Geological Society of America
Special Paper 368
2003

Late Pleistocene lakes along the Mojave River, southeast California

Yehouda Enzel*
Institute of Earth Sciences and Department of Geography, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

Stephen G. Wells
Nicholas Lancaster
Desert Research Institute, 2215 Raggio Parkway, Reno, Nevada 89512-1095, USA

ABSTRACT

Closed and semiclosed basins along the Mojave River in southern California were occupied by pluvial lakes during the latest Pleistocene. The chronologies of Harper Lake, Lake Manix (Coyote Lake and Troy Lake playas and the Afton basin), and Lake Mojave (Soda Lake and Silver Lake playas) are summarized here from available data. We evaluate the chronologies, compare them with each other, and then use them to determine coexistence of lakes within the Mojave River hydrological system. The average annual flow in the lower reaches of the Mojave River that is needed to form and maintain a lake in one of these basins is at least an order of magnitude larger than the present-day average discharge of 9.5 x10^6 m^3. The discharge could have increased by (a) more frequent storms and floods, and/or (b) reduced loss by transmission of flood water along the river length. This reduction in transmission losses could have been caused by longer river reaches either covered by lakes or characterized by base flow that, in turn, was formed by water table near or at the surface. The increase in flood discharge is caused by an increased storm frequency in the headwater of the river. The discharge increase needed to support individual lakes is multiplied when the total lake area of coexisting lakes fed by the Mojave River is considered. It demands an even larger increase of the number of storms in the headwaters than the number needed to support an individual lake. This indicates a large increase in atmospheric moisture transported to this relatively low latitude along the coast of western North America. The coexistence of lakes during the last glacial maximum and the highstands of other lakes in similar latitudes in the southwestern United States indicate that the storm tracks were frequently directed at 32°–34° N latitude at that time.

The chain of lake basins along the Mojave River is an example of a hydrological system that is integrated through time into one large arid river basin. This was possible mainly because of the elevated headwaters located at the San Bernardino Mountains where orographic effects cause heavy storms and large floods. These large floods fill the depositional basins along the river with water and sediments and allow them to overflow downstream. Afton Canyon was formed by such an overflow from the Manix basin to the Lake Mojave basin. The incision of the 150-meter-deep canyon was previously proposed to be rapid and geomorphically catastrophic. Here we propose that a time-transgressive incision lasting over a few thousand of years is more plausible explanation for the formation of this canyon; geologically it is still a rapid event.

---

*E-mail: yenzel@vms.huji.ac.il

Enzel, Y., Wells, S.G., and Lancaster, N., 2003, Late Pleistocene lakes along the Mojave River, southeast California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin Deserts: Boulder, Colorado, Geological Society of America Special Paper 368, p. 61–77. © 2003 Geological Society of America.

In addition, we discuss how the findings along the Mojave River reflect upon two long-term hypotheses of (a) mega–Lake Manly that supposedly filled a large area in the Mojave Desert sometimes in the middle Pleistocene, and (b) Lake Manix and/or Lake Mojave overflow to Bristol Lake and to the Colorado River.

INTRODUCTION

The present-day Mojave River (Fig. 1) drainage system (9500 km^2) is the largest hydrological system in the Mojave Desert. It heads at high elevations in the San Bernardino Mountains of the Transverse Ranges of southern California and terminates in the Soda Lake and Silver Lake playas in the heart of the Mojave Desert (Williamson et al., 1856; Wells et al., this volume). The headwaters of the Mojave River in the San Bernardino Mountains located at 34° latitude (Fig. 1) are far south of the average latitude of the North Pacific winter storm track that currently affects western North America (Pyke, 1972). This relatively low latitude makes the Mojave River an excellent candidate to detect past shifts to the south of the storm tracks during glacial times (e.g., Antevs, 1938). The closed basins of the Mojave River provide the key environment for storing lacustrine and playa deposits and therefore the evidence of the past shifts in storm tracks and wetter conditions in the Mojave Desert. Because of the size of the Mojave River drainage basin, the paleohydrology and/or paleoclimate deduced from these chronologies are applicable to the entire Mojave Desert, the southern Great Basin, and perhaps the southwestern United States in general.

The Mojave River crosses several tectonic basins bounded by northwest-southeast–trending right-lateral strike-slip faults (e.g., Garfunkel, 1974), which control both the configuration of the Mojave River groundwater aquifer (Mojave River Agency, 1982, 1985) and the irregular shape of the Mojave River surface-water drainage basin (Fig. 1). These basins and their groundwater are recharged by floodwaters from the Mojave River, which is therefore a central factor in the water resources of the western and central Mojave Desert. This was recognized very early in this century (e.g., McClure et al., 1918) and is the reason for many studies of the subsurface geology (e.g., Martin, 1994).

During the Pleistocene the Mojave River filled these basins with fluvial, deltaic, playa, and lacustrine deposits (see Cox et al., this volume; Jefferson, this volume). These lacustrine deposits record the paleohydrology of the Mojave River and the regional paleoclimatology. The late Pleistocene lakes of Harper Lake, Lake Manix (now the Afton basin, the Coyote and Troy Lake playas), Mojave Lake (now the Soda Lake and Silver Lake playas) (Figs. 1 and 2) that formed in the Mojave River drainage basin raise questions about the degree to which they coexisted, and the pattern, hydrography, and evolution of the overall drainage basin. Earlier studies of the chronologies of these lakes tried to identify coexistence and overflowing from one lake basin to another, and inferred major geomorphic events and changes along the river (e.g., Meek, 1989). From earlier studies we summarize chronologies of various latest Pleistocene and early Holocene paleolakes

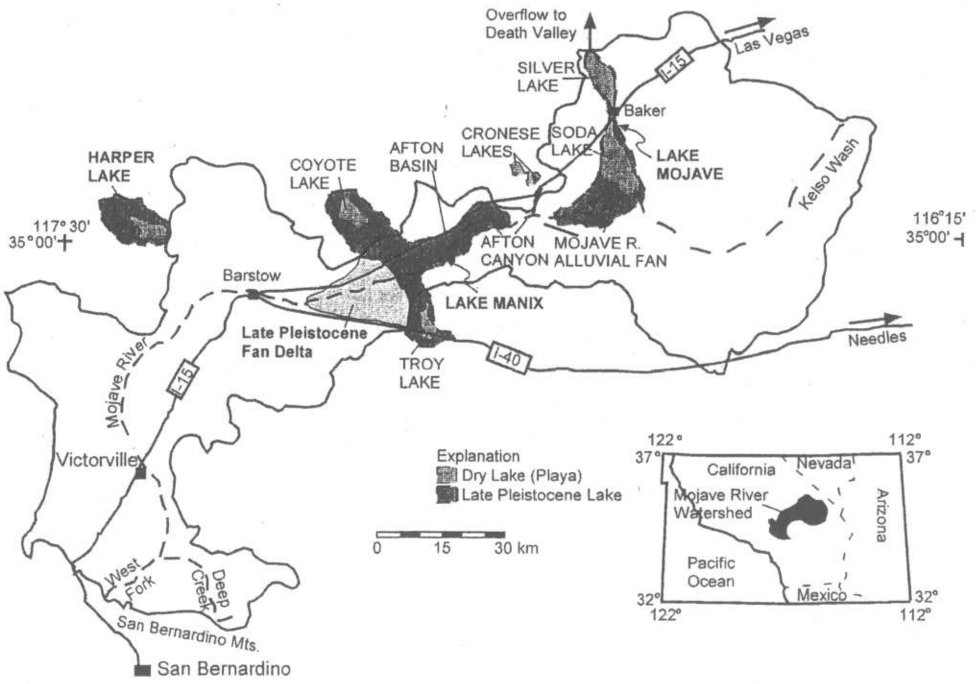

Figure 1. The Mojave River drainage basin and the area draining to Silver Lake playa in southeastern California. Note the late Pleistocene Mojave River fan delta west of the dissected Lake Manix basin. Currently the Mojave River has a large alluvial fan at the southern end of Soda Lake playa. Its floodwaters fill both East and West Cronese Lakes and Silver Lake playas.

in the depositional basins affected by the Mojave River. We mainly concentrate on available information that points to the major paleohydrologic and paleoclimatic conditions. Later we compare the chronologies of these Mojave River lakes with the Great Basin pluvial lakes to the north and other lake chronologies from latitudes similar to Lake Mojave. We finally discuss the paleoclimatic implications of these chronologies.

The summary of chronologies of the individual basins also describes the more general process of integration of several basins into the hydrological system of the present-day Mojave River. Understanding this long-term evolution of the river, in turn, is a necessary stage in deciphering the interplay between hydrology and basin physiography. Only then can the paleohydrology deduced from sediments in the individual basins, be transformed qualitatively or quantitatively into regional paleoclimatology (Wohl and Enzel, 1995). For example, it was pointed out (e.g., Benson and Paillet, 1989) that the surface area of a lake is the most sensitive parameter to variations in climate. Therefore, the areas of one, two, or more coexisting lakes reflect very different hydrologic and climatic conditions and Mojave River inflow for them to be maintained.

Current climatic conditions

Southern California experiences a Mediterranean climate with a relatively hot dry summer and a winter precipitation maximum, which are related to the cyclonic activity over the North Pacific Ocean. In the San Bernardino Mountains, the mean

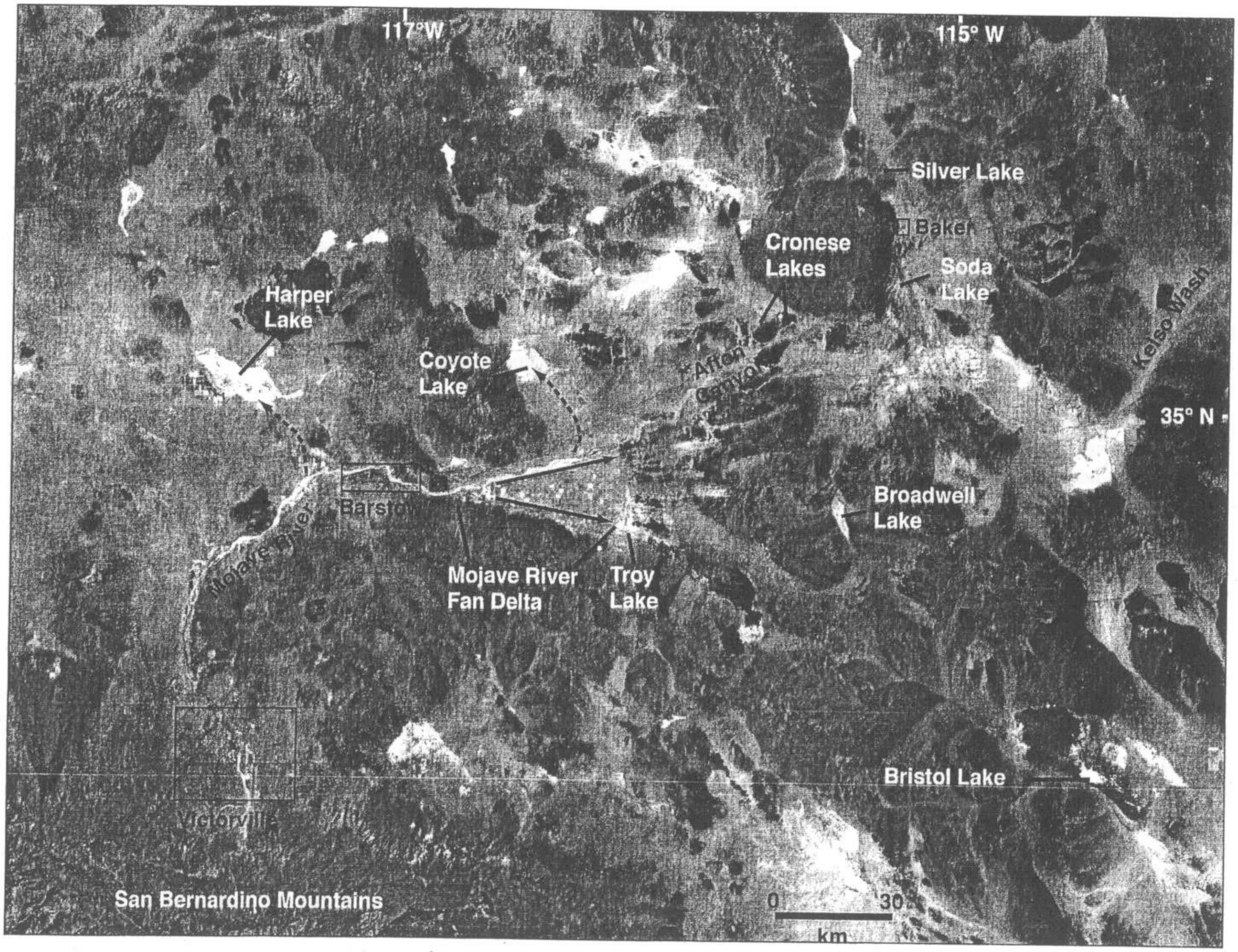

Figure 2. Satellite images (LANDSAT™) of the Mojave River and vicinity. The images were produced from data by Mojave Desert Ecosystem Program of the U.S. Department of Defense (Legacy Program) and the Department of the Interior. Arrows with solid and dashed lines represent proposed Mojave River flow directions during the progradation of the Mojave River fan delta into the Lake Manix subbasins of Coyote Lake, Afton basin, Troy Lake, and during earlier times into the upstream Harper Lake.

annual precipitation exceeds 1000 mm, in the Victorville area it is 125–150 mm, and in the Silver Lake area it is 75 mm. Rainfall seasonality changes across the drainage basin. For example, summer rainfall constitutes 40% and <10% of the annual rainfall in Silver Lake playa and in the headwaters, respectively (Enzel, 1990). Potential lake evaporation in the headwaters area at elevations above 1500 m is 1000 mm/year or less (Crippen, 1965; Mojave River Agency, 1985). The extremely high temperatures at elevations lower than 500 m in Mojave Desert result in ~2000 mm/year equivalent lake evaporation in the terminal basins (Blaney, 1957; Mojave River Agency, 1985; Enzel, 1990). These extremely arid conditions demand a major change in the Pleistocene that introduced into the area the moisture that was necessary to form the paleolakes that occupied several subbasins along the Mojave River.

Anecdotal observations and early research in the lower Mojave River

All early documents that mention the Mojave River seem to assume that it flowed to the Colorado River. For example, in 1776 Fray Francisco Garcés, who crossed Soda Lake playa and continued through Afton Canyon to San Gabriel Mission, thought that the river flowed to the Colorado River (Coues, 1900). He named it "*Arroyo De Los Martires*," which is the name on a map from 1777 that shows that the Mojave River flowing to the Colorado River (Font's map; "*R. de Los Martires*"; Preston, 1988). Jedediah Smith mentioned the playa in 1825 and 1826. However, he (Morgan, 1953) and later Captain Ewing Young and Kit Carson in 1829 and even later the Frémont Expedition in 1844 (e.g., Dale, 1918; Sabin, 1914; Jackson and Spence, 1970), did not notice that the Mojave River terminates in dry playas. Frémont claimed that he continued all the way to "the end of the river." He did not mention, however, the playas at that end; Thompson (1929) claimed that they did not reach the playas.

Williamson et al. (1856), who explored the Mojave River during the Pacific Railroad Expeditions in 1853, first documented that (a) the Mojave River does not flow to the Colorado River, and (b) the playas presently named Soda Lake and Silver Lake are the actual termini of the river. In 1853, even after the Williamson discovery, the Whipple party of the Pacific Railroad Expeditions was still looking for the confluence of the Mojave River and the Colorado River.

Hydrological and paleohydrological observations began much later. Gale (1914), Buwalda (1914), and Free (1914, 1916) identified the presence of an ancient lake in the playas, and Free (1916) concluded that the outflow from this ancient lake was "both small and transient." Huntington (1915) proposed that the Mojave River was more vigorous in the past, overtopping its terminal basin and flowing into the Amargosa River in Death Valley. Thompson (1921, 1929), in his seminal study of the area, termed the ancient lakes that occupied Soda/Silver Lake playas and the East and West Cronese playas "Lake Mojave" and "Little Mojave Lake," respectively.

Buwalda (1914) suggested that ancient Lake Manix, once the terminus of the Mojave River, overtopped its hydrologic barrier, cut a channel, and drained rather rapidly into the Lake Mojave basin. Thompson (1921, 1929) agreed with Buwalda that Lake Manix was once the terminus of the Mojave River. He hypothesized that Lake Manix and Lake Mojave did not exist at the same time and that the formation of Afton Canyon and filling of Lake Mojave occurred relatively recently as a consequence of the draining of Lake Manix. Antevs (1937) estimated that Lake Mojave existed between 25 and 10 ka, and Crozer-Campbell et al. (1937) and Hubbs and Miller (1948) postulated that Lake Mojave and Lake Manix might have been contemporaneous. These opposing assertions have major implications for the estimation of past regional climates: There is a need for lower Mojave River discharge to support only one lake at a time if lakes are not contemporaneous. Thompson's (1921, 1929) hypothesis may have been the basis for the conclusion of a recent study on the history of Lake Manix and the formation of Afton Canyon (Meek, 1989, 1990). These studies conclude that late Wisconsin Lake Manix did not overflow into Soda Lake and Silver Lake basins and that Lake Manix was rapidly drained by the rapid incision of Afton Canyon between 13.8 and 13.3 ka (Meek, 1989, 1990). To address this issue, we will present the chronologies of Lake Mojave and Lake Manix and then discuss the incision of Afton Canyon. The Mojave River is a good example of a river that through time integrates a few subbasins into one hydrological system that reaches further downstream into a closed basin. We stress, however, that not all the data exist to resolve this issue completely. Therefore, the main goal is to summarize available information and to discuss the possible conclusions based on them.

OBSERVATIONS FROM THE MOJAVE RIVER BASINS

Harper Lake playa

Thompson (1929) was the first to raise the possible existence of a paleolake within the Harper basin. He reported shells and blue clays in boreholes from the basin. Dibblee (1960, 1968) identified the highest shoreline at the 2160 foot (~658 m) elevation contour and a few lower recessional shorelines in this basin. The preservation of these features indicates that the lake that filled the basin occurred recently. Dibblee considered unlikely the possibility that Harper Lake received overflow from Lake Thompson (which previously occupied the present-day Rogers and Rosamond Dry Lakes, 70 km southwest of Harper Lake playa). According to Meek (1999), who surveyed the highest wave-cut cliff of Harper Lake, the elevation of the highest lake level is 656.9 m (2155 feet). Reynolds and Reynolds (1994) raised a question regarding the source of water for the formation of such a lake. They observed that the highest shoreline is only 6 m below the wide alluvial saddle that separates the Mojave River drainage basin from the Harper Lake basin. This low water divide and the lacustrine fauna led Reynolds and Reynolds

(1994) to suggest: (a) a past connection between the Mojave River and the Harper Lake basin, (b) that minor vertical tectonic activity was responsible for connecting the basins and later the isolation of the Harper Lake, and (c) that the isolation of the Harper Lake from the Mojave River occurred during the late Pleistocene. Meek (1999) proposed a possible route for the Mojave River to flood Harper Lake (Fig. 2) under the reasonable assumption that groundwater could not have caused the late Wisconsin Harper Lake stand.

Recently, Meek (1999) dated two *Anodonta* samples from the same horizon, ~2 m below the highest shoreline, that yielded ages of 24,440 ± 2190 (UCLA-2627a) and 25,000 ± 310 (UCR 2867) ^{14}C yr B.P. (all ages in this manuscript are not calibrated). A third age of an *Anodonta* from ~5 m below the shoreline resulted in >30,000 ^{14}C yr B.P. (UCLA-2627b). Beach deposits that contain lacustrine clays yielded abundant ostracodes with *Limnocythere bradburyi* dominating (Meek, 1999). This taxon has been found in other late Wisconsin lakes along the Mojave River (Wells et al., this volume), but it was not identified in the 300–40 ka lacustrine units of Lake Manix (Steinmetz, 1988, 1989; Meek, 1999). In Lake Mojave, this taxon was identified only in deposits associated with the last glacial maximum stand of Lake Mojave I phase (Wells et al., 1989, this volume).

Lake Manix

Late Pliocene to early Pleistocene sediments from the Manix basin indicate stream flow to the southwest (Nagy and Murray, 1991; Jefferson, this volume). This observation, in turn, indicates that the eastward-flowing Mojave River did not reach that area and probably terminated in one of the upstream basins (Cox and Tinsley, 1999; Jefferson, this volume; Cox et al., this volume). During the period 2.5–1 Ma, the Manix basin was probably internally drained and was occupied occasionally by ephemeral saline lakes or playas (Jefferson, 1985, this volume). Although older sediments contain gypsiferous deposits, the earliest known lakes in the Manix basin are ~500,000 yr old (Jefferson, this volume). The first appearance of these full-lake conditions with their diverse environmental conditions (Jefferson, 1985, this volume; Steinmetz, 1988), indicates the first large discharge of the Mojave River. Steinmetz (1988) suggested that the appearance and abundance of sensitive ostracodes in the various beds of Lake Manix peak with expanded favorable habitats during glacial conditions. Shlemon and Budinger (1990) emphasized the potential importance of the Lake Manix paleoenvironments to early humans in the region.

The following paragraphs summarize the latest Pleistocene chronology of Lake Manix. Earlier lake phases in the Manix basin, from ca. 500 ka to the latest Pleistocene, are summarized by Jefferson (this volume). Although a large number of radiocarbon ages exist for Lake Manix subbasins and vicinity (Fergusson and Libby, 1962; Hubbs et al., 1962, 1965; Bassett and Jefferson, 1971; Jefferson, 1985; Reynolds and Reynolds, 1985; Meek, 1990, 1999), the latest Pleistocene chronology of Lake Manix is yet not well established, even though it is crucial to understanding the paleohydrology of the Mojave River.

In the Lake Manix basin, ages have been derived from radiocarbon analyses on *Anodonta*, tufa, bone and rock-varnish samples, U/Th analyses on identified faunal fragments, and "cation ratios" on rock varnish (Jefferson, 1985; Meek, 1990, 1999; Berger and Meek, 1992). In this summary we do not use the calibrated ages based on the rock-varnish cation ratios or the radiocarbon ages from rock-varnish samples. These ages were found to be problematic (Beck et al., 1998; Watchman, 2000; Gillespie, 2003) and even R. Dorn, who conducted the rock-varnish cation ratios analyses on samples from Lake Manix (Meek, 1990), deemphasized their importance (Whitley and Dorn, 1993). In his recent discussion of Lake Manix, Meek (1999) also avoids using the various rock-varnish ages. We choose also not to use the 480-years correction for *Anodonta* suggested by Meek (1990) and Berger and Meek (1992), not because we do not agree with them on the need for correction, but because the value proposed for the reservoir correction is based on limited data.

Meek (1990, Plate 4) used the elevations of dated samples rather than dated morphostratigraphy of shore features from Lake Manix to produce a lake-level curve. Because the sequence of events represented by the various shore features is based on the ages of the shore features and not on stratigraphic relations, this curve is subject to modifications with additional ages, different ages, and whether or not the varnish ages are included. Meek (1990) defined four highstands of Lake Manix that reached 543 m in the Afton basin: ca. 31–30, 21–20, 18, and 15–14 ka. Based on two additional age determinations, the 15–14 ka stand was recently discarded (Meek, 1999) and the same beach ridge from which the earlier age came is now dated at ca. 29 ka (Meek, 1999). This change emphasizes the problem of using ages without a clear stratigraphic context; a beach ridge once considered the youngest in the sequence is now considered older than other late Pleistocene lacustrine features.

The highstands of Lake Manix all reached repeatedly the same elevation of 543 m (Meek, 1990, Plate 4), probably indicating that the lake reached a topographic threshold of either its spillway elevation downstream or a sudden increase of area within Lake Manix at that elevation. We suggest that Lake Manix probably reached its spillway elevation a few times during the late Pleistocene and overflowed downstream to Lake Mojave basin. Low lake stands are not defined for Lake Manix, although Meek (1999) argues that a gap in ages means either a drop in lake level and/or Mojave River discharge was diverted to another basin. We suggest that both are possible but too simplistic assertions.

Coyote Lake and Troy Lake playa basins

The Coyote and Troy Lake playas were part of the area inundated when Lake Manix was at its highstand but, because of limited exposures of lacustrine deposits (Meek, 1990), they have attracted much less attention than the Afton basin. Some lacustrine features in Lake Coyote and Troy Lake basins were discussed by Thompson (1929) and Blackwelder and Ellsworth (1936), and mapped by Byers (1960) and Dibblee and Bassett (1966a, 1966b). Hagar (1966) mapped the surface characteristics of the Coyote Lake playa and described shore features and the stratigraphy and sedimentology of the Mojave River delta front in Coyote Lake basin; Groat (1967) mapped in detail the Troy Lake basin. Subsurface information is available for Coyote Lake in Thompson (1929), Dyer et al. (1963), and Meek (1990). Meek (1990) indicates the existence of ~100 boreholes from the basin that have not been published or interpreted. Several ages of shore features are available from these basins, and one age has been determined from the base of a delta that prograded into the lake (Meek, 1990). The ages on samples collected from shore features of Coyote Lake basin are 13,800 ± 600 (LJ-958); 13,560 ± 145 (UCLA-2609b); 12,900 ± 120 (UCLA-2606); and 11,810 ± 100 (UCLA-2609c) ^{14}C yr B.P.; from the base of the exposed portion of the delta that prograded into the Coyote Lake basin and on the lakebed, the radiocarbon ages on Anodonta are 17,590 ± 1500 (UCLA-2603) and 15,125 ± 270 (UCLA-2608) ^{14}C yr B.P. (Hubbs et al., 1965; Meek, 1990). From these ages and their elevations, but without any stratigraphic relationships, Meek (1990) interpreted a fluctuating lake in the Coyote Lake basin between ca. 15 and 11 ka. The age from the base of the delta indicates that a lake existed in the Coyote Lake basin also ca. 17 ka. The two ages from radiocarbon (Dorn et al., 1986) and a cation-ratio analysis of rock varnish (Meek, 1990) from the Coyote Lake shore features are problematic, as discussed above, and therefore are not used here. It should be noted that all the ages acquired from Coyote Lake are ca. 17 ka or younger (Fig. 3). However, the thickness of lake deposits identified in a few of the 100 borehole cores indicates that earlier lakes occupied the basin (Meek, 1990). Only one age is available from Troy Lake basin, 15,025 ± 230 ^{14}C yr B.P. (UCLA-2605) (Meek, 1990). This age is directly related to the Lake Manix levels in the Afton basin because both basins are fed directly by the Mojave River (Meek, 1990). The 15 ka age from the Troy Lake basin becomes the youngest age associated with the 543-meter shoreline that is common around the Lake Manix basin.

The Mojave River fan delta

When the Mojave River began flowing into Lake Manix basin sometime in the early to middle Pleistocene it probably formed a delta along the western margins of that lake. The large delta that is observed at the surface and termed "Mojave River braid delta" (e.g., Meek, 1990) is of late Quaternary age (Figs. 1 and 2). The oldest age (U-series age) from any fan-delta deposits in the Afton basin is >68 ka (Jefferson, 1985; Meek, 1990). Other prograding delta sediments were deposited in that basin since 55–60 ka (G. Jefferson, 2000, written commun.), between ca. 55 and 19 ka, and immediately after 19 ka (Jefferson, 1985; Meek, 1990). Part of this late Quaternary delta prograded north into Coyote Lake (Hagar, 1966, p. 128) soon after 17 ka (see above; Meek, 1990). Hagar (1966) analyzed the stratigraphy and sedimentology of the delta front of the Mojave River in the Coyote Lake playa and suggests that the deltaic area in the Coyote Lake basin is not typical of deltas because of the presence of an arcuate bar. He reported that the gravel content decreases, the sands thin, and the silt layers increase in clay content from the delta-front toward the present-day margins of the Coyote Lake playa. The delta deposits interfinger with the lacustrine deposits (e.g., Hagar, 1966) indicating progradation into an existing lake throughout the time of deposition. The surface of the delta that prograded into the Coyote Lake exhibits remnants of meandering and braided channels (Hagar, 1966, Plate 1) that are associated with the final stages of the Mojave River fluvial activity prior to a later incision. From the available data, it is not possible to determine whether the delta propagated into a lowstand or highstand of Lake Manix. Sediments deposited during this late Quaternary deltaic progradation are probably responsible for the topographic separation of the Afton, Coyote Lake, and Troy Lake basins of Lake Manix. This separation allows for independent lake histories in the Coyote Lake basin and perhaps in the Troy Lake basin after the incision of the Afton Canyon.

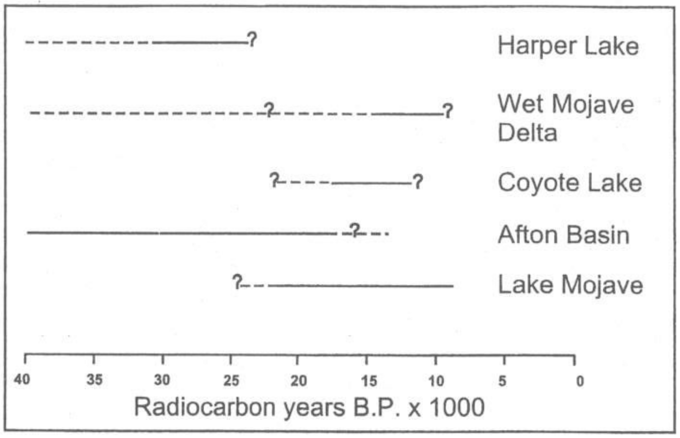

Figure 3. A chart showing the range of ages for the various lakes that were fed by the Mojave River during the late Pleistocene: Lake Mojave, Harper Lake, and Lake Manix (Afton, Coyote Lake, and Troy Lake subbasins). The Mojave River fan delta upstream of Lake Manix indicates repeated wet depositional environment. Proposed lowstands and gaps in radiocarbon ages are not marked. See Figures 1 and 2 for locations of the basins.

The Mojave River today flows in a channel incised into its late Pleistocene delta. Reynolds and Reynolds (1985) suggest that the incision in the western part of the delta occurred around or soon after 7.5 ka. They provide ages and sedimentological and paleontological data that indicate that the Mojave River was flowing on the wide plain of the delta before ca. 13 ka and 9 ka (Fig. 3). The eastward increase in abundance of mesic and aquatic fauna, relative to xeric fauna, during that time interval indicates that wetter environments in the delta increase to the east, with abundant freshwater riparian, oxbow, fluvial, and lacustrine environments (Reynolds and Reynolds, 1985). These environments may represent the persistence of groundwater either near or at the surface at the eastern part of the delta and at somewhat greater depth at the western part of the delta where xeric indictors are more abundant during the same period.

Lake Mojave

The Lake Mojave chronology (Ore and Warren, 1971; Wells et al., 1989; Wells et al., this volume) is determined by dating of two depositional environments. Most of the dates are from the shore and beach environments of the lake and are based on samples of lustrous whole pelecypod shells (*Anodonta*) and lithoid tufa coating on gravel clasts (Ore and Warren, 1971; Wells et al., 1989, this volume; Brown et al., 1990). A few dates are from disseminated organic matter, extracted from fine-grained lacustrine deposits obtained in core samples from Silver Lake playa (Wells et al., 1989, this volume; Enzel et al., 1989; Brown et al., 1990).

The range of all radiocarbon ages acquired from Lake Mojave is >20 ka to 8.5 ka (Fig. 3), and ages from shore features range between 16.2 ^{14}C ka and 8.7 ^{14}C ka (Wells et al., this volume). The oldest date from the beach environment is 16,270 ± 310 ^{14}C yr B.P. (Beta-29553), from the lower of two beach-ridge complexes at the northeast of Silver Lake playa (Wells et al., this volume). No age is available for the older and higher beach ridge. However, the existence of a higher beach ridge points to two conclusions (Wells et al., this volume) crucial to the regional paleohydrology: (a) prior to 16.2 ^{14}C ka, and probably during the last glacial maximum, Lake Mojave existed as a higher and deeper lake than later in its history, and (b) during that earlier period, the lake reached the elevation of the highest shoreline (287–288 m), which is controlled by the bedrock-spillway elevation, and the lake probably overflowed toward the Amargosa River and Death Valley.

The higher and lower beach ridges are related respectively to an older and a younger lake stand (Wells et al., this volume). Wells et al. (1989) tested the existence of the earlier lake stand by drilling core SIL-G (Fig. 23 of Wells et al., 1989) into the center of the small basin between the two beach ridges. About 3 m of lacustrine sediments were recovered at this site. Sedimentologic and paleontologic evidence from these deposits indicate that they are related to Lake Mojave I lithozone (Wells et al., this volume). Their thickness indicates at least a few thousands of years of lacustrine environment prior to 16.2 ka (Wells et al., this volume). Therefore, we conclude that Lake Mojave I lithozone was deposited by a deep, overflowing lake with only minor fluctuations during the last glacial maximum (we use this term as the uncalibrated radiocarbon age of 18,000 yr B.P.).

Ages from the Silver Lake playa core SIL-I indicate that a lacustrine environment dominated the basin during the last glacial maximum (Wells et al., this volume). From the two ages of 20,320 ± 740 (Beta-21801) and 14,660 ± 260 (Beta-21800) ^{14}C yr B.P., Wells et al. (this volume) extrapolated the sedimentation rate down the core and concluded that a lake existed in this basin by 22 ka or earlier. To test the use of these rates, they also extrapolated the rate up the core to the well-recognized and dated transition from lacustrine to playa deposits. This transition marks the desiccation of Lake Mojave, which was dated to ca. 8500 ^{14}C yr B.P. by Ore and Warren (1971) who used shore features. An additional age from immediately below the sediments associated with the lake desiccation in core SIL-M (Enzel et al., 1989; Wells et al., 1989; Enzel and Wells, 1997) indicates that the desiccation occurred soon after 9330 ± 95 ^{14}C yr B.P. (Beta-24342; Wells et al., this volume). The extrapolation of the sedimentation rates resulted in an estimated age of 8700 ^{14}C yr for the desiccation. This similarity among the ages for desiccation indicates that the 22 ka estimated age for the lake's initiation in the Silver Lake basin is reasonable. In turn, it also indicates that a lake already existed in the Soda Lake subbasin of Lake Mojave by 22,000 ^{14}C yr B.P. The internally consistent ages from both the shore and the lacustrine environments of Silver Lake playa indicate that these ages are acceptable.

Subsurface information indicates that water in Soda Lake subbasin of Lake Mojave was almost twice as deep as the Silver Lake subbasin (Wells et al., this volume). A bedrock sill just south of Baker, California separates the two subbasins (Williamson et al., 1856; Thompson, 1929; Wells et al., 1989, this volume). Therefore, Soda Lake was filled before any water could flow to Silver Lake. This indicates that the lower part of the late Pleistocene lacustrine sequence from Soda Lake was probably deposited even earlier than 22 ka. However, no direct age control is available.

In boreholes, from the area now termed the Mojave Sink, between Afton Canyon and Soda Lake playa, Dickey et al. (1979) identified relatively thick lacustrine gypsiferous silt-clay below the latest Wisconsin Lake Mojave deposits. This small moist playa and/or shallow lake was temporally more persistent, although evidently they were smaller than was Lake Mojave (Brown and Rosen, 1995). There is no information on the age of these deposits or whether this lake was fed by Mojave River water.

DISCUSSION

Age of the Afton Canyon incision

We agree with earlier studies (Buwalda, 1914; Thompson, 1929; Muessig et al., 1957; Jefferson, 1985; Meek, 1989, 1990) that Afton Canyon is geologically young. However, Wells and Enzel (1994) concluded that there is little conclusive evidence in Afton Canyon and downstream basins to indicate that the canyon formed shortly after 14 ka during a single relatively rapid incision, as was advocated by Meek (1989). The rapid incision was estimated to take as little as "10 days" or "three weeks" (N. Meek, 1988, 1990, written commun.), or as much as 500 yr (Meek, 1989, 1990). The rapid-incision idea was based mainly on the lack of recessional shorelines in the Afton basin, the lack of terraces within the canyon, and the presence of deeply incised tributary channels into the canyon (Meek, 1989). Wells and Enzel (1994) analyzed the geomorphology of Afton Canyon and these specific observations, and concluded that an alternative hypothesis such as time-transgressive incision during at least a few thousands of years is a more realistic explanation. The supportive evidence to this explanation is: (a) the slow upstream migration of the nickpoint formed by the incision (Meek, 1999), (b) the existence of marsh and lacustrine conditions in the Mojave River delta in western Lake Manix as late as 12–9 ka (Reynolds and Reynolds, 1985), indicating that the river was not yet incised back that far by that period (note that at its eastern end Lake Manix could have overflowed at the same time and even earlier), and (c) the existence of pronounced Holocene terraces within the canyon (Wells and Enzel, 1994), indicating that the incision of Afton Canyon to its present form was not a continuous but episodic and a relatively long process. In addition, we observe recessional shorelines in the Afton basin at elevations below the highest level of Lake Manix, suggesting a longer period of downcutting.

The timing of the incision (Meek, 1989) was based on the comparison of the youngest age (ca. 14 ka) from the shore features of the Afton basin of Lake Manix and the ages of Lake Mojave, with the assumption that these two lakes did not coexist (Meek, 1989). The 14 ka age is now considered problematic (Meek, 1999). The chronology of Lake Mojave discussed above and in Wells et al. (this volume) indicates that Lake Mojave was overflowing prior to 16.2 ka and that a lacustrine environment existed in Silver Lake playa as early as 22 ka, and somewhat earlier in the Soda Lake basin. Lake Dumont north of Silver Lake playa (Fig. 4), which was supported by Lake Mojave overflow existed during the last glacial maximum (Anderson, K., and Wells, this volume) and probably overflowed to Death Valley (Anderson, D., and Wells, this volume). These overlapping ages indicate that both Lake Manix and Lake Mojave were full during the last glacial maximum, indicating a much larger water supply by the Mojave River.

Because of the importance of the single 14 ka age for the youngest shore feature in the Afton basin of Lake Manix, recently Meek (1999) reexamined the evidence for it, discarding the 14 ka

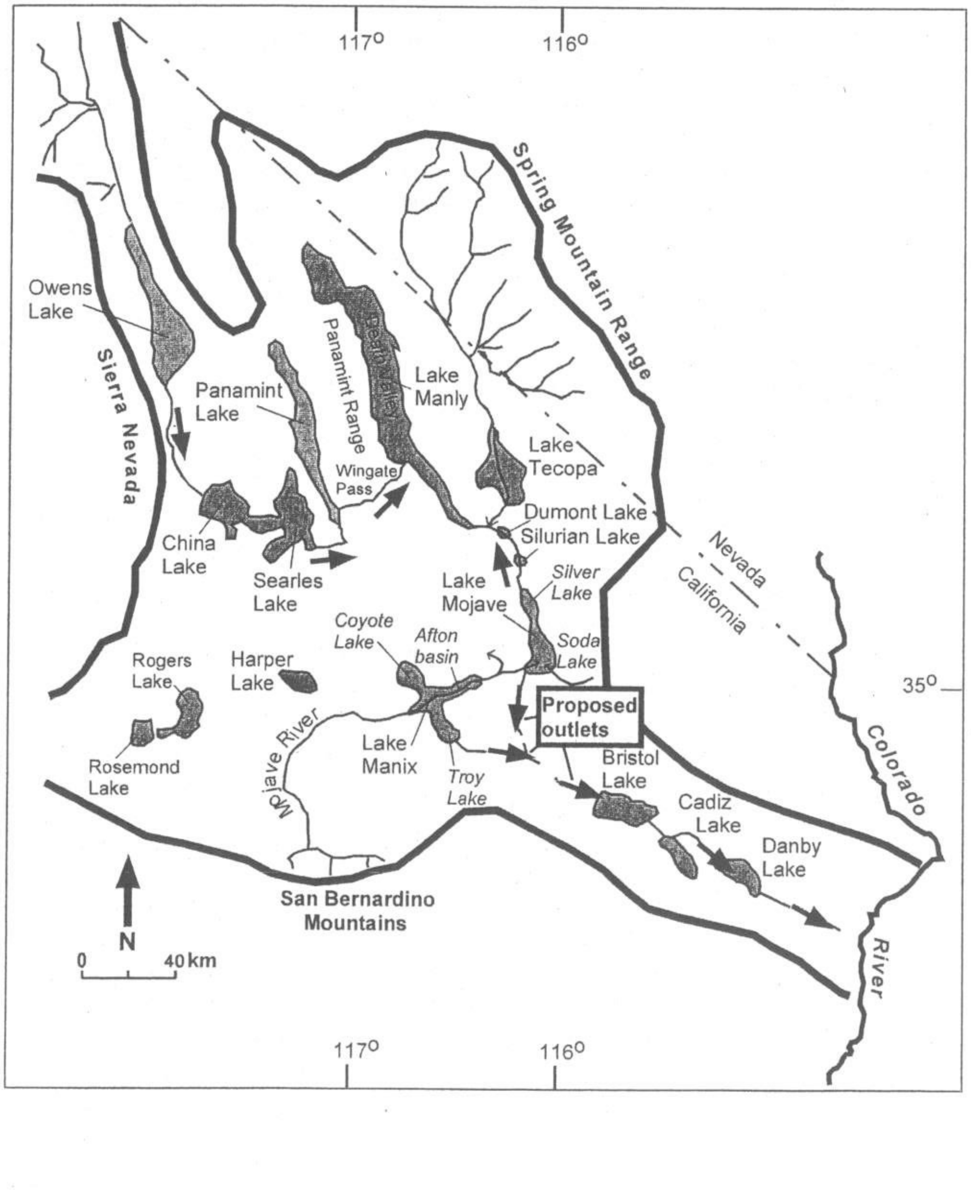

Figure 4. Pleistocene drainage paths in the Mojave Desert as proposed by Blackwelder (1954). It presents the hypotheses: (a) Mojave River flow through Troy Lake into Bristol, Cadiz, and Danby Lake to the Colorado River, and (b) overflow through the southern end of Soda Lake playa of a mega–Lake Manly into Bristol Lake.

age, and providing two new ages from the same shell deposit [28,960 ± 2490 (UCLA-2601c) and 29,310 ± 310 ^{14}C yr B.P. (CAMS-1856); Meek, 1999]. These dates fit the timing of an earlier lake stand in the Afton basin dated by Meek (1990) to 31–28 ka. Discarding the 14 ka age leaves an 18.1 ka age as the youngest age in the Afton subbasin, and a 15 ka age as the youngest age from Troy Lake basin based on *Anodonta* (Meek, 1999). We ask again the key question: When did the Afton basin of Lake Manix drain (i.e., the beginning of the lowering of its highest stand from 543 m by spillway incision)? Catastrophically ca. 13 ka (Meek, 1989)? Or after 18 ka (Meek, 1999)? Was it in fact a catastrophic event, or was it a time-transgressive process that continued into the early Holocene (Wells and Enzel, 1994)? Specific answers to these questions will require additional research. However, if the Afton Canyon incision occurred sometimes after 20 ka, Lakes Manix and Mojave and probably Lake Dumont coexisted and the Mojave River thus supported a very large joint lake area.

We agree with Meek (1999) that understanding the history of the different lakes in all the basins affected by the Mojave River discharge is crucial to understanding the paleohydrology of this system. In fact, two major conclusions can already be drawn from the current knowledge on Lake Manix, Lake Mojave and the other basins: (1) Lake Mojave is a good recorder of the paleohydrology of the basin during the latest Pleistocene, and (2) Lakes Manix and Mojave coexisted during the last glacial maximum, at least for a short period, to form a joint lake area that could have reached up to ~500 km^2 that was supported by the Mojave River. Observation (2) requires a very large atmospheric moisture transport to this part of the world at that time, nearly double the earlier discharge estimates (Wells et al., this volume) for the late Pleistocene Mojave River that were calculated based on the area and volume associated with Lake Mojave alone. If Lake Dumont, downstream of Lake Mojave also received Mojave River discharge during that time (K. Anderson and Wells, this volume) the total lake area thus supported is even greater.

The Mojave River fan delta and Coyote Lake

The aquatic environments at the broad Mojave River fan delta as late as 13–9 ka indicate that the water table was still high and not yet experiencing the drop that should be associated with incision of the Mojave River channel or the draining of the downstream Afton basin. The delta was also synchronous with (a) the fully or partially incised Afton Canyon, (b) an already drained Afton basin, and (c) an upstream propagation of the nickpoint formed by the incision, exposing erodible sediments of Lake Manix. These observations may indicate either only partial incision at Afton Canyon at 13–9 ka or a very slow knickpoint propagation upstream through unconsolidated deposits.

An overlap of ages exists among the various shore features of Coyote Lake and the Mojave River prograding delta (Meek, 1990; Reynolds and Reynolds, 1985). The delta that prograded into the Coyote Lake basin was probably part of the Mojave River fan delta (Fig. 2). If so, this coexistence of the Mojave River delta and Coyote Lake indicates that the Mojave River was still feeding and maintaining lacustrine conditions in that basin as recently as 11 ka (the youngest age from Coyote Lake) and perhaps even more recently. According to N. Meek (1990, written commun.): (1) Coyote Lake basin could have received Mojave River water only as an overflow from the Afton and Troy basins after these basins reached a sill elevation of 543 m, and (2) only after Coyote Lake also filled to that elevation could the joint Lake Manix have risen to higher levels. Therefore, Meek (1990, written commun.) suggested that the lakes in the Coyote Lake basin after 13 ka (i.e., after his proposed draining of Afton basin ca. 13.5 ka) are residual water bodies that were trapped as remnants of the larger Lake Manix after the formation of Afton Canyon. However, the retraction of the 14.5 ka age means that all the ages from Coyote Lake are <18.1 ka, which is the youngest age from Afton basin (Meek, 1999). We postulate that simple calculations will show that even for lowest estimations of latest Pleistocene evaporation rates, Coyote Lake would dry up within a few to tens of years were it not being fed continuously by discharge of the Mojave River. The overlapping ages of the unincised Mojave River delta, the lakes in Coyote Lake basin, and the prograding delta into that basin all indicate that a direct link between the Mojave River and the Coyote Lake persisted until ca. 13–11 ka.

When lakes occupied the Coyote Lake basin, full-lake phases Lake Mojave I (ca. 18–16 ka), and Lake Mojave II (ca. 14–12 ka), and Intermittent Lake II (ca. 16–14 ka) occupied Soda Lake and Silver Lake playas (Wells et al., this volume). After 13 ka the Afton basin of Lake Manix is supposedly already drained (Meek, 1989, 1990, 1999), but the Mojave River delta still included active fluvial, lacustrine, and marshy environments (Reynolds and Reynolds, 1985) and was capable of delivering water simultaneously to Coyote Lake and, through an incising Afton Canyon, to Lake Mojave. The persistence of wet environments indicates that the upstream migration of incision of the Mojave River after the formation of Afton Canyon reached the delta only after ca. 9 ka. After the Mojave River incised a channel in its delta ca. 7.5 ka (or soon thereafter), its floods could no longer reach either Coyote Lake or Troy Lake, and river discharge reached only the playas of Soda Lake, Silver Lake, and Cronese Lakes.

Overlapping ages of lakes

Meek (1999) estimated that Lake Harper had a maximum surface area of 255 km^2 and storage capacity of water of ~6 km^3. This large volume of water and the nonoverlapping ages discussed above led him to conclude that Harper Lake was not contemporaneous with late Wisconsin highstands of Lake Manix. He interpreted that the gaps in the Manix dates could be explained by dates from Lake Harper suggesting to him that Lake Harper was filled when Lake Manix was low. This is a very plausible hypothesis, but we think its implications are so important for paleohydrological interpretations of the Mojave River and for the regional paleoclimatological interpretations that intensive stratigraphic and dating efforts are needed to confirm or deny it. In this regard, we note that during at least one episode, the Mojave River was able to support Lake Manix and Lake Mojave at the same time. Lake Mojave's area (~290 km^2) is ~1–1.5 times the estimated area of Harper Lake. The large delta of the Mojave River, the low water divide (if it existed) between the Harper Lake basin and the Mojave River floodplain, and the magnitudes of the Mojave River floods could all have contributed one or more of the following scenarios: (1) shifting of the river between basins on millennial time scales (Meek, 1999), (2) the river feeding both basins all the time, and/or (3) frequent shifting of the river on its delta resulting in a permanent but shallow body of water in each basin. In the deltaic sediments of the Manix Formation's type section, which span the time interval of the proposed shift from Lake Manix to Harper Lake, G. Jefferson (2000, written commun.) did not identify an obvious break in the stratigraphy. Therefore, the possibility of coexisting Manix and Harper lakes should be examined thoroughly, including dating of the continuous lacustrine record so that its paleohydrological interpretation is clear. Chronologies based on shoreline features are by definition episodic and therefore cannot be used for detailed correlation between basins. The migration of the Mojave River between various subbasins well may have occurred; we consider it to be an untested hypothesis.

The mega-lake and alternative Mojave River routes

Two longstanding hypotheses in the Quaternary geology of the Mojave Desert are associated with the Mojave River and its current terminal basins. The first hypothesis is that a mega–Lake Manly covered very large areas from Death Valley to south of Soda Lake playa. This large lake was proposed in various forms, most recently by Hooke (1999). The second hypothesis indicates that the Mojave River was connected through a topographic trough from Troy Lake through Bristol Lake (Figs. 2 and 4) to the lower Colorado River (Thompson, 1929, p. 112; Miller, 1946; Hubbs and Miller, 1948; Hewett, 1954, p. 19). These two hypotheses are sometimes mixed in the literature as the mega-lake was suggested (Blackwelder, 1933; Hale, 1985) to overflow from the southern Soda Lake area through Broadwell Lake to Bristol Lake playas, thence to the Colorado River (Figs. 2 and 4). In the paragraphs below we suggest that available information does not support either of these hypotheses.

The mega–Lake Manly hypothesis

In deep boreholes along the Mojave River Wash in the southern Soda Lake playa, Dickey et al. (1979) encountered fine-grained, brownish to greenish clastic sediments with minor amounts of evaporite minerals beneath the latest Wisconsin Lake Mojave deposits. They suggested that a small, moist playa or a shallow lake existed during the early-middle Pleistocene. This "Ancestral Soda Lake" was temporally more persistent, although areally more restricted, than latest Quaternary Lake Mojave (Brown and Rosen, 1995). However, sedimentologic evidence from continuous, 326-meter-deep cores in the center of the Soda Lake playa basin indicates only one lacustrine sequence in this largest subbasin of pluvial Lake Mojave (Muessig et al., 1957; Smith, 1991a; Brown and Rosen, 1995). This sequence at a depth of 14–36 m from the playa surface is related to the latest Pleistocene Lake Mojave sediments (Wells et al., 1989, this volume; Brown and Rosen, 1995). The single lacustrine sequence supports Thompson's (1921, 1929) hypothesis that Lake Mojave formed only later in the geologic history of the Mojave River (e.g., Smith, 1991a).

Below this late Pleistocene sequence, the Soda Lake cores contain playa, alluvial fan, and eolian sediments (Muessig et al., 1957; Smith, 1991a; Brown and Rosen, 1995). Brown and Rosen (1995) used various sedimentation rates to estimate that the age of the bottom of the deep core range from 0.82 Ma to 3.2 Ma. They conclude that at least since the early Pleistocene, there is no evidence of the supposedly large lake that occupied vast areas in the Mojave Desert as suggested by Blackwelder (1933, 1954), Hubbs and Miller (1948); Miller (1981), Hale (1985), and more recently by Hooke (1999). Soda Lake, which (a) is located in the center of the proposed lake and (b) constitutes the essential link between the basins that such a lake supposedly occupied, does not contain any known sedimentary sequence to support the mega–Lake Manly hypothesis (Muessig et al., 1957; Smith, 1991a; Brown and Rosen, 1995).

The recent attempt by Hooke (1999) to revive a version of the "mega–Lake Manly" hypothesis by adding regional large-scale tilting to fit the elevations of the various shore features of the hypothetical mega-lake is not supported by the available data from Soda Lake and Silver Lake playas (Enzel et al., 2002). He proposed that the tilting was at a rate of 2 mm/year. Over the last 18–12 ka, which is the age of the shorelines associated with Lake Mojave, such a rate should have lowered northern Silver Lake playa by 24–36 m relative to southern Soda Lake playa (a distance of 35–40 km). All the highest shoreline features around Silver Lake and Soda Lake playas were surveyed in detail relative to existing benchmarks (Wells et al., 1989, this volume). No tilting or any other deformation was observed from this survey. Actually, this survey indicates that the most pronounced shorelines around Silver Lake and Soda Lake playas are within 10–20 cm of the 287 m and 285.5 m shorelines A and B, respectively of Wells et al. (1987). Furthermore, there are no shorelines at elevations higher than the 287 m, which is the spillway elevation at the northern end of Silver Lake playa and therefore also the expected shoreline elevation if tilting did not occur. Therefore, the significant tilting proposed by Hooke (1999) seems not to include Silver Lake and Soda Lake, so it apparently did not occur. In addition, all ages from the highest shoreline features around the Soda Lake and Silver Lake playas are associated with the latest Pleistocene lake (Wells et al., this volume). Not one age supports the idea that an earlier lake occupied this basin as proposed by Hale (1985) and Hooke (1999). We also visited all the Mesquite Hills deposits mentioned by Hooke (1999) and concluded that (a) none has the characteristics of shore deposits, (b) they are probably spring deposits along an active fault, and (c) their absolute and/or relative ages are not yet determined. Therefore, we suggest that the mega-lake hypotheses do not stand the test of field evidence.

The Mojave River–Bristol Lake–Colorado River route

Thompson (1929), Miller (1946), Hubbs and Miller (1948), and Hewett (1954) suggested that after the filling of Lake Manix, the Mojave River overflowed into Bristol Lake basin through a spillway at southeast Troy Lake (Fig. 4). It then overflowed from Bristol Lake to the basins of Cadiz and Danby Lakes and reached the Colorado River.

The summaries of Jefferson (this volume), Cox et al. (this volume), and Smith (1991a) indicate that Lake Manix could have overflowed only after 500 ka, when the Mojave River water first filled that lake. Therefore, Bristol Lake basin could have received Mojave River water only after that period.

Bristol Lake cores show that throughout the Pleistocene, the basin was occupied by only shallow lakes fluctuating between a saline lake to a playa (Rosen, 1989; Brown and Rosen, 1995). A deep overflowing lake that could have overflowed sometime during the last 0.5 ka to downstream basins and to the Colorado River is not documented in the Bristol Lake cores (Rosen, 1989; Brown and Rosen, 1995). Therefore, we note that currently, evidence does not support this hypothesis.

Estimating Mojave River discharge needed for coexisting lakes

During the latest Pleistocene it appears that the Mojave River fed more than one lake at the same time. The clearest example is a Lake Mojave-Lake Manix coexistence during the last glacial maximum. To get an estimate of the Mojave River discharge needed to support these two lakes we use the estimates of discharge calculated for Lake Mojave alone (Wells et al., this volume).

Average present-day annual flow, recorded at the lower reaches of the Mojave River, is ~9.5×10^6 m^3 (Enzel, 1990; Wells et al., this volume). Rare floods (>10 yr recurrence time) that reach the lower Mojave River deliver ~75×10^6 m^3 per flood on average. To form Lake Mojave during the last glacial maximum demands an order of magnitude greater river discharge than today's average annual flow, even with 50% reduction in evaporation (Wells et al., this volume). Fifty percent reduction in evaporation is probably an overestimation of the evaporation during the late Pleistocene. Annual flow into the lake basins in the magnitude of twice the average flow of the eight largest modern extreme floods is necessary to form a lake. Reducing modern rates of evaporation by 50%, and doubling modern rainfall would result in a full lake almost at the elevation of the Lake Mojave shoreline. To feed and form simultaneously an additional lake with Mojave River discharge, and therefore doubling the total lake area supported by the river, would demand a further increase of the annual discharge to ~300×10^6 m^3. This annual discharge is approximately a factor of three larger than the discharge of the 1938 flood, the largest flood that reached Afton Canyon in the last 110 yr.

Presently, the Mojave River experiences large transmission losses into its alluvial aquifer (e.g., Buono and Lang, 1980; Enzel et al., 1989; Enzel, 1990, 1992; Enzel and Wells, 1997) and only the largest floods reach the terminal playas. When they reach the playas they have greatly reduced peaks and total discharges. We assume that during the late Pleistocene, with the increased flood frequency and discharge, higher water tables, and longer reaches with base flow or even occupied by lakes, the transmission losses of today were dramatically reduced. Large transmission losses are observed today in the Barstow-Afton reach of the Mojave River (Enzel, 1990). During the late Pleistocene most of this reach was occupied either by the fan delta, with aquatic environments at the surface (Reynolds and Reynolds, 1985), or by Lake Manix, indicating a limited potential transmission losses. In contrast with the Holocene conditions (Enzel, 1992), under which only the largest floods reach the lower Mojave River, under late Pleistocene conditions most floods that originated at the headwaters could have reached and contributed to the two coexisting lakes. Observations at the late Pleistocene delta of the Mojave River west of Lake Manix support the existence of very high groundwater levels at this time, probably at or near the surface (Reynolds and Reynolds, 1985), elevations that are much higher than under present-day conditions. Therefore, the floods routed along the Mojave River channel probably were attenuated but without the high transmission losses that characterize Holocene and present conditions.

We note that flood discharges of the magnitude demanded by these calculations have occurred during the twentieth century (Enzel, 1990), in the upper reaches of the Mojave River. For example, upstream of Victorville, California (Fig. 1) ~30% of the modern floods have discharges >100×10^6 m^3. Ten percent of the floods have discharges >300×10^6 m^3. If these floods were more frequent, did not experience the present-day transmission losses in downstream reaches, and if the evaporative losses were at the proposed late-Pleistocene levels, a large lake could form.

Implication for paleoclimatology

Increase in Mojave River discharge probably requires more frequent heavy storms over its upper reaches and its headwaters in the San Bernardino Mountains, located at a latitude of 34°N (Enzel et al., 1990). A persistent winter North Pacific storm track delivering moisture to relatively low latitude along the west cost of North America is also indicated. As coexistence of lakes is most pronounced during the last glacial maximum, the moisture transport to this latitude was probably most effective during that time. During later stages of the deglaciation (14–9 ka) Lake Mojave was fluctuating more and probably overflowed less permanently to downstream reaches. This indicates less-frequent water supply by storms at its headwaters than during the glacial maximum. We suggest that this indicates that the average storm track was located farther north.

This implication to the changes in the moisture transported to the area during glacial maximum and deglaciation, is supported by the deeper water in lakes and "wetter" conditions interpreted from other basins at similar latitudes. Quade et al. (this volume) indicate that the wettest conditions associated with discharge to the surface in valleys in southern Nevada (Fig. 5) were recorded during the last glacial maximum. Although discharge to the surface in this area continued also during 14–12 ka, conditions were then drier than during the last glacial maximum (Quade et al., this volume). The chronology of Lake Estancia in central New Mexico (Fig. 5; latitude 34°–35°N) (Allen, 1991; Allen and Anderson, 2002) shows that the highest and most persistent lake stand occurred during the glacial maximum, with mostly lower and less-persistent lake stands occurring later, in the latest Wisconsin. Other paleolakes also show maximum highstands during the last glacial maximum: (a) Lake Cloverdale (Fig. 5) occupied the southern Animas Valley at 32° N latitude (Krider, 1998) between ca. 20 and 18 ka; (b) a paleolake occupied the San Agustin Plains (Fig. 5; 34°N) in west-central New Mexico between 22 and 17 ka (Markgraf et al., 1984; Phillips et al., 1992); (c) Lake Cochise (Fig. 5) in southeastern Arizona (32°30′ N) experienced a highstand during full glacial times (Long, 1966), but latest Wisconsin lake stands probably reached the same elevation (Waters, 1989) in this relatively shallow lake basin; and (d) Laguna Diablo located in northern Baja California, Mexico (Fig. 5; 31°N) was high during the glacial maximum (Y. Enzel, L. Ely, B. Allen, and M. Palacios, 1993, written commun.).

All these high lake stands at latitudes of 32°–35°N indicate intensive moisture transport to that region during the glacial maximum, diminishing during the later stages of the deglaciation. The source of the moisture that supported these lakes was probably winter precipitation from a North Pacific source (e.g., Van Devender et al., 1987; Enzel, 1990; Smith, 1991b; Allen and Anderson, 1993; Stute et al., 1995; Anderson et al., 2002). So far there is no evidence for the later deglaciation lakes in the San Agustin Plains (Phillips et al., 1992) and Lake Cloverdale (Krider, 1998) that were observed in Lake Estancia (Allen and Anderson, 1993), Lake Cochise (Waters, 1989), Lake Mojave (Wells et al., this volume), and in southern Nevada as discharge deposits (Quade et al., 1998, this volume).

In contrast to the highstand of lakes in the 32°–35° latitude range in the southwestern United States, the northern Great Basin Lake Lahontan and Lake Bonneville of Utah and Nevada at latitude of 40°N, experienced their highest stands at 14–12 ka (Benson and Thompson, 1987; Benson et al., 1990, 1995; Oviatt et al., 1992; Adams and Wesnousky, 1998). The last glacial maximum lake stands in these basins were somewhat smaller (Benson and Thompson, 1987; Benson et al., 1990, 1995; Oviatt et al., 1992).

Figure 5. Proposed average storm track over the West Coast of North America during the last glacial maximum (18 ka) and late deglaciation (14–12 ka). SN—southern Nevada stream deposits; Mo—Lake Mojave; SA—San Agustin Plains; E—Lake Estancia; Co—Lake Cochise; Cl—Lake Cloverdale; Di—Laguna Diablo.

Antevs (1938, 1952) hypothesized that the growth and retreat of the Laurentide Ice Sheet caused shifts in the average position of the polar jet and storm track along the western coast of North America. As maximum precipitation, cloud coverage, lower maximum temperatures, and reduced evaporation are associated with the core of the jet stream and the area just north of it (Starrett, 1949), a northward shift of the jet stream following the glacial maximum is a reasonable cause for the rise of Great Basin pluvial lakes at this time (e.g., Hostetler and Benson, 1990; Benson et al., 1995). The results of atmospheric general circulation models (Manabe and Broccoli, 1985; Kutzbach and Wright, 1985; Kutzbach and Guetter, 1986; Kutzbach, 1987; Kutzbach et al., 1998) indicated that glacial-age boundary conditions such as the size and shape of Laurentide Ice Sheet, were sufficient to produce the effect that Antevs had earlier hypothesized (Benson et al., 1995). As a result, shifts in the polar jet positions were advocated as the cause for the Great Basin and Mojave Desert lakes by other researchers (e.g., Harrison and Metcalf, 1985; Benson and Thompson, 1987; Enzel et al., 1989; Hostetler and Benson, 1990; Benson et al., 1995). Note, however, that the shifts indicated by the global climate models were to 30°N latitudes (e.g., Kutzbach et al., 1998); i.e., to even lower latitudes than indicated by these available lake chronologies.

At present, the average annual position and the episodic shifts to the south of the jet stream are related to persistent anomalies in the sea surface temperature of the North Pacific Ocean (e.g., Namias et al., 1988). Smith (1991b) used sea-air interaction and suggested that the compressed isotherms of the sea-surface temperatures of the North Pacific at 30°–40° latitudes during the winter for 18 ka (CLIMAP, 1981) might be the explanation for the increased moisture transported into the southwestern United States. Furthermore, he argued that this configuration allows for storms from warmer, lower latitudes of the North Pacific to reach the area carrying much larger quantities of moisture. The interaction of similar subtropical moisture sources with the polar jet and associated mid-latitude low pressure systems was proposed by Enzel et al. (1989) as a major mechanism to resolve the moisture quantities needed during the late Pleistocene. In light of this hypothesis and model results, we postulate that the systematic changes in timing of highest stands of late Pleistocene lakes in western United States reflect systematic latitudinal differences in the average storm track and polar jet position along the western coast of North America. During the glacial maximum (ca. 18 ka) the storm track was frequently farther to the south, probably at 32°–35° latitudes (Fig. 5). During the latest Wisconsin (14–12 ka) the average storm track was at ~40° latitude, feeding the Lake Lahontan and lake Bonneville basins.

The polar jet position varies along the western coast of North America from intraseasonal (Pyke, 1972) to probably millennial scales. The passage (and average position) of the jet stream over a specific drainage basin in the Great Basin and Mojave Deserts for hundreds to thousands of years will sustain a lake or a pronounced spring discharge during the late Pleistocene (Benson and Thompson, 1987; Enzel et al., 1989; Benson et al., 1995).

Relatively high-resolution lake records from 34° to 35° N latitude (Lake Estancia in New Mexico [Allen and Anderson, 1993] and Lake Mojave [Wells et al., this volume]) indicate decadal to centennial lake-level changes even during the last glacial maximum. Therefore, Allen and Anderson (1993) argue that the shifts in the average storm track cannot be attributed solely to the millennial-scale forcing boundary conditions used in the models (i.e., growth and decay of the Laurentide Ice Sheet and astronomical parameters) because of the different temporal scales of variations in the ice sheets and lakes. We suggest that the shift to the south of the polar jet and storm tracks is caused partially by the ice sheet, but that the high-frequency lake fluctuations are caused by seasonal to centennial variations in storm-track position that are superimposed on the lower-frequency, larger-scale shifts. Lakes located farther to the south will record more variations because the average storm track is located north of them, and only episodically would they have experienced persistent storms over seasons, years, or decades. The causes for these shorter episodes are unknown but probably are related to oceanic and atmospheric conditions over the North Pacific Ocean or upwind in East Asia.

The summary above indicates that millennial-scale shifts in the position of the storm track during the latest Pleistocene affected very large regions; consequently, high-resolution records are needed along the coast of North America to identify the temporal and spatial structure of the shifts.

Integration of the Mojave River hydrological basin

The Mojave River is a hydrological system that integrates closed basins to one relatively long arid river basin. In this volume Cox et al. present data on the late Pliocene and early Pleistocene evolution of the upstream reaches of the Mojave River. They associate this evolution with tectonic activity at the Transverse Ranges of southern California (e.g., Meisling and Weldon, 1989). They summarize earlier work (see also Jefferson, this volume) on the first appearance of Mojave River water and sediments at ca. 500 ka in the Manix basin in the middle reaches of the river. In this paper we have discussed our observations of the Mojave River integration to the downstream basins of the Soda Lake and Silver Lake playas during the latest Pleistocene. Although they are rare, present-day continuous flows of the Mojave River terminate at the Silver Lake basin. Anderson, D., and Wells (this volume) and Anderson, K., and Wells (this volume) indicate that, during the latest Pleistocene, the Mojave River overflowed and contributed to the Lake Dumont and the Death Valley lakes (Fig. 4) as proposed by Free (1914) and Huntington (1915). The breaching of the sill of Lake Dumont after 18 ka allowed more Mojave River discharge to reach Death Valley (Anderson, D., and Wells, this volume; Anderson, K., and Wells, this volume). Whereas Soda Lake basin contains a very thick sequence of deposits that were generated from local sources prior to the impact of the Mojave River (Brown and Rosen, 1995; Wells et al., this volume), it contains only relatively thin layer of sediments from the Mojave River, the oldest dating from the last glacial maximum.

Since its inception in result of the uplift of the San Bernardino Mountains, the Mojave River required >1 million years to fill its upstream basins with sediments and an additional 0.5 million years to reach the Manix basin. It then took 0.5 million years to fill the Manix basin and to overflow and integrate this basin with the Soda Lake and Silver Lake basins downstream. This last major integration was accomplished by incising the sediments at the Lake Manix spillway in the Afton Canyon area. This incision caused the loss of the storage capacity of the Manix basin (Meek, 1989) that was already reduced owing to the 0.5 million years of discharge of Mojave River sediments. The storage capacities of the Soda Lake and Silver Lake basins were reduced by sedimentation at much faster rates than were the basins upstream. From 22 ka to 8.5 ka storage was reduced from ~7 km^3 to ~1 km^3 (Wells et al., this volume). Since 8.5 ka the storage capacity of these basins was further reduced to ~0.15 km^3 (Enzel, 1990). This rapid loss of storage was probably related to the incision of the Manix basin (Meek, 1989) and transport of the eroded sediment to the Soda Lake and Silver Lake basins. The spillway of Lake Mojave did not and probably will not erode in the same way as the spillway of Lake Manix, because it is composed of metamorphic rocks, and not by weaker sediments. The emptying of sediments from one basin into a downstream basin can accelerate integration and probably is associated with active faulting (i.e., Manix fault) that uplifted unconsolidated basin-fill sediments to the spillway elevation during prelake times.

The integration of the Mojave River into Death Valley, its ultimate terminal basin, is in its final stages. Under Holocene conditions large floods generated in the Mojave River headwaters deposit most of their load of sand and gravel in southern

Soda Lake and their finer fraction in northern Soda Lake and Silver Lake playas. Although some of the sand and finer-grained deposits are blown out of the basins by wind, net Holocene deposition (e.g., Enzel and Wells, 1997) is observed and the deposition of the coarse alluvium is rapidly migrating north on top of the Soda Lake playa sediments. When the terminal basins of the Mojave River ultimately fill to the spillway elevation, Mojave River floodwaters will flow downstream even under Holocene conditions. According to Enzel (1992), the possibility that modern floods will overcome the transmission losses along the alluvial reaches between Silver Lake and Death Valley is not realistic under present-day conditions.

CONCLUSIONS

The available data on chronologies of the late Pleistocene lakes along the Mojave River (Harper Lake, Lake Manix and its subbasins, and Lake Mojave) and its late Pleistocene fan delta, indicate that high lake stands in these individual lake basins could have coexisted. If so, the Mojave River, which at present rarely delivers water to its terminal basin in Silver Lake playa, was able to support a very large lake area during the late Pleistocene. In turn, this relation indicates that southern California and the Mojave Desert experienced frequent, intensive North Pacific storms that draw moisture from the tropical and subtropical Pacific Ocean, the most probable moisture source for these large lakes. We think that this warm, moisture laden subtropical source is the only one that can explain the very large water volume needed to support lakes along the Mojave River. The similarity in the chronology of late Pleistocene highstands of the Mojave River lakes, and lakes in closed basins in southern Arizona and New Mexico, indicates a regional hydrological cause of this shift. The observed chronologies require that the storm tracks along the West Coast of North America were at a very low latitude of ~34°–35° N during the last glacial maximum. Later in the deglaciation the storm track shifted to the north, consistent with the observed highstands of the northern Great Basin lakes and the fluctuating lake levels in the southwestern United States.

The vigorous floods of the Mojave River originating in the San Bernardino Mountains delivered large quantities of sediments that progressively filled a series of basins. The reduction in storage capacity of these basins caused the lakes that these floods maintained to overflow downstream and to integrate the hydrological system during the Pleistocene. The overflow of Lake Manix to Lake Mojave caused the incision of Afton Canyon during a geologically short episode during the latest Pleistocene, but this incision lasted longer and was less catastrophic than has been proposed in earlier studies.

The Mojave River as we know it today is a young and evolving hydrological system. It owes its evolution to late Pliocene to early Pleistocene tectonic uplift of the Transverse Ranges, heavy storms at these elevated areas, transport of sediments by the resulting flows, and the filling of the downstream basins by those sediments. The integration during the Pleistocene of a few closed basins across the Mojave Desert formed the modern river. The last integration occurred during the late Pleistocene, when Lake Manix overflowed to the Soda Lake basin of Lake Mojave, and ultimately to Death Valley.

ACKNOWLEDGMENTS

The manuscript was written when YE was visiting the Division of Earth and Ecosystem Sciences, Desert Research Institute, Reno, Nevada; the support of this institute is greatly appreciated. Tim Minor and Alan Gillespie helped produce Figure 2. Several of the ideas presented here were reshaped by discussions over the years with Bruce Allen, Roger Anderson, Ray Weldon, Bruce Harrison, Les McFadden, George Jefferson, and Bob Reynolds. Tom Bullard, Alan Gillespie, George Smith, and John Tinsley provided excellent and constructive reviews.

REFERENCES CITED

Adams, K.D., and Wesnousky, S.G., 1998, Shoreline processes and the age of the Lake Lahontan highstand in the Jessup embayment, Nevada: Geological Society of America Bulletin, v. 110, p. 1318–1332.

Allen, B.D., 1991, Effect of climatic change on Estancia Valley, New Mexico: Sedimentation and landscape evolution in closed-drainage basin: New Mexico Bureau of Mines and Mineral Resources Bulletin 137, p. 166–171.

Allen, B.D., and Anderson, R.Y., 1993, Evidence from western North America for rapid shifts in climate during the last glacial maximum: Science, v. 260, p. 1920–1923.

Allen, B.D., and Anderson, R.Y., 2000, A continuous, high-resolution record of late Pleistocene climate variability from the Estancia Basin, New Mexico: Geological Society of America Bulletin, v. 112, p. 1444–1458.

Anderson, R.Y., Allen, D.B., and Menking, K.M., 2002, Geomorphic expression of abrupt climate change in southwestern North America at the Glacial termination: Quaternary Research, v. 57, p. 371–381.

Antevs, E., 1937, Age of Lake Mojave culture, *in* Crozer-Campbell, W.E., et al., eds., The archaeology of Pleistocene Lake Mohave: A symposium: Los Angeles, California, Southwest Museum Publishing, Southwest Museum Papers, v. 11, 118 p.

Antevs, E., 1938, Postpluvial climatic variations in the southwest: Bulletin of the American Meteorological Society, v. 19, p. 190–193.

Antevs, E., 1952, Cenozoic climates of the Great Basin: Geologische Rundschau, v. 40, p. 94–108.

Bassett, A.M., and Jefferson, D.T., 1971, Radiocarbon dates of Manix Lakes, central Mojave Desert, California: Geological Society of America Abstracts to Meeting, v. 3, no. 2, p. 79.

Beck, W., Donohue, D., Jull, A.J., T., Burr, G., Broecker, W.S., Berani, G., Hajdas, I., and Malotki, E., 1998, Ambiguities in direct dating of rock surfaces using radiocarbon measurements: Science, v. 280, p. 2132–2135.

Benson, L.V., and Paillet, F.L., 1989, The use of total lake-surface area as an indicator of climatic change: Examples from the Lahontan basin: Quaternary Research, v. 32, p. 262–275.

Benson, L.V., and Thompson, R.S., 1987, The physical record of lakes in the Great Basin, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 241–260.

Benson, L.V., Currey, D.R., Dorn, R.I., Lajoie, K.R., Oviatt, C.G., Robinson, S.W., Smith, G.I., and Stine, S., 1990, Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 yr: Palaeogeography, Paleoclimatology, Paleocology, v. 78, p. 241–286.

Benson, L., Kashgarian, M., and Rubin, M., 1995, Carbonate deposition, Pyramid Lake subasin, Nevada, 2: Lake levels and polar jet stream positions reconstructed from radiocarbon ages and elevations of carbonates (tufas) deposited in the Lahontan basin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 117, p. 1–30.

Berger, R., and Meek, N., 1992, Radiocarbon dating of *Anodonta* in the Mojave River basin: Radiocarbon, v. 34(3), p. 578–584.

Blackwelder, E., 1933, Lake Manly, an extinct lake in Death Valley: Geographical Review, v. 23, p. 464–471.

Blackwelder, E., 1954, Pleistocene lakes and drainage in the Mojave region, southern California, *in* Jahns, R.H., ed., The geology of southern California: California Division of Mines and Geology Bulletin, v. 170, p. 35–40.

Blackwelder, E., and Ellsworth, E.W., 1936, Pleistocene lakes of the Afton basin, California: American Journal of Science, v. 231, p. 453–463.

Blaney, F.H., 1957, Evaporation study at Silver Lake in the Mojave Desert, California: Eos (Transactions, American Geophysical Union), v. 38, p. 209–215.

Brown, W.J., and Rosen, R.M., 1995, Was there a Pliocene-Pleistocene fluvial-lacustrine connection between Death Valley and the Colorado River?: Quaternary Research, v. 43, p. 286–296.

Brown, W.J., Wells, S.G., Enzel, Y., Anderson, R.Y., and McFadden, L.D., 1990, The late Quaternary history of pluvial Lake Mojave: Silver Lake and Soda Lake basins, California, *in* Reynolds, R.E., et al., eds., At the end of the Mojave: Quaternary studies in the eastern Mojave Desert: Redlands, California, Special Publication of the San Bernardino County Museum Association, 1990 Mojave Desert Quaternary Research Center Symposium, May 18–21, 1990, p. 55–72.

Buono, A., and Lang, D.J., 1980, Aquifer discharge from the 1969 and 1978 floods in the Mojave River basin, California: U.S. Geological Survey Water-Resources Investigations Report 80-207, 25 p.

Buwalda, J.P., 1914, Pleistocene beds at Manix in the eastern Mojave Desert region: University of California Publication, Bulletin of the Department of Geology, v. 7, no. 24, p. 443–464.

Byers, F.M., Jr., 1960, Geology of the Alvord Mountain quadrangle, San Bernardino County, California: U.S. Geological Survey Bulletin 1089-A, 71 p.

CLIMAP Project Members, 1981, Seasonal reconstruction of the Earth's surface at the last glacial maximum: Geological Society of America Map and Chart Series 36.

Coues, E., 1900, On the Trail of a Spanish Pioneer—The diary and itinerary of Francisco Garcés in his travels through Sonora, Arizona, and California 1775–1776: New York, Francis P. Harper, 608 p.

Cox, B.F., and Tinsley, J.C., III., 1999, Origin of the late Pliocene and Pleistocene Mojave River between Cajon Pass and Barstow, California, *in* Reynolds, R.E., and Reynolds, J., eds., Tracks along the Mojave: Quarterly of the San Bernardino County Museum Association, v. 46, no. 3, p. 49–54.

Crippen, J.R., 1965, Natural water loss and recoverable water in mountain basins of southern California: U.S. Geological Survey Professional Paper 417-E, 24 p.

Crozer-Campbell, W.E., Cambell, H.W., Antevs, E., Amsden, A.C., Barbierry, A.G., and Bode, D.F., editors, 1937, The archaeology of Pleistocene Lake Mohave: A symposium: Los Angeles, California, Southwest Museum Publishing, Southwest Museum Papers, v. 11, 118 p.

Dale, H.C., 1918, The Ashley-Smith exploration and the discovery of a central route to the Pacific, 1822–1829: Cleveland, Ohio, Arthur H. Clark Company, 352 p.

Dibblee, T.W., Jr., 1960, Geology of the Rogers Lake and Kramer quadrangles, California: U.S. Geological Survey Bulletin 1089-B, 139 p.

Dibblee, T.W., Jr., 1968, Geology of the Fremont Peak and Opal Mountain quadrangles, California: California Division of Mines and Geology Bulletin 188, 64 p.

Dibblee, T.W., Jr., and Bassett, A.M., 1966a, Geologic map of the Cady Mountains quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-467.

Dibblee, T.W., Jr., and Bassett, A.M., 1966b, Geologic map of the Newberry quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-461.

Dickey, S.K., Neimeyer, R.A., and Sholes, R.C., 1979, Soda Lake groundwater investigations—phase II: Los Angeles, California, Southern California Edison Company, 72 p.

Dorn, R.I., Bamforth, D.B., Cahill, T.A., Dohrenwend, J.C., Turrin, B.D., Donahue, D.J., Jull, A.J.T., Long, A., Macko, M.E., Weil, E.B., Whitley, D.S., and Zabel, T.H., 1986, Cation-ratio and accelerator radiocarbon dating of rock varnish on Mojave artefacts and landforms: Science, v. 231, p. 830–833.

Dyer, H.B., Bader, J.S., and Giessner, F.W., 1963, Wells and springs in lower Mojave Valley area, San Bernardino County, California: California Department of Water Resources Bulletin 91-10.

Enzel, Y., 1990, Hydrology of a large, closed arid watershed as a basis for paleohydrological and paleoclimatological studies in the Mojave River drainage system, southern California [Ph.D. thesis]: Albuquerque, University of New Mexico, 316 p.

Enzel, Y., 1992, Flood frequency of the Mojave River and the formation of late Holocene playa lakes, southern California: The Holocene, v. 2, p. 11–18.

Enzel, Y., and Wells, S.G., 1997, Extracting Holocene paleohydrology and paleoclimatology information from modern extreme flood events: An example from southern California: Geomorphology, v. 19, p. 203–226.

Enzel, Y., Cayan, R.D., Anderson, R.Y., and Wells, S.G., 1989, Atmospheric circulation during Holocene Lake stands in the Mojave Desert: Evidence of a regional climatic change: Nature, v. 341, p. 44–48.

Enzel, Y., Anderson, R.Y., Brown, W.J., Cayan, D.R., and Wells, S.G., 1990, Tropical and subtropical moisture and southerly displaced North Pacific storm track: Factors in the growth of late Quaternary lakes in the Mojave Desert, *in* Betancourt, J.L., and MacKay, A.M., eds., Proceedings of the Sixth Annual Pacific Climate (PACLIM) Workshop: Sacramento, California, California Department of Water Resources Technical Report 23, p. 135–139.

Enzel, Y., Knott, J.R., Anderson, K., Anderson, D.E., and Wells, S.G., 2002, Is there any evidence of mega–Lake Manly in the eastern Mojave Desert during Oxygen Isotope Stage 5e/6?: Quaternary Research, v. 52, p. 173–176.

Fergusson, G.J., and Libby, W.F., 1962, UCLA radicarbon dates I: Radiocarbon, v. 4, p. 113.

Free, E.E., 1914, The topographic features of the desert basin of the United States with reference to the possible occurrence of potash: U.S. Department of Agriculture Bulletin 54, p. 45.

Free, E.E., 1916, An ancient lake basin on the Mohave River: Washington, D.C., Carnegie Institute of Washington, Yearbook No. 15, p. 90–91.

Gale, H.S., 1914, Note on the Quaternary lakes of the Great Basin, with special references to the deposition of potash and other salines, *in* White, D., ed., Contribution to economic geology, Part I: Metals and nonmetals except fuels: U.S. Geological Survey Bulletin 540, p. 399–406.

Garfunkel, Z., 1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent region: Geological Society of America Bulletin, v. 86, p. 1931–1944.

Gillespie, A.R., 2003, Rock-art dating at the end of the millennium: Epigraphic Society Occasional Papers, v. 24 (in press).

Groat, C.G., 1967, Geology and hydrology of the Troy playa area, San Bernardino County, California [M.S. thesis]: Amherst, University of Massachusetts, 133 p.

Hagar, D.J., 1966, Geomorphology of Coyote Valley, San Bernardino County, California [Ph.D. thesis]: Amherst, University of Massachusetts, 210 p.

Hale, G.R., 1985, Mid-Pleistocene overflow of Death Valley toward the Colorado River, *in* Hale, G.R., ed., Quaternary Lakes of the eastern Mojave Desert, California: Friends of the Pleistocene, Pacific Cell Field Trip Guidbook, p. 36–81.

Harrison, S.P., and Metcalf, S.E., 1985, Spatial variations in lake levels since last glacial maximum in the Americas north of the equator: Zeitschrift fur Gletscherkund und Glazialgeologie, Band 21, p. 1–15.

Hewett, D.F., 1954, General geology of the Mojave Desert region, California, *in* Jahns, R.H., ed., Geology of southern California: California Division of Mines, Bulletin 170 p. 5–20.

Hooke, R.LeB., 1999, Lake Manly(?) shorelines in the eastern Mojave Desert, California: Quaternary Research, v. 52, p. 328–336.

Hostetler, S., and Benson, L.V., 1990, Paleoclimatic implications of the highstand of Lake Lahontan dervied from model of evaporation and lake level: Climate Dynamics, v. 4, p. 207–217.

Hubbs, C.L., and Miller, R.R., 1948, The Great Basin, II: The zoological evidence: University of Utah Bulletin, v. 38, p. 17–166.

Hubbs, C.L., Bien, G.S., and Suess, H.E., 1962, La Jolla natural radiocarbon measurements II: Radiocarbon, v. 4, p. 204–238.

Hubbs, C.L., Bien, G.S., and Suess, H.E., 1965, La Jolla natural radiocarbon measurements IV: Radiocarbon, v. 7, p. 66–117.

Huntington, E., 1915, The curtailment of rivers by desiccation: Washington, D.C., Carnegie Institution of Washington, Yearbook for 1915, p. 96.

Jackson, D., and Spence, M.L., 1970, The expedition of John Charles Frémont, v. 1: Chicago, Illinois, University of Illinois Press, p. 674–677.

Jefferson, G.T., 1985, Stratigraphy and geologic history of the Pleistocene Lake Manix Formation, central Mojave Desert, California, *in* Reynolds, R.E., ed., Cajon Pass to Manix Lake: Geological investigations along Interstate 15: Redlands, California, San Bernardino County Museum Association Special Publication, p. 157–169.

Krider, P.R., 1998, Paleoclimatic significance of late Quaternary lacustrine and alluvial stratigraphy, Animas Valley, New Mexico: Quaternary Research, v. 50, p. 283–289.

Kutzbach, J.E., 1987, Model simulation of climatic patterns during the deglaciation of North America, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 425–446.

Kutzbach, J.E., and Guetter, P.J., 1986, The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 yr: Journal of the Atmospheric Sciences, v. 43, p. 1726–1759.

Kutzbach, J.E., and Wright, H.E., 1985, Simulation of the climate of 18,000 yr B.P.: Results for North America/North Atlantic/European Sector: Quaternary Science Review, v. 4, p. 147–187.

Kutzbach, J., Gallimore, R., Harrison, S., Behling, P., Selin, R., and Laarif, F., 1998, Climate and biome simulations for the past 21,000 yr: Quaternary Science Reviews, v. 17, p. 473–506.

Long, A., 1966, Late Pleistocene and recent chronologies of playa lakes in Arizona and New Mexico [Ph.D. thesis]: Tucson, University of Arizona, 141 p.

Manabe, S., and Broccoli, A.J., 1985, The influence of continental ice sheet on the climate of an ice age: Journal of Geophysical Research, v. 90, p. 2167–2190.

Markgraf, V., Bradbury, J.P., Forester, R.M., Singh, G., and Sternberg, R.S., 1984, San Agustin Plains, New Mexico: Age and paleoenvironmental potential reassessed: Quaternary Research, v. 22, p. 336–343.

Martin, P., 1994, Southern California basins regional aquifer, *in* McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America, Cordilleran Section Guidbook, p. 166–169.

McClure, W.F., Sourwine, J.A., and Tait, C.E., 1918, Report on the utilization of Mojave River for irrigation in Victor Valley, California: Sacramento, California, State of California, Department of Engineering Bulletin No. 5, 93 p.

Meek, N., 1989, Geomorphologic and hydrologic implications of the rapid incision of Afton Canyon, Mojave Desert, California: Geology, v. 17, p. 7–10.

Meek, N., 1990, Late Quaternary geochronology and geomorphology of the Manix Basin, San Bernardino County, California [Ph.D. thesis]: Los Angeles, University of California, 212 p.

Meek, N., 1999, New discoveries about the late Wisconsin history of the Mojave River system, *in* Reynolds, R.E., and Reynolds, J., eds., Tracks along the Mojave: Quarterly of the San Bernardino County Museum Association, v. 46, no. 3, p. 113–117.

Meisling, K., E., and Weldon, R.J., 1989, Late Cenozoic tectonics of the northwestern San Bernardino Mountains, southern California: Geological Society of America Bulletin, v. 101, p. 106–128.

Miller, R.R., 1946, Correlation between fish distribution and Pleistocene hydrography in eastern California and southwestern Nevada, with map of the Pleistocene waters: Journal of Geology, v. 54, p. 43–53.

Miller, R.R., 1981, Coevolution of deserts and pupfishes (Genus *Cyprinodon*) in the American Southwest, *in* Naiman, R.J., and Soltz, D.L., eds., Fishes in North American deserts: New York, John Wiley and Sons, p. 39–94.

Mojave River Agency, 1982, Report on historic and present conditions, Newberry Groundwater Basin: Victorville, California.

Mojave River Agency, 1985, Historic and present conditions, Upper Mojave River Basin: Victorville, California.

Morgan, L.D., 1953, Jedediah Smith and the opening of the west: The Bobbs-Merrill Company, New York, New York, p. 205–207.

Muessig, S., White, N.G., and Byers, M.F., 1957, Core Logs from Soda Lake, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-C, p. 81–96.

Nagy, E.A., and Murray, B.C., 1991, Stratigraphy and intrabasin correlation of the Mojave River Formation, central Mojave Desert, California: San Bernardino County Museum Association Quarterly, v. 38(2), p. 5–30.

Namias, J., Yuan, X., and Cayan, D.R., 1988, Persistence of North Pacific sea surface temperature and atmospheric flow patterns: Journal of Climate, v. 1, p. 682–703.

Ore, H.T., and Warren, C.N., 1971, Late Pleistocene–early Holocene geomorphic history of Lake Mojave, California: Geological Society of America Bulletin, v. 82, p. 2553–2562.

Oviatt, C.G., Currey, D.R., and Sack, D., 1992, Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 99, p. 225–241.

Phillips, F.M., Campbell, A.R., Kruger, C., Johnson, P., Roberts, R., and Keyes, E., 1992, A reconstruction of the response of the water balance in western United States lake basins to climatic changes: New Mexico Water Resources Research Institute Report No. 269, v. 2, 259 p.

Preston, R.N., 1988, Early California Atlas—Southern edition, 2nd edition: Portland, Oregon, Binford and Mort Publishers, 76 p.

Pyke, C.B., 1972, Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California: Los Angeles, California, University of California Water Resources Center Contribution No. 139.

Quade, J., Forester, R.M., Pratt, W.L., and Carter, C., 1998, Black mats, spring-fed streams, and late-glacial-age recharge in southern Great Basin: Quaternary Research, v. 49, p. 129–148.

Reynolds, R.E., and Reynolds, R.L., 1985, Late Pleistocene faunas from Daggett and Yermo, San Bernardino County, California, *in* Reynolds, R.E., ed., Cajon Pass to Manix Lake: Geological investigations along Interstate 15: San Bernardino County Museum Association Special Publication, p. 175–191.

Reynolds, R.E., and Reynolds, R.L., 1994, The isolation of Harper Lake Basin, *in* Reynolds, R.E., ed., Off limits in the Mojave Desert: Field trip guidebook: San Bernardino County Museum Association Special Publication 94-1, p. 34–37.

Rosen, M.R., 1989, Sedimentologic, geochemichal and hydrologic evolution of and intracontinental closed-basin playa (Bristol Dry Lake): A model for playa development and its implications for paleoclimate [Ph.D. thesis]: Austin, Texas, University of Texas, 256 p.

Sabin, E.L., 1914, Kit Carson days: Chicago, Illinois, A.C. McLurg and Company, 686 p.

Shlemon, R.J., and Budinger, F.E., 1990, The archaeological geology of the Calico site, Mojave Desert, California, *in* Lasca, N.P., and Donahue, J., eds., Archaeological Geology of North America: Boulder, Colorado, Geological Society of America, Centennial Special Volume 4, p. 301–313.

Smith, G.I., 1991a, Stratigraphy and chronology of Quaternary-age lacustrine deposits, *in* Morrison, R.B., ed., Quaternary nonglacial geology: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-2, p. 339–346.

Smith, G.I., 1991b, Continental paleoclimatic records and their significance, *in* Morrison, R.B., ed., Quaternary nonglacial geology: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-2, p. 35–41.

Starrett, L.G., 1949, The relation of precipitation patterns in North America to certain types of jet stream at the 300-millibar level: Journal of Meteorology, v. 6, p. 347–352.

Steinmetz, J.J., 1988, Biostratigraphy and paleoecology of limnic ostracodes from the late Pleistocene Manix Formation [M.Sc. thesis]: Department of Biological Sciences, Pomona, California State Polytechnic University, 64 p.

Steinmetz, J.J., 1989, Ostracoda of the late Pleistocene Manix Formation, central Mojave Desert, California, *in* Reynolds, R.R., ed., The west-central Mojave

Desert: Quaternary studies between Kramer and Afton Canyon: Redlands, California, Mojave Desert Quaternary Research Center, San Bernardino County Museum Association Special Publication, p. 70–77.

Stute, M., Clark, J.F., Schlosser, P., Broecker, W.S., and Bonani, G., 1995, A 30,000 yr continental paleotemperature record dervied from noble gases dissolved in groundwater from the San Juan Basin, New Mexico: Quaternary Research, v. 43, p. 209–220.

Thompson, G.D., 1921, Pleistocene lakes along the Mojave River, California: Journal of the Washington Academy of Science, v. 11, no. 17, p. 423–424.

Thompson, G.D., 1929, The Mojave Desert region, California: A geographic, geologic, and hydrologic reconnaissance: U.S. Geological Survey Water-Supply Paper 578, p. 1–143 and p. 371–572.

Van Devender, T.R., Thompson, R.S., and Betancourt, J.L., 1987, Vegetation history of the deserts of southwestern North America; the nature and timing of the late Wisconsin–Holocene transition, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 323–352.

Watchman, A., 2000, A review of the history of dating rock varnishes: Earth-Science Reviews, v. 49, p. 261–277.

Waters, M.R., 1989, Late Quaternary lacustrine history and paleoclomatic significance of pluvial Lake Cochise, southeastern Arizona: Quaternary Research, v. 32, p. 1–11.

Wells, S.G., and Enzel, Y., 1994, Fluvial geomorphology of the Mojave River in the Afton Canyon area, eastern California: Implications for the geomorphic evolution of Afton Canyon, *in* McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America, Cordilleran Section Guidebook, p. 177–182.

Wells, S.G., McFadden, L.D., and Dohrenwend, J.C., 1987, Influence of late Quaternary climate changes on geomorphic and pedogenic processes on desert Piedmont, eastern Mojave Desert, California: Quaternary Research, v. 27, p. 130–146.

Wells, S.G., Anderson, R.Y., McFadden, L.D., Brown, W.J., Enzel, Y., and Miossec, J-L., 1989, Late Quaternary paleohydrology of the eastern Mojave River drainage basin, southern California: Quantitative assessment of the late Quaternary hydrologic cycle in a large arid watershed: New Mexico Water Resources Research Institute, Technical Report 242, 250 p.

Whitley, D.S., and Dorn, R.I., 1993, New perspectives on the Clovis versus pre-Clovis controversy: American Antiquity, v. 58, p. 626–647.

Williamson, R.S., Blake, W.P., Durand, E., and Hilgard, T.C., 1856, Reports of explorations and surveys to ascertain the most practicable and economical route for a railroad from the Mississipi River to the Pacific Ocean in 1853–1854, v. 5: Washington, D.C., House of Representatives, Ex. Doc. No. 91, p. 30–34.

Wohl, E.E., and Enzel, Y., 1995, Data for paleohydrology, *in* Gregory, K.J., et al., eds., Continental Paleohydrology, John Wiley and Sons, New York, p. 23–59.

MANUSCRIPT ACCEPTED BY THE SOCIETY AUGUST 1, 2002

Printed in the USA