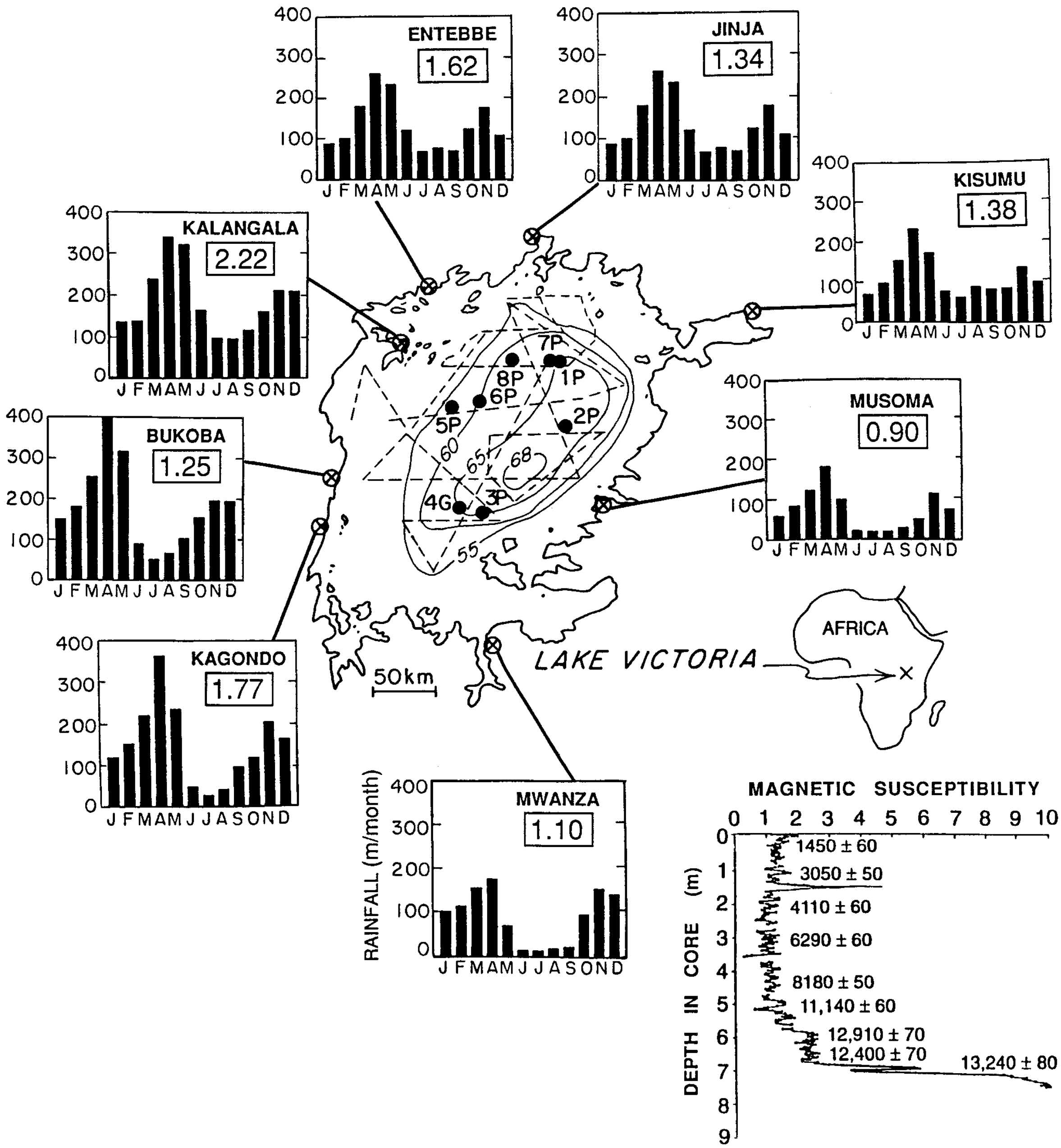

FIG. 1. Map showing the depth contours (in m) for Lake Victoria, the locations of piston cores studied by Johnson *et al.* (1996), and the seismic profiling tracks along which the soil horizon formed during the dry period was mapped. Also shown are the mean monthly rainfall rates (histograms, mm/month) and the mean annual rainfall (in boxes, m/yr) for eight stations (Crul, 1995). Shown on the lower right are the radiocarbon dates obtained by Johnson *et al.* (1996) for core V95-2P which document that the dry period came to a close about 12,800 ^{14}C yr ago.

in the Red Sea (Deuser and Degens, 1969; Hemleben *et al.*, 1996), as indicated by the absence of planktonic foraminifera (Fig. 3) and by thick secondary aragonite coatings on the pteropod shells (Fig. 4). As shown by Bijma (1991), planktonic foraminifera growth is highly impaired at salinities above 44 g/L. In this case, the end of this period of hypersalinity was abrupt. It occurred close to 13,000 ^{14}C yr B.P. (Fig. 4). One could postulate that the abruptness of this change merely reflects the point at which a more gradual end to the period of dry conditions brought the salinity down to the point where foraminifera could survive. However, in this case, the match between the timing of Lake Victoria's rejuvenation and the Red Sea's passage through a salinity threshold would have to be written off as a coincidence. To us, this match suggests a rapid change in regional climate.

Having maintained a continuing interest in the history

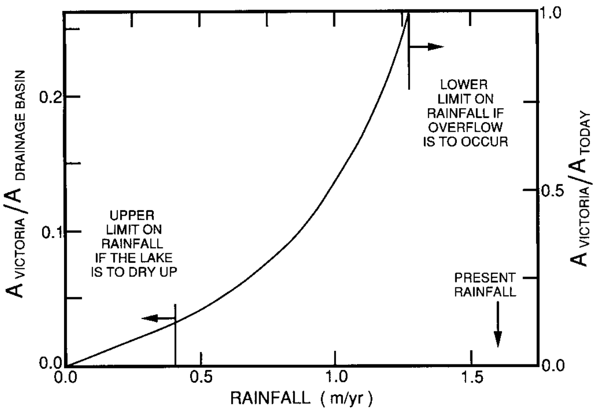

FIG. 2. Steady-state size of Lake Victoria as a function of the rate of rainfall. The assumption is made that the rate of evaporation over the lake (i.e., 1.6 m/yr) and the fractional runoff of rain falling on the dry portion of the drainage basin (i.e., 0.09) remain unchanged. The rainfall required to maintain the lake just below its outflow level is 1.25 m/yr. Assuming that in order to dry up entirely the area of the lake must be reduced to less than 10% of its present area, the rainfall during the period of desiccation could have been no more than 0.4 m/yr (i.e., less than a quarter of the present rate).

of another similar large intermountain water body, i.e., Lake Lahontan, located in the western part of the Great Basin (36°–42°N), we were struck by the asymmetry of its late-glacial wetness record with that of Lake Victoria. During the interval 21,000 to 13,000 ^{14}C yr B.P., Lake Lahontan and other lakes in the Great Basin (i.e., Bonneville, Searles, and Russell) were far larger than today's small remnants (Benson *et al.,* 1990, 1995). Very close to the time that Victoria was rejuvenated, Lake Lahontan experienced a dramatic desiccation that reduced its area close to that occupied by its late Holocene remnants (Table 4). The area of these lakes in the year 1900 (i.e., before diversions of its feed rivers for irrigation use) was about one tenth that of Lake Lahontan at its maximum extent (Benson *et al.,* 1990).

While not precisely defined, the desiccation of Lake Lahontan was well underway no later than 12,300 ^{14}C yr ago and it began no earlier than about 13,800 ^{14}C yr ago. The lower age limit is firm because it is based on radiocarbon dating of terrestrial wood samples from packrat middens in small rock shelters 90 m below the highest level of the lake (Table 5). Studies dating back to that of Russell (1885) conclude that the largest size achieved by the lake occurred close to the end of the last pluvial interval. Radiocarbon dates for $CaCO_3$ associated with the highest shorelines of these lakes average about 12,800 yr and range from 12,200 to 13,800 yr B.P. (Table 5, Fig. 5). Although consistent with the interpretation that this high stand was brought to an end by a sudden desiccation, several red flags must be raised. First, a reservoir correction must be made to account for the difference between the ^{14}C/C for lake ΣCO_2 and that for atmospheric CO_2. As discussed by several authors (Broecker and Walton, 1959; Benson, 1993), this correction could be anywhere from 200 to 700 yr. If the proper correction was toward the high end of this range, when made, it would bring most of these radiocarbon ages below the firm limit set by the packrat midden wood ages. But, another factor could swing the pendulum back toward older ages; namely, exchange with younger CO_2 or HCO_3^- or the deposition of secondary $CaCO_3$ likely reduced the ^{14}C age of all these samples. In hindsight, the early measurements on bulk uncleaned tufa made by Broecker and Orr (1958) clearly document such contamination. Later attempts by Benson (1981) and by Lin *et al.* (1996) using dense and acid-leached tufa give the ^{14}C ages summarized in Figure 5. However, there is still no guarantee that all the contamination was entirely removed. The fact that several quite different types of material (tufa, shell, and organic matter encased in tufa) yield similar ages suggests that contamination is under control. If the proper reservoir correction is at the low end of the permissible range (i.e., ~200 yr), one could take the ages at face value and conclude that the lake stood within 20 m of its highest level between 13,800 and 12,400 yr ago.

However, this conclusion presents a major problem. Uranium series ages of high shoreline tufas having ^{14}C ages of

TABLE 3
Radiocarbon Ages Related to the Onset of the Bølling-Allerød Warm Interval in Northern Europe[a]

Location	Material	Radiocarbon age (yr B.P.)	Reference
Ballybetagh, Ireland	Twig	12,540 ± 80	Cwynar and Watts, 1989
Neuchatel, Switzerland	Ter. macro-fossils	12,490 ± 95	Schwalb *et al.*, 1994
Lobsigensee, Switzerland	Ter. macro-fossils	12,300 to 12,800	Ammann and Lotter, 1989
Zurichsee, Switzerland	Ter. macro-fossils	12,600 ± 200	Lister, 1988
Holzmaar, Germany	Ter. macro-fossils	12,560 ± 80	Zolitschka, 1996
Lago di Monticchio, Italy	Betula seeds	12,540 ± 130	Watts *et al.*, 1996

[a] The radiocarbon ages for this transition all lie in the range 12,550 ± 100 yr B.P.

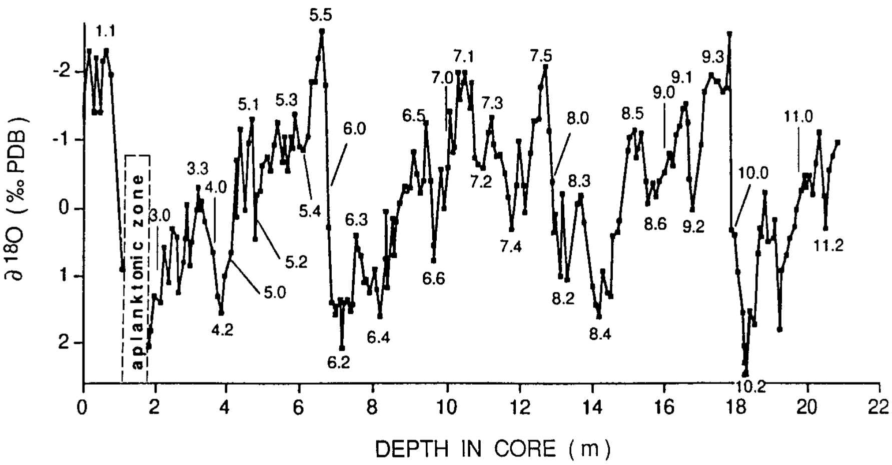

FIG. 3. Oxygen isotope record for planktonic foraminifera from a Red Sea sediment core, KL11 (Hemleben *et al.,* 1996). The exceptionally large glacial to interglacial $\delta^{18}O$ swings are attributed to hypersalinity during glacial times when much of the water flowing in from the Indian Ocean was lost to evaporation. The absence of planktonic foraminifera in the 80-cm-long-section of the core corresponding to marine isotope stage 2 suggests that the interval of hyperaridity lasted ca. 10,000 yr.

~12,500 yr are close to 16,500 cal yr for both Lahontan and Searles (Lin *et al.,* 1996). These calendar ages translate to about 13,700 yr on the radiocarbon time scale (Bard *et al.,* 1992). For Lake Lahontan, the ^{230}Th age is based on a well-constrained isochron (Lin *et al.,* 1996). For Searles Lake, the ^{230}Th/^{232}Th ratio measured in a tufa from the highest shoreline is so large that the isochron approach is not required (Lin 1996; Lin *et al.,* in press). It is possible, of course, that uranium has been lost from the tufas over their lifetime. This explanation seems unlikely because it would be fortuitous that the loss affected the Lahontan and the Searles tufas by the same amount. Thus, in the absence of any satisfactory explanation for the large range in the ^{14}C ages for high shoreline samples and for the discordance between the ^{230}Th and ^{14}C ages on identical tufas, we can conclude only that the desiccation of Lake Lahontan occurred sometime between 13,700 and 12,300 ^{14}C yr ago. While this range brackets the ^{14}C age for the end of Lake Victoria's period of desiccation and that for the end of the

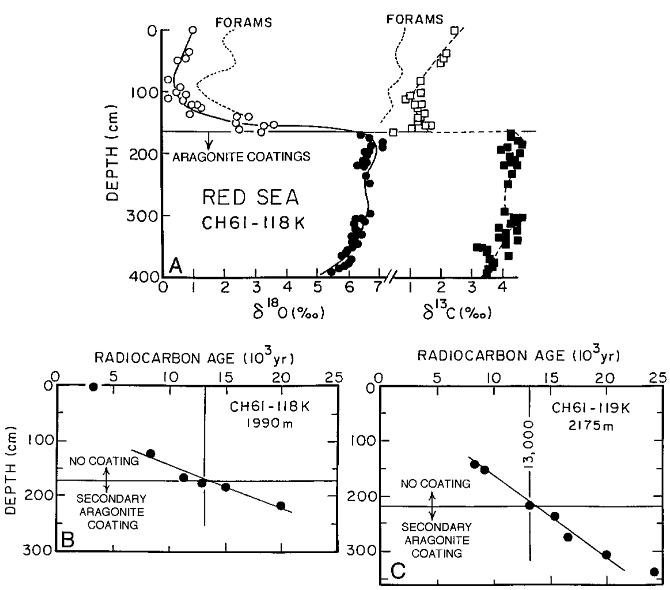

FIG. 4. (A) Oxygen and carbon isotope records from pteropods from the Red Sea sediment cores (Deuser and Degens, 1969). The open circles are for measurements on pteropods free of secondary coatings and the closed circles for those on pteropods heavily encrusted with secondary aragonite. (B and C) ^{14}C ages (corrected for a 400-yr age of surface-water) versus depth in two Red Sea cores. In both, the transition from hypersaline to present conditions occurred about 13,000 ^{14}C yr ago.

TABLE 4
Change in Area of Lakes in the African Equatorial Rist Valley and in the North American Great Basin

Lake	Area of present-day lake (km^2)	Area ~14,000 ^{14}C yr ago (km^2)	$A_{14,000}/A_{present}$
	Africa		
Victoria	69,000	<7000	$<\frac{1}{10}$
	North America[a]		
Lahontan	2420	22,300	~9
Bonneville	5140	51,300[b]	~10
Searles	315	1725	~5
Russell	190	790	~4

[a] See Benson *et al.,* 1990.
[b] Area before overflow and downcutting of outlet (Currey, 1988).

TABLE 5
Radiocarbon Ages for the High Stands of Lakes Lahontan, Searles, and Russell in the Western Great Basin[a]

Location	Elevation (m)	Material	Radiocarbon age (yr B.P.)	Reference
Lahontan post highstand desiccation				
Fishbone Cave	1235	Equus	12,280 ± 180	Benson and Thompson, 1987
Crypt Cave	1240	Juniper	12,350 ± 180	″
Crypt Cave	1240	Juniper + dung	12,240 ± 180	″
Lahontan Basin (Highest Level ∼1330 m)				
Pyramid Lake	1321	Tufa	12,540 ± 190	Benson, 1981
″	1321	″	12,570 ± 190	″
″	1325	″	12,610 ± 180	″
″	1326	″	12,770 ± 190	″
″	1312	″	13,820 ± 200	″
″	1331	″	12,850 ± 190	″
″	1303	″	12,890 ± 190	″
″	1324	″	13,050 ± 190	″
″	1312	″	13,130 ± 190	″
Pyramid Lake	1311	Tufa	13,430 ± 200	Benson, 1981
″	1311	″	13,550 ± 200	″
″	1330	″	13,060 ± 100	Lin *et al.*, 1996
″	1330	″	13,150 ± 100	″
″	1330	″	12,200 ± 100	″
″	1330	″	12,850 ± 100	″
″	1327	″	12,320 ± 100	″
″	1327	″	12,200 ± 100	″
″	1327	″	12,980 ± 100	″
″	1327	″	12,690 ± 100	″
″	1327	″	12,830 ± 95*	″
″	1327	″	12,790 ± 110	″
″	1327	″	12,260 ± 100	″
″	1328	Organic matter	12,870 ± 120	Lin, 1996
″	1311	Shell	13,260 ± 200	Benson, 1981
Black Rock Desert	1306	Tufa	13,810 ± 600	Benson and Thompson, 1987
″	1332	″	12,850 ± 600	″
Walker Lake	1318	″	12,240 ± 160	Benson, 1981
″	1327	″	12,280 ± 160	″
″	1324	″	12,340 ± 160	″
Walker Lake	1324	Tufa	12,690 ± 160	Benson and Thompson, 1987
″	1330	″	13,300 ± 190	Benson, 1981
″	1330	″	13,300 ± 190	″
″	1330	″	13,300 ± 180	″
Carson Sink	1311	″	12,310 ± 150	Benson and Thompson, 1987
″	1323	″	12,980 ± 540	″
″	1327	″	12,700 ± 95	Lin, 1996
″	1325	Shell	13,110 ± 110	″
″	1325	″	13,280 ± 110	″
Searles Lake (Highest stand 695 m)				
Navy Road	695	Tufa	12,430 ± 90	Lin, 1996
Lake Russell (Highest stand 2155 m)				
Monocraters	2155	Tufa	12,910 ± 70	Benson *et al.*, 1990
Black Point	2144	″	12,770 ± 70	″

[a] Ages range from 12,200 to 13,800 ^{14}C yr. Almost all these dates are on beachrock deposits (tufa). Only two are on shell and one is on organic matter encapsulated in the tufa. A reservoir correction estimated to be somewhere between 200 and 700 years has not been included in the table. Uranium series dating of tufas from the high shoreline of Lahontan and Searles give age close to 17,00 or ∼14,000 yr on the radiocarbon scale (Bard *et al.*, 1992). Terrestrial organic matter from pack-rat middens in the Winnemucca caves located 90 m below the highest shoreline of Lake Lahontan demonstrate that drying was well underway by 12,300 ^{14}C yr ago. Therefore, at least some and perhaps all of the ^{14}C ages have been shifted downward by the incorporation of younger $CaCO_3$.

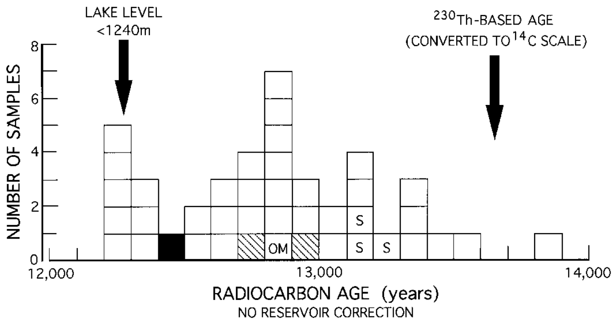

FIG. 5. Histogram of radiocarbon ages (Table 2) for samples collected within 20 m of the highest shorelines of Lake Lahontan (open), Searles Lake (filled), and Lake Russell (shaded). Except for the squares marked S (for shell) and OM (for organic matter encapsulated in the tufa), the results are all on tufa $CaCO_3$. Note that ^{230}Th dates (transformed to the ^{14}C scale) suggest that the raw ^{14}C ages (i.e., without reservoir correction) range up to 1800 years too young. At least the youngest of the tufas must be contaminated with younger carbon, as their ^{14}C ages overlap firm ^{14}C ages on woody terrestrial plants from packrat middens 90 m below the highest shoreline of Lake Lahontan.

Red Sea's hypersalinity period, it leaves open the question as to whether these events were synchronous.

We were interested to learn from B. D. Allen and R. Y. Anderson (personal communication, 1997) of the University of New Mexico that Lake Estancia desiccated shortly after 12,490 ± 60 ^{14}C yr B.P. (based on AMS measurements on thoroughly cleaned hand-picked ostracods). This playa, located southeast of Albuquerque, has deflation blowouts in which the sedimentary record for the last ca. 50,000 yr is well displayed, allowing a more detailed history of pluvial conditions to be reconstructed than is possible for any other Great Basin lake.

We would like to believe that this evidence points to an abrupt change in the pattern of global rainfall. Of course, were this conclusion based on the records from just two places on the globe, it could be passed off as a coincidence. However, the time of this change is tantalizingly close to that of the abrupt onset of the northern Atlantic basin's Bølling-Allerød warm interstade. This event is one of the most prominent features in the Greenland ice core records and also in the pollen records from small lakes north of the Alps (Lotter, 1991). Its radiocarbon age is 12,550 yr B.P. (Table 3). Furthermore, pollen changes in eastern North America (Peteet *et al.*, 1990, 1993; Maenza-Gmelch, 1997a, 1997b; Kneller and Peteet, 1998), and changes in the beetle assemblage in the Rocky Mountains (Elias, 1996) and of pollen in the Chilean lake district (Lowell *et al.*, 1995) occurred at about this time. Also, meltwater event #1 revealed in the Barbados coral record occurred on the heels of this event (Fairbanks, 1989). As proponents of abrupt and globally synchronous climate changes, we take these similarities in timing to indicate, as is the case for the abrupt onset and demise of the Younger Dryas cold event, that the climate change at the onset of the Bølling-Allerød interstade was a global event. Nevertheless, we must admit that at present the accuracy of relative dating is no better than ±500 yr.

It should be noted that we take a different view of Africa's pluvial history than do many authors. Following the lead of Kutzbach and Street-Perrott (1985), it has become common practice to relate the changes discussed here to the cycle in the strength of the monsoon caused by the orbitally induced cycles in seasonality over Africa and Asia. The fact that the transition from dry to wet conditions occurred during the rise toward a maximum in northern hemisphere seasonality fits well with this explanation. On the other hand, the timing of this transition also seems to fit neatly into the record of abrupt events in the northern Atlantic basin. The frequency of these events is far too high to be attributable to Milankovitch forcing, so the question is: did rainfall in equatorial Africa follow seasonality or did it respond abruptly to a switch in the climate system's mode of operation? Whereas there is no doubt that, when averaged over thousands of years, the Earth's climate has been paced by Milankovitch cycles, the climate record appears to be telling us that, rather than preceding in smooth sinusoids, climate has responded by jumping from one mode of operation to another (Broecker and Denton, 1989). Thus, whereas Kutzbach and his followers may be correct in concluding that the wetting of equatorial Africa was brought about by the increasing seasonality, it is our view that the wetting did not smoothly follow the rise in seasonality but came mainly in a single jump that reflected a reorganization of the Earth's climate system at the onset of the Bølling-Allerød warm interval.

This conclusion is consistent with the records of δ^{18}O (Dansgaard *et al.*, 1989), dust fall (Taylor *et al.*, 1993), the atmospheric methane content (Chappellaz *et al.*, 1993) of the Greenland ice cores, and of conditions in the Santa Barbara Basin (Behl and Kennett, 1996) and the Cariaco Trench (Hughen *et al.*, 1996). Indeed, the onset of the Bølling-Allerød warm interval appears to have been marked by an abrupt reorganization of the Earth's climate system.

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