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Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada

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Abstract

Continuous, high-resolution δ^{18}O records from cored sediments of Pyramid Lake, Nevada, indicate that oscillations in the hydrologic balance occurred, on average, about every 150 years (yr) during the past 7630 calendar years (cal yr). The records are not stationary; during the past 2740 yr, drought durations ranged from 20 to 100 yr and intervals between droughts ranged from 80 to 230 yr. Comparison of tree-ring-based reconstructions of climate change for the past 1200 yr from the Sierra Nevada and the El Malpais region of northwest New Mexico indicates that severe droughts associated with Anasazi withdrawal from Chaco Canyon at 820 cal yr BP (calendar years before present) and final abandonment of Chaco Canyon, Mesa Verde, and the Kayenta area at 650 cal yr BP may have impacted much of the western United States.During the middle Holocene (informally defined in this paper as extending from 8000 to 3000 cal yr BP), magnetic susceptibility values of sediments deposited in Pyramid Lake's deep basin were much larger than late–Holocene (3000–0 cal yr BP) values, indicating the presence of a shallow lake. In addition, the mean δ^{18}O value of $CaCO_3$ precipitated between 6500 and 3430 cal yr BP was 1.6‰ less than the mean value of $CaCO_3$ precipitated after 2740 cal yr BP. Numerical calculations indicate that the shift in the δ^{18}O baseline probably resulted from a transition to a wetter ($>30\%$) and cooler (3–5°C) climate. The existence of a relatively dry and warm middle-Holocene climate in the Truckee River–Pyramid Lake system is generally consistent with archeological, sedimentological, chemical, physical, and biological records from various sites within the Great Basin of the western United States. Two high-resolution Holocene-climate records are now available from the Pyramid and Owens lake basins which suggest that the Holocene was characterized by five climatic intervals. TIC and δ^{18}O records from Owens Lake indicate that the first interval in the early Holocene (11,600–10,000 cal yr BP) was characterized by a drying trend that was interrupted by a brief (200 yr) wet oscillation centered at 10,300 cal yr BP. This was followed by a second early-Holocene interval (10,000–8000 cal yr BP) during which relatively wet conditions prevailed. During the early part of the middle Holocene (8000–6500 cal yr BP), high-amplitude oscillations in TIC in Owens Lake and δ^{18}O in Pyramid Lake indicate the presence of shallow lakes in both basins. During the latter part of the middle Holocene (6500–3800 cal yr BP), drought conditions dominated, Owens Lake desiccated, and Lake Tahoe ceased spilling to the Truckee River, causing Pyramid Lake to decline. At the beginning of the late Holocene ($\sim$3000 cal yr BP), Lake Tahoe rose to its sill level and Pyramid Lake increased in volume. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

From the perspective of the Greenland ice-core records, the onset of the Holocene occurred $\sim$11,600 cal yr BP with the termination of the Younger Dryas cold interval (Alley, 2000). Within North America, the Holocene has generally been assigned a

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tripartite structure with the middle Holocene being generally warmer or drier than the early and late Holocene. Because climate does not evolve synchronously throughout North America, the boundaries between the three intervals differ from region to region. For the purposes of this paper, the middle Holocene is considered to have occurred within the Great Basin between approximately 8000 and 3000 cal yr BP.

In this paper we use the word drought in a variety of ways. For the historical period (the last 100 yr), drought indicates times when water shortage adversely affected human populations. For the late Holocene (the last 3000 yr), drought in the Truckee River–Pyramid Lake surface–water system indicates times of persistent lake-size decline. And for the middle Holocene, drought signifies times when Lake Tahoe did not overflow.

During the 1930s, severe drought impacted the western and mid-continental United States (Hecht, 1983; Woodhouse and Overpeck, 1998), generating great concern regarding the frequency and duration of such events. In the Sierra Nevada and the Great Basin of the arid West, climate records were extended by dating stumps of submerged trees that had taken root during drier times (Harding, 1935; Lawrence and Lawrence, 1961; Harding, 1965) and by using tree-ring widths to reconstruct records of prehistoric river discharge (Hardman and Reil, 1936). Droughts have reoccurred since the late 1930s but it was not until the late 1980s and early 1990s that prolonged drought once again affected the Sierra Nevada, as evidenced by hydrologic closure of Lake Tahoe and persistent below-average discharge of the Truckee River (Fig. 1).

Seven years of drought within an 8-yr period (1987–1994) (Fig. 1) spawned renewed interest in the history and prehistory of such events. Recent tree-ring reconstructions, employing sophisticated statistical calibrations, have extended Sierra Nevada and Great Basin precipitation and discharge records back more than a 1000 yr (Graumlich, 1993; Hughes and Funkhouser, 1998; Meko et al., 1999) and AMS ^{14}C studies of stumps from Sierran lakes have highlighted severe droughts that terminated about 840 and 600 cal yr BP (Stine 1990, 1994).

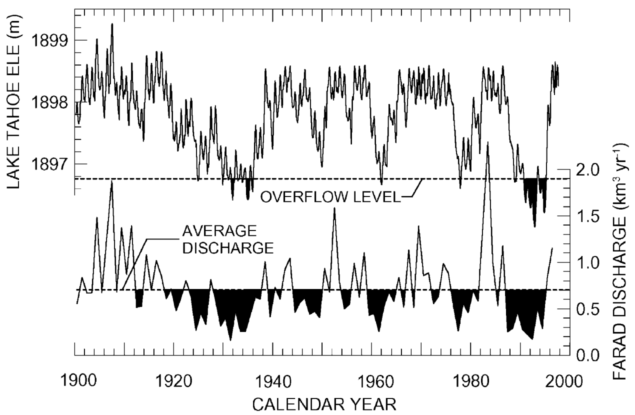

Fig. 1. Annual discharge of the Truckee River at Farad, California, and monthly elevation of Lake Tahoe at Tahoe City, California, since 1900. Only minor consumptive losses of Truckee River water occur upstream of the Farad gage (Fig. 5). Solid areas in top panel indicate times that Lake Tahoe did not overflow to the Truckee River. Solid areas in lower panel indicate times when flow of the Truckee was less than the historical mean-annual rate of 0.70 km^3 yr^{-1}. Note that most minima in lake level correspond to minima in discharge rates.

During the 1930s drought, Harding observed 11 rooted stumps which had been exposed by receding water along the south shore of Lake Tahoe. Harding (1965) later reported ^{14}C ages of two of these stumps rooted at elevations ~9 cm below that of the natural sill of Lake Tahoe (1896.8 m). One stump yielded dates of 4250 ± 200 and 4790 ± 200 ^{14}C yr BP, and the other stump yielded a date of 4460 ± 250 ^{14}C yr BP. Harding (1965) was not able to determine if the submerged stumps were the result of drier climate or tectonics, stating that "…the age of these stumps is sufficiently long to include time enough for climate changes and orographic movement". In a later section of this paper we show that δ^{18}O and magnetic susceptibility data from Pyramid Lake sediments indicate that Lake Tahoe remained below its overflow level during much of the middle Holocene.

Between 1989 and 1992, Lindström (1990) located 20 more stumps along the south side of Lake Tahoe. Some of the stumps reach depths as much as 4 m below sill level, and ^{14}C ages from 14 of the stumps range from 5510 ± 90 to 4240 ± 200 ^{14}C yr BP (6290–4840 cal yr BP) (Fig. 2).

There are additional indicators of climate change that point toward a relatively dry middle Holocene in the Great Basin. Thompson (1992) showed that between 7660 and 5450 cal yr BP sedimentation rates in the Ruby Marshes of western Nevada decreased by a factor of three, relative to the late Holocene, indicating either a lowered deposition rate or sediment deflation. In either case, the data suggest a drier middle-Holocene. More recently, Grayson (2000), using a well-dated small mammal sequence from Homestead Cave, Utah, has shown that faunas underwent a decrease in species richness in the middle Holocene in response to more xeric conditions. For example, the decreasing abundance of harvest mice between 9200 and ~3500 cal yr BP indicates a much drier climate than during the early and late Holocene (Grayson, 2000). Farther south in the Great Basin, black mats, formed by spring discharge to wet meadows and shallow ponds, are absent from 7250 to 2500 cal yr BP, also indicating a period of relative aridity (Quade et al., 1998).

Data from lakes fed by Sierran streams also provide evidence of middle-Holocene dryness. The onset of a generally drier climate in the Owens Lake basin, characterized by abrupt oscillations in TIC and δ^{18}O,

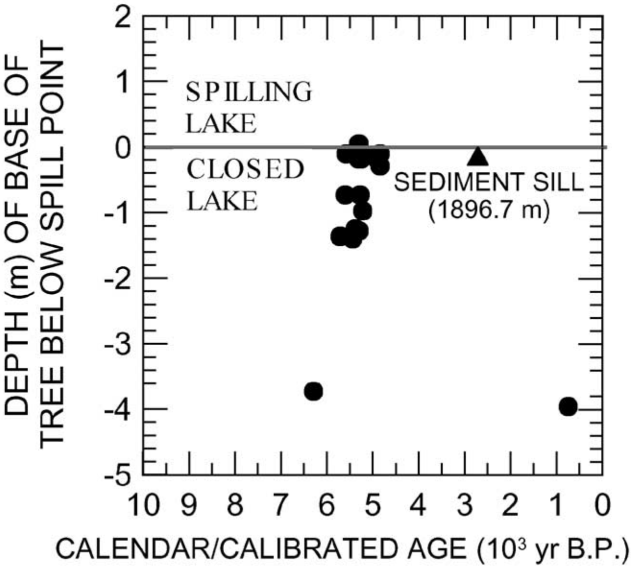

Fig. 2. Age–depth relationships of radiocarbon-dated tree stumps located at or below the natural (sediment) sill level of Lake Tahoe, California. Most of the data were taken from Lindström (1990). Three samples from Baldwin Beach (4250 ± 200 ^{14}C yr BP, 1896.41 m, Beta 56632), and Trout Creek delta (4480 ± 60 ^{14}C yr BP, 1895.82 m, Beta 90208; 4590 ± 60 ^{14}C yr BP, 1895.52 m, Beta 90207) were previously unpublished. Note that the death of a stump as indicated by the ^{14}C age of its outer rings pinpoints the timing of a rise in Lake Tahoe; e.g., a rising lake at $\sim$6290 cal yr BP killed the oldest stump.

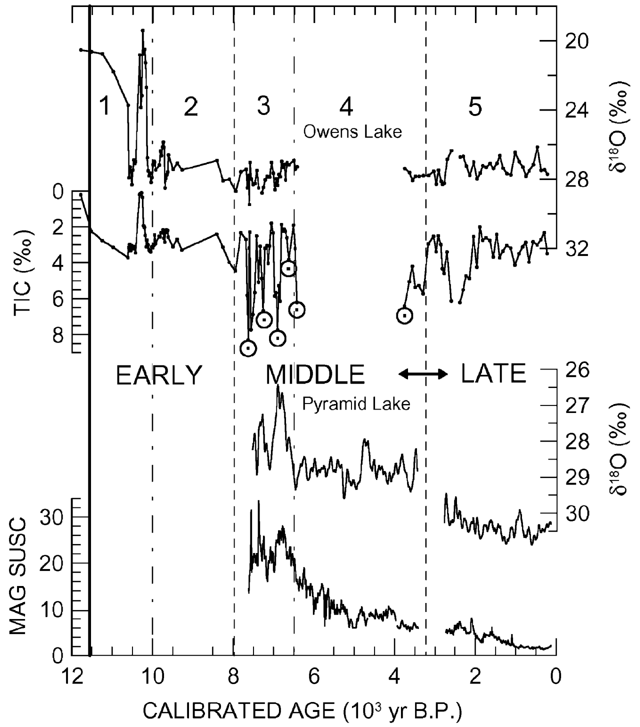

Fig. 3. TIC and δ^{18}O records from Owens Lake core OL84B since 11,600 cal yr BP and δ^{18}O and magnetic susceptibility records from Pyramid Lake since 7630 cal yr BP. Data used in the construction of the Owens Lake records were taken from Benson et al. (2001). The data sets indicate that the Holocene of the western Great Basin can be divided into five distinct climatic intervals.

began at 7700 cal yr BP and ended $\sim$3200 cal yr BP (Fig. 3). A sediment hiatus between 6480 and 3930 cal yr BP suggests that that the lake had desiccated or was below the elevation of the core site during this time (Benson et al., 1997, 2001). It is possible that deflation removed sediment from the lakebed after the lake desiccated, implying that the age of the sediment on the bottom of the hiatus represents a maximum estimation of the beginning of the desiccation. On the other hand, it is also possible that a thick salt formed over the lakebed in this part of the basin as it has in the historical period, preventing sediment deflation. Data from a sediment core taken from Walker Lake, Nevada, indicate that it desiccated at or before 5030 cal yr BP (assuming a 300-yr reservoir effect, Benson et al., 1991).

A warmer middle Holocene has also been inferred from various climate indicators. In the Sheep Mountain area located on the east slope of the White Mountains of California, tree-line elevations were relatively high between >5700 and 4100 cal yr BP. The tree line fell 100 m between 4100 and 3500 cal yr BP, implying a 1°C decrease in warm-season temperatures (La Marche, 1973). Tree line fell another 70 m $\sim$900 cal yr BP, indicating an additional 0.7°C decrease in air temperature. Grayson (1993) has shown that pikas, which cannot bear the heat of desert environments, disappeared from low-elevation sites throughout the Great Basin $\sim$7850 cal yr BP. Montane species of plants are common in middens from the eastern Great Basin before $\sim$7400 cal yr BP, whereas younger assemblages are dominated by plant species that point to a rise in summer temperatures, perhaps coupled with an increase in summer rainfall (Thompson, 1990).

Middle-Holocene aridity also appears to have affected indigenous populations. Textile dates from archeological sites located in the western Great Basin suggest that few people inhabited rock shelters between 10,000 and 2500 cal yr BP (Fig. 4). Distributions of this type, with a characteristically low middle-Holocene site occupation, are common in the Great Basin (Grayson, 1993, 2000).

The various climate indicators show that Great Basin middle-Holocene climate was characterized by warmer summers and aridity. However, the timing of the middle-Holocene warm/dry period appears to vary with site location and with the type of climate indicator, a subject we will return to later. We also hasten to point out that the middle Holocene was not always dry. There is evidence for wet periods during the middle Holocene from the Lahontan basin, the Mono Lake basin, and from Diamond Pond. Kramer Cave is part of the Falcon Hill archeologic site located at the northwestern edge of the Winnemucca Lake basin. Ten radiocarbon dates ranging from 3900 ± 100 to 3620 ± 30 ^{14}C yr BP

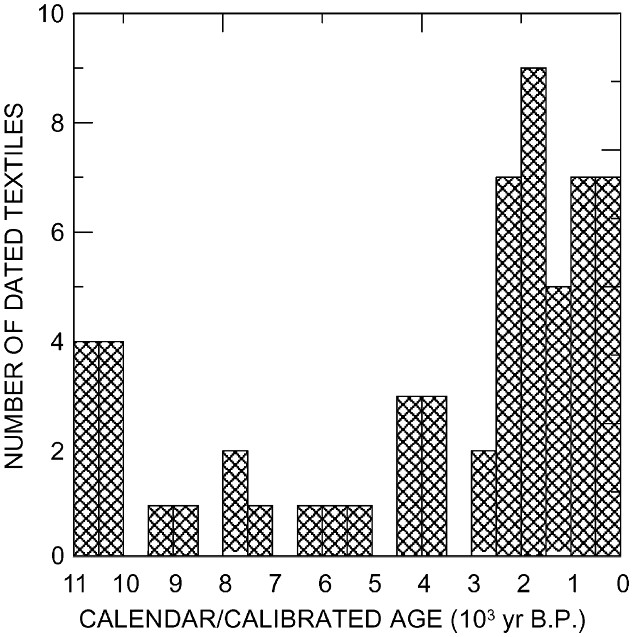

Fig. 4. Histogram of dates on archaeological textiles from the western Great Basin (from data base compiled by Susan McCabe and Eugene Hattori). Multiple dates on samples from a single time horizon have been eliminated.

(~4320–3920 cal yr BP) were obtained on artifacts recovered from the deposits (Long and Rippeteau, 1974). Included within the deposits were fish vertebrae (*cui-ui* and cutthroat trout) and the remains of western pond turtles, indicating that the Winnemucca Lake basin held water at this time (Hattori, 1982). Spikes in cattail pollen found in Hidden Cave between 3800 and 3600 ^{14}C yr BP (4160–3880 cal yr BP) (Wigand and Mehringer, 1985) may attest to the presence of nearby marshes and deepening of lakes in the Lahontan Basin's Carson Sink at this time (Grayson, 1993). There is also an increase in the number of archeological textiles between 4500 and 3500 cal yr BP in the western Great Basin, suggesting an increase in indigenous populations (Fig. 4). Evidence for an extremely wet period in the Mono Lake basin also occurs at this time (the Dechambeau Ranch highstand, ~3770 cal yr BP) (Stine, 1990a, b). In addition, Diamond Pond in southeastern Oregon experienced a sharp increase in aquatic plant seeds between 3720 and 3480 ^{14}C yr BP (4010 and 3700 cal yr BP) (Wigand, 1987).

2. The Truckee River–Pyramid Lake system

In this paper we discuss a 7630-yr record of climate change from Pyramid Lake Nevada. Pyramid Lake was selected as a study site for several reasons:

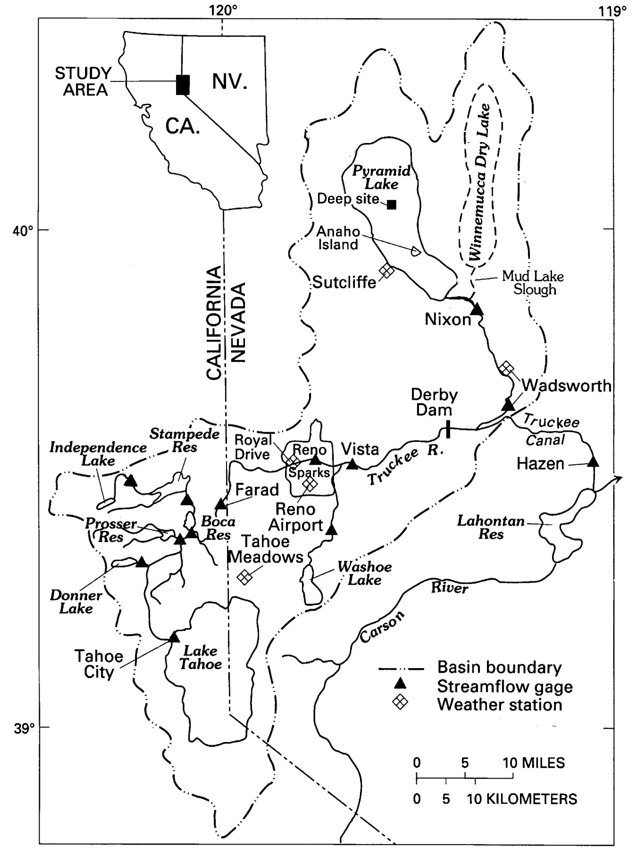

Fig. 5. Location map of the Lake Tahoe and Truckee River–Pyramid Lake surface–water system. Greater than 90% of the Truckee River input to Pyramid Lake occurs above the Farad, California, gage. Since 1906, diversion of ~54% of the flow of the Truckee River has occurred via the Derby Dam.

2.1. Pyramid Lake is part of a relatively simple hydrologic system

The Truckee River (watershed area = 7050 km^2) represents the principal input of water to Pyramid Lake (Fig. 5). Cold-season precipitation falling in the Sierra Nevada is released to the Truckee River surface–water system as snowmelt in the spring and early summer. Approximately 32% of Truckee River flow reaching the Farad gage in eastern California emanates from Lake Tahoe and 38% of Truckee River flow reaching the Farad gage passes through small-capacity reservoirs. The remaining 30% of the flow enters the river as overland flow (Benson, 1994a, b). Above Farad the Truckee River is largely unaffected by diversion and downstream contributions of water are small. Groundwater input to Pyramid Lake is negligible and prior to 1918 overflow to Winnemucca Lake occurred frequently.

In 1906, Derby Dam located 53 km upstream of Pyramid Lake was completed. Since that time an average of 54% of Truckee River flow has been diverted