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ICE AGE LAKES IN NEW MEXICO

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Abstract–Estimates of lake surface area, drainage-basin area, and modern evaporation and precipitation for 11 of the pluvial lake basins in New Mexico have been obtained using available GIS coverages. These properties of the lake basins, coupled with an expression for the water budget, provide estimates of the hydrologic response of the basins to ice-age climate. Comparison of the lacustrine records from New Mexico to regional chronologies of hydrologic and climatic change requires information regarding the timing of the lake expansions. A continuous record of hydrologic change spanning the last glacial maximum has been reconstructed for the Lake Estancia basin of central New Mexico. The Lake Estancia record indicates wetter climatic conditions beginning approximately 40-45 kyrs B.P., culminating in a series of pluvial episodes beginning after 24 kyrs B.P. and lasting through the last glacial maximum and termination. Investigation of the geologic records of the ice-age lakes may also provide information about the tectonic development and hydrogeologic characteristics of their associated basins. Although a considerable amount of information regarding the ice-age lakes has been reported in the literature, basic information such as the maximum extent and timing of episodes of lake expansion is lacking for most of the lake basins in New Mexico.

INTRODUCTION

Permanent lakes occupied several of the large, topographically closed basins in New Mexico during the last ice age (Fig. 1). Complimentary evidence for changes in climate and hydrology during past glacial episodes, including evidence for mountain glaciers at higher elevations, spatial shifts in floral and faunal communities, and changes in the hydraulic regime of river systems, have shown that ice ages in the region were characterized by cooler temperatures, increased moisture, and comparatively greener landscapes. The evidence for large perennial lakes on the floors of today's semiarid basins invokes and reinforces this picture of a wetter ice-age Southwest.

A comprehensive review of the known distribution of latest Pleistocene lakes in New Mexico was presented by Hawley (1993). Various morphometric properties and pertinent hydrologic characteristics of the lake basins are tabulated in the report, and a literature review is provided. In addition, the regional physiographic and geologic setting is summarized and aspects of the geology of specific lake basins are presented.

Since Hawley's review, new studies of Lake King, TX (Wilkins and Currey, 1997), Lake Cloverdale, NM (Krider, 1998), Lake Estancia, NM (Allen and Anderson, 2000), Lake Tahoka, TX (Hall, 2001), and lakes in the Palomas basin of northern Chihuahua, Mexico (Castiglia, 2002) have been reported. Hawley and others (2000) recently provided an updated summary of the pluvial lake basins in southwestern New Mexico and northern Chihuahua, Mexico. These studies, together with Hawley's (1993) review represent the current state of knowledge regarding the large perennial lakes that existed in New Mexico and the immediate surroundings during the last (Wisconsin) glacial episode. The intent of this contribution is to provide additional information concerning the ice-age lakes of New Mexico, including aspects that were not explicitly discussed in Hawley's (1993) compilation. In particular, drainage-basin areas for the major lake basins are tabulated, and simple water-budget considerations are briefly examined. Results from the Lake Estancia study of Allen and Anderson (2000) are summarized in order to provide a general chronology of hydrologic and climatic changes that occurred in the region during the last ice age. Finally, a few observations and suggestions for future studies are offered. More complete reviews of the literature concerning the ice-age lakes in New Mexico are provided in Hawley's (1993) compilation and the recent studies cited above.

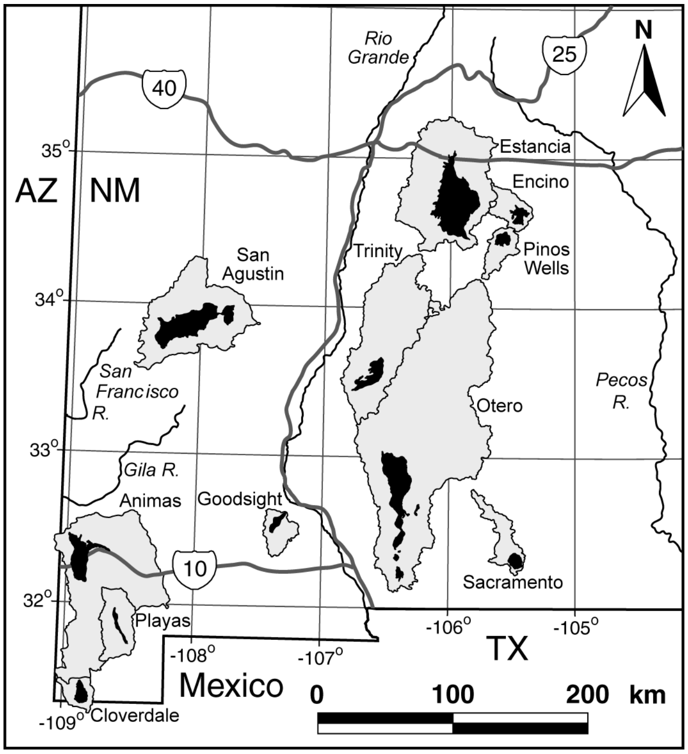

FIGURE 1. Distribution of ice-age lakes in New Mexico. Elevation and surface area of the ice-age lakes (black fill) and surrounding drainage basins (shaded) are listed in Table 1.

MORPHOMETRIC CHARACTERISTICS

The location and extent of major ice-age lake basins in New Mexico are shown in Figure 1. Lake basins in adjacent areas of southeastern Arizona (Lake Cochise), northern Chihuahua, Mexico (Lakes Hachita and Palomas), and southwestern Texas (Lake King) are not discussed here. Surface elevations of the pluvial lakes (highstand elevations) ranged from approximately 3950 ft (1204 m) for Lake Otero in the Tularosa basin, to about 7000 ft (2134 m) for Lake San Agustin. None of the pluvial lake basins presently contain perennial bodies of

TABLE 1. Morphometric characteristics of late Wisconsinan lakes in New Mexico based on USGS 10 m digital elevation models and a geographic information system (GIS) delineation of the lake basins. Highstand lake elevations are from Hawley (1993, table 1). Values of mean annual precipitation and evaporation are the spatial average for the area covered by the highstand lakes. Precipitation and evaporation estimates were obtained from a GIS grid interpolated from contour maps compiled by the National Oceanic and Atmospheric Administration (the digital contour maps of precipitation and evaporation and associated metadata are available from the RGIS Clearinghouse at http://rgis.unm.edu/). Estimates of evaporation are for a free water surface (see Farnsworth et al., 1982 for a discussion of the evaporation data).

Lake	Lake Elevation m (ft)	Lake Area km^2	Basin Area km^2	Lake Area/Basin Area ratio	Modern Precipitation cm/yr	Modern Evaporation cm/yr
Animas	1279 (4195)	374	5670	.066	25	184
Cloverdale	1576 (5170)	102	460	.222	41	178
Encino	1882 (6175)	96	620	.155	35	137
Estancia	1890 (6200)	1125	5050	.223	31	127
Goodsight	1372 (4500)	65	590	.110	25	183
Otero	1204 (3950)	745	12,600	.059	25	166
Pinos Wells	1859 (6100)	82	560	.146	36	132
Playas	1311 (4300)	49	1120	.044	27	190
Sacramento	1347 (4418)	86	780	.116	25	165
San Agustin	2115 (6940)	786	3880	.203	29	115
Trinity	1431 (4695)	207	4240	.049	25	159

water because annual evaporation exceeds the overall rate of inflow to the basin floors from precipitation, runoff, and groundwater discharge. Groundwater discharge to the floor of the Estancia basin is presently sufficient to maintain a complex of perennially moist playas, but the floors of many of the basins are several meters or more above local water tables, signifying an additional net loss of water from these basins by subsurface leakage.

A fundamental parameter in evaluating the hydrologic budget of a basin is its size. Surface areas of the drainage basins associated with the pluvial lakes, together with other morphometric and climatic characteristics of the lake basins, are tabulated in Table 1. As might be expected, larger drainage basins tended to produce larger lakes during the last ice age. The correspondence between lake surface area and drainage-basin area is poor, however. For example, the surface area of Lake Estancia was substantially larger than that of Lake Animas, even though the drainage-basin areas for these two basins are similar.

The surface extent of the ice-age lakes can be scaled using the ratio of lake area to drainage-basin area in order to facilitate comparisons between different size basins. Ratios of lake area to total basin area for the ice-age lakes depicted in Figure 1 range from approximately 5% to 20% (Table 1), and there was a weak tendency for higher elevation lakes to occupy larger proportions of their respective drainage basins (Fig. 2). A general increase in the ratio of lake area to basin area with higher lake elevation is consistent with expected elevational gradients in climate (i.e., increased precipitation and decreased evaporation with increasing elevation). There are, of course, many other factors in addition to drainage-basin area and lake elevation that may have influenced the size attained by lakes in individual basins, including hydrogeologic and geomorphic characteristics specific to each of the basins, possible latitudinal or longitudinal gradients in climate between basins, and local influences on the climatology of individual basins, such as orographic effects. The influence of local climatological features on a drainage basin's hydrologic budget may have been comparatively important for the smaller basins because local climatic conditions may have affected a large proportion of a smaller basin's total area.

HYDROLOGIC-CLIMATIC CONSTRAINTS

The general water budget for a steady-state lake in a topographically closed basin can be expressed as:

$$A_L(P-E) + SR + GWD = 0$$

where A_L is the surface area of the lake (units length^2), P is the precipitation on the lake (units length/time), E is the evaporation from the lake (units length/time), SR is the contribution to the lake as surface runoff from the surrounding drainage basin (units length^3/time), and GWD is the contribution to the lake from groundwater discharge (units length^3/time). The SR term may range from zero (no runoff) to some positive value, whereas values for GWD may range from negative (leaky basin) to positive. Values for SR and GWD are divided by the surface area of the contributing drainage basin (i.e., total drainage-basin area minus lake area) in order to express these terms in units of length/time (same units as P and E).

The hydrologic-budget equation provides a link between the geomorphic record of the surface extent of the ancient lakes, as indicated by relict shorelines, and climatic conditions that may have existed during their formation. Application of the water-budget method to obtain estimates of ice-age climate has been thoroughly discussed in the scientific literature. Indeed, the major assumptions and shortcomings of this approach were methodically contemplated five decades ago by Leopold (1951) and Antevs (1954), using the shorelines of ancient Lake Estancia as an example.

If a value for P-E is specified, the water-budget equation can be used to assess the hydrologic contribution required from the drainage basin (SR + GWD) in order to maintain a lake of a given size. For example, it might be hypothesized that precipitation in New Mexico was 1.7 times greater than modern values, and evaporation was 60% of modern values when the late Wisconsinan lakes stabilized at their high shorelines. Required contributions from the surrounding drainage basins under this climatic scenario are illustrated in Figure 3. The range of values suggests that 3 to 11 cm/year distributed evenly over the contributing drainage basins would have maintained the lakes at recorded highstand elevations. By way of comparison, Langbein's (1949) estimate of mean annual surface runoff from the conterminous U.S. is 22 cm/yr. In contrast, the present contribution from the surrounding drainage basin to the floor of the Estancia basin, mostly as groundwater discharge, is estimated to be less than 1 cm/yr (e.g., DeBrine, 1971).

The value of P-E for the Estancia basin used in the preceding example (-24 cm/yr) is similar to values used by Leopold (1951) and Brackenridge (1978) in their calculations of glacial-maximum climate. In

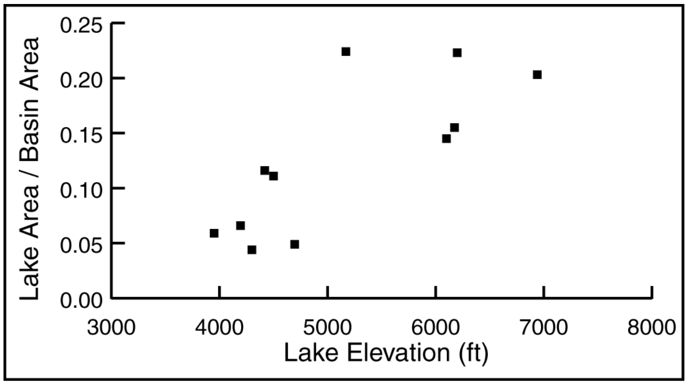

FIGURE 2. Ratio of lake area to drainage-basin area, plotted against lake elevation, for the ice-age lakes depicted in Figure 1.

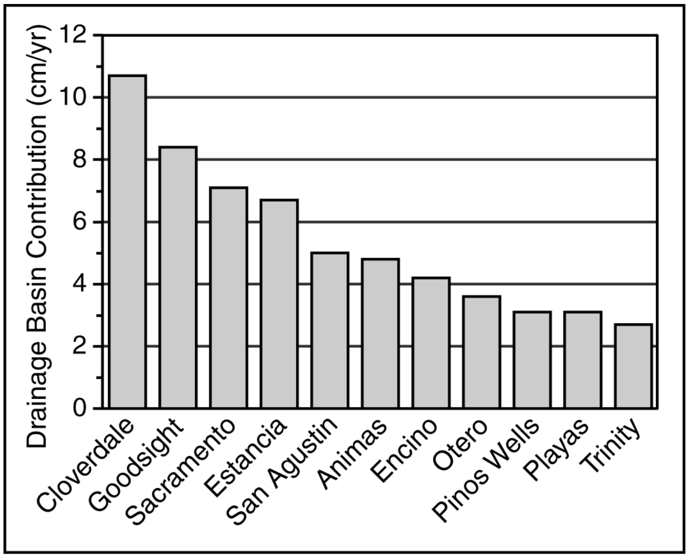

FIGURE 3. Histogram showing hydrologic contribution from the surrounding drainage basin (surface runoff plus groundwater discharge) needed to sustain the ice-age lakes at highstand elevations under specified conditions of climate (1.7 X modern precipitation, 0.6 X modern evaporation).

these studies, evaporation was empirically estimated using inferred, ice-age air temperatures. A simplified water-budget equation (neglecting groundwater discharge) was than applied to Lake Estancia to evaluate glacial-maximum precipitation. Leopold's (1951) analysis suggested a somewhat cooler and wetter glacial climate, whereas Brackenridge (1978) argued for even cooler temperatures, with no increase in precipitation.

Considering the large magnitude of evaporation relative to precipitation under modern climatic conditions (Table 1), it is clear that substantial decreases in evaporation must have occurred in order for the ice-age lakes to expand to their highstand elevations. Roughly two-thirds of the annual, free water surface evaporation presently occurs during the warm months May-October at lower elevation stations in New Mexico (Farnsworth and Thompson, 1982), so a likely prerequisite for the formation of the ice-age lakes was a significant reduction in summer evaporation. As noted by Leopold (1951), there is no direct (i.e., physically based) relationship between air temperature and evaporation. Changes relative to present climatic conditions that may have played a direct role in decreasing the summer evaporation include a reduction in net radiation, suggesting relative increases in summer cloudiness.

As for changes in the amount of precipitation, the cold-dry hypothesis for glacial-maximum climate in the Southwest as discussed by Brackenridge (1978) is inconsistent with a number of independent paleoclimate proxy records, including reconstructed distributions of vegetation in the northern Chihuahuan Desert (Van Devender, 1990), and is difficult to reconcile with geologic evidence for rapid rates of freshening and increases in the surface area of Lake Estancia during the last glacial maximum (Allen and Anderson, 1993). Thus, the term "pluvial" appears to be an appropriate adjective when referring to the late Wisconsinan lakes of New Mexico.

THE LAKE ESTANCIA RECORD

Because of their proximity, the ice-age lakes in New Mexico are generally assumed to have expanded to highstand elevations at similar times. Of the 11 pluvial lakes shown in Figure 1, radiometric ages of shoreline deposits have been published only for Lakes Cloverdale (Krider, 1998) and Estancia (Allen and Anderson, 2000). Records of relative changes in lake level are also preserved in the bottom muds that were deposited in deeper parts of the lakes. Stratigraphic studies of basin-center lake beds that include radiometric ages of associated materials have been done for Lakes San Agustin (e.g., Markgraf et al., 1984; Phillips et al., 1992) and Estancia (e.g., Bachhuber, 1989, 1992; Allen and Anderson, 2000). Aspects of the latest Pleistocene history of Lake Estancia are summarized below.

A comparative abundance of paleoclimatic information has been obtained from the Estancia basin, due in part to good preservation of shoreline features and nearshore deposits, and in part to extensive outcrop exposures of the basin-center lacustrine sequence. As with many of the pluvial lake basins in New Mexico, deflation at Estancia excavated large amounts of sediment from the floor of the basin during the mid-Holocene. Deflation at Estancia, however, resulted in the formation of numerous discrete blowouts, rather than wholesale removal of the upper part of the lacustrine sequence over the entire basin floor. Thus, the complete basin-center lacustrine sequence is well exposed in the walls of individual blowouts (Fig. 4). The presence of distinctive biostratigraphic zones and availability of material for radiocarbon dating makes it possible in some cases to correlate relative lake-level changes recorded in the continuous basin-center stratigraphic sequence with specific shoreline elevations.

The basin-center lacustrine sequence at Estancia consists mainly of calcareous clay and detrital gypsum silt and sand. In the exposed lacustrine sequence these major components are commonly interlaminated or thinly interbedded. Laminated facies alternate vertically on a scale of decimeters to meters with beds of weakly bioturbated, calcareous clay and gypsiferous, calcareous clay (Fig. 5), generally indicating deeper water. The blowouts at Estancia expose up to about 10 m of this vertical succession of laminated and bedded lithofacies.

At a depth of 11 to 12 m below the top of the lacustrine sequence, the basin-center lake beds overlie (in subsurface) a comparatively homogeneous accumulation of massive, gypsiferous clay. The massive deposits underlying the exposed lacustrine sequence are texturally similar to sediments that have accumulated in the playas that occupy the floors of the present-day deflation basins at Estancia. Based on textural similarities and a relative lack of remains of aquatic organisms (e.g., Bachhuber, 1992, fig. 7), these sediments are interpreted as primarily representing deposition in an ephemeral lake (playa) setting. Auger samples and sediment cores obtained from basin-center localities (Bachhuber, 1992; Allen, 1993) indicate that the massive, gypsiferous deposits continue to a depth of at least 20 m below the top of the lacustrine sequence.

The basal ~3 m of the overlying lacustrine sequence include laminated intervals that contain dense mats of algal material and relatively large fragments of aquatic plant remains, suggesting shallow water or a marsh-like depositional environment. The disappearance of algal mats and an increase in abundance of faunal remains indicating relative freshening of the lake, beginning about 8 m below the top of the lacustrine sequence, mark the onset of major expansions of the late Wisconsinan lake system.

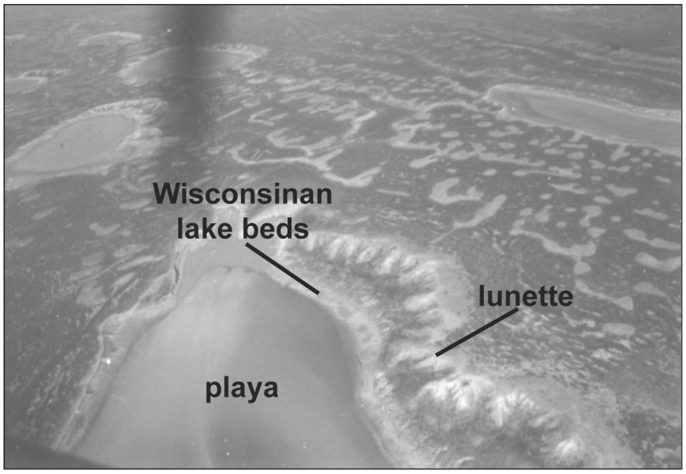

FIGURE 4. Oblique aerial photograph of the Estancia basin floor looking north-northeast, showing a deflation basin (blowout), leeward dune (lunette), and associated playa. The upper part of the basin-center lacustrine sequence is exposed in the walls of the Estancia deflation basins. Width of playa along lower edge of photograph is approximately 600 m.

The upper 5 m of the lacustrine sequence contain two relatively thick intervals composed of weakly bioturbated, calcareous clay and gypsiferous calcareous clay, separated by approximately 2 m of laminated sediments (Allen and Anderson, 2000, fig. 3). The weakly bioturbated, clayey intervals contain faunal remains, including fossil trout (Bachhuber, 1989), that indicate freshening of the lake. Radiocarbon dates from nearshore deposits (Allen and Anderson, 2000, table 1) show that Lake Estancia expanded to highstand elevations during deposition of these two stratigraphic intervals.

The uppermost several decimeters of the lacustrine sequence grade back into laminated gypsum sand and calcareous clay, and are overlain by ~0.5 m of massive gypsum and magnesite ($MgCO_3$) that formed during initial desiccation of the perennial lake. This desiccation layer is typically overlain in blowout exposures by eolian deposits consisting of gypsum sand and clay pellets that were deflated from the blowouts during the Holocene.

The lake beds in the Estancia basin contain an abundance of fossil ostracodes that are represented by several species with known environmental preferences and salinity requirements (e.g., DeLorme, 1969). The calcite shells of this bivalved crustacean are well preserved in the Estancia lake beds and provide material for carbonate geochemical analyses and radiocarbon dating. Distributions of species of ostracodes obtained from basin-center localities are shown in Figure 6. *Limnocythere staplini* tolerates very saline waters and is present throughout the lacustrine sequence. It is the dominant species in the lower part of the exposed sequence, where lithologies and sediment textures suggest predominantly shallow water and frequent oscillations in lake level. *Candona rawsoni*, which is less tolerant of high salinities, becomes increasingly abundant in the upper part of the lacustrine sequence. Stratigraphic ranges of the other species shown in Figure 6 correspond to episodes of substantial freshening of the lake. *Candona caudata*, for example, indicates total dissolved solids (TDS) in lake waters of less than 3000 mg/L, and appears twice in the lacustrine sequence, beginning ca. 23.3 kyrs B.P., and again at ca. 20.1 kyrs B.P. *Cytherissa lacustris*, which appears in the sequence during the second appearance of *Candona caudata*, indicates lake-water TDS values of less than 500 mg/L.

Stratigraphic changes in geochemical proxies such as the ratio of strontium to calcium in lacustrine carbonates and changes in the bulk composition of basin-center sediments also indicate relative degrees of freshening and inferred episodes of lake expansion and drawdown (Allen and Anderson, 2000). Reconstructed millennial-scale changes in the size of Lake Estancia, based on sedimentary texture and lithology, distributions of species of ostracodes, and geochemical proxies obtained from the basin-center sequence are indicated schematically in Figure 6.

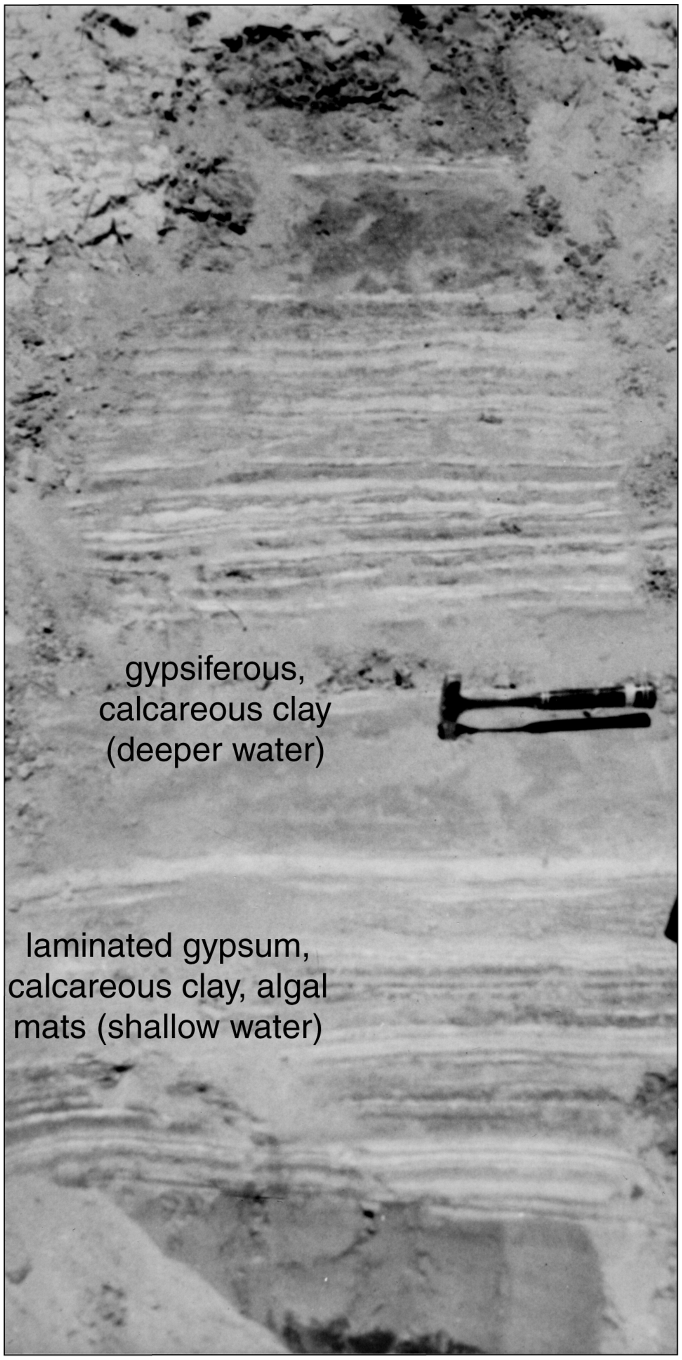

FIGURE 5. Basal part of exposed lacustrine sequence in the Estancia basin, showing alternating, decimeter-scale intervals of laminated and bedded sediments. Laminated intervals consist of detrital gypsum sand (light-colored layers), calcareous clay, and mats of algal and aquatic plant remains. Intervening beds of calcareous clay and gypsiferous, calcareous clay were deposited in deeper water. Clay bed in vertical cut near base of photograph was deposited approximately 30 kyrs B.P. Sediment layers appear thicker than actual because of sloped surface of outcrop. Rock hammer is ~30 cm long.

Major features of the Estancia record include: (1) a change from predominantly playa conditions to primarily shallow lake and marsh environments beginning approximately 40 to 45 kyrs B.P. (extrapolated age), (2) onset of major expansions of the lake after 24 kyrs B.P., separated by drawdowns of the lake to its minimum pool, (3) maxi-

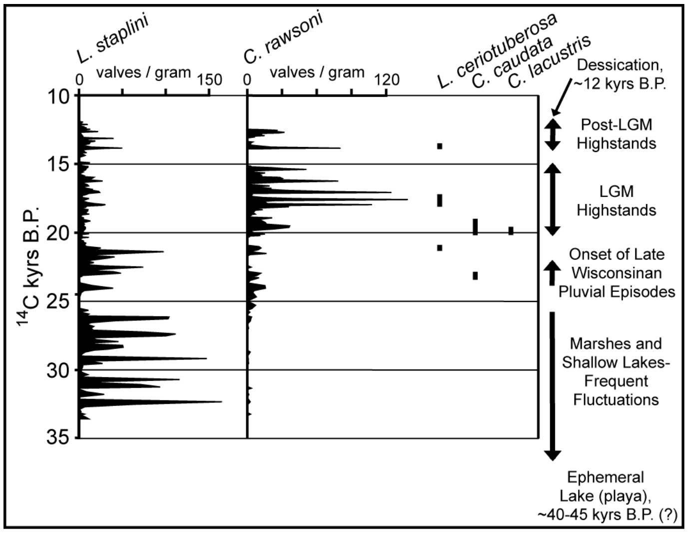

FIGURE 6. Stratigraphic distribution of selected species of ostracodes and generalized paleoenvironmental interpretations for the basin-center lacustrine sequence, Estancia basin. Time scale (y-axis) is based on 22 AMS radiocarbon dates (Allen and Anderson, 2000, table 1); base of ostracodes census (~33.8 kyrs B.P.) corresponds to a depth of ~9.8 m below the top of the lacustrine sequence. Arrows along right side of diagram show timing of inferred changes in the size of the lake as indicated by the text labels. LGM - last glacial maximum.

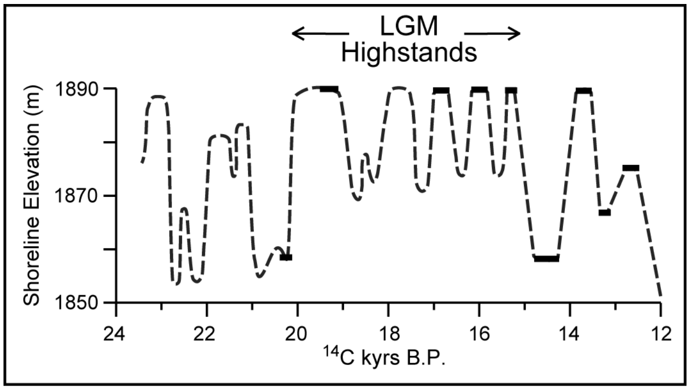

FIGURE 7. Reconstructed elevation of Lake Estancia during late Wisconsinan pluvial episodes, ca. 24 to 12 kyrs B.P (modified from Allen and Anderson, 2000). Solid lines indicate portions of curve constrained by shoreline evidence.

mum pluvial conditions (glacial-maximum highstands) from about 20 to 15 kyrs B.P., (4) drawdown of the lake to the minimum pool ca. 15 to 14 kyrs B.P., (5) two more expansions to highstand elevations between 14 and 12.5 kyrs B.P., and (6) desiccation of the perennial lake by approximately 12 kyrs B.P.

A final expansion of Lake Estancia occurred after the initial desiccation of the late Wisconsinan lake, forming a series of beach ridges along the eastern margin of the lake floor. This poorly dated expansion probably occurred between about 11 and 10 kyrs B.P., after formation of the gypsum-magnesite desiccation layer and an early episode of deflation along the western side of the relict lake floor (Anderson et al., 2002). This final expansion of Lake Estancia was apparently short lived and was eventually followed by extensive deflation and excavation of the numerous blowouts that occupy the floor of the basin today. Radiocarbon ages from near the base of associated lunettes suggest that the major episode of basin-floor deflation was underway by about 7 kyrs B.P.

The stratigraphic record of Lake Estancia indicates an increase in effective moisture and major expansions of the lake beginning about 24 kyrs B.P., culminating in maximum highstands during the last glacial maximum. The detailed record of lake-level fluctuations from Estancia indicates that significant, century-scale fluctuations in the water budget occurred during the overall expansion of the lake system (Fig. 7). Thus, an aspect of the regional climate system during the last ice age, equal in importance perhaps to the overall trend toward wetter climate, was large, century- and millennial-scale fluctuations in precipitation and evaporation (Allen and Anderson, 1993, 2000).

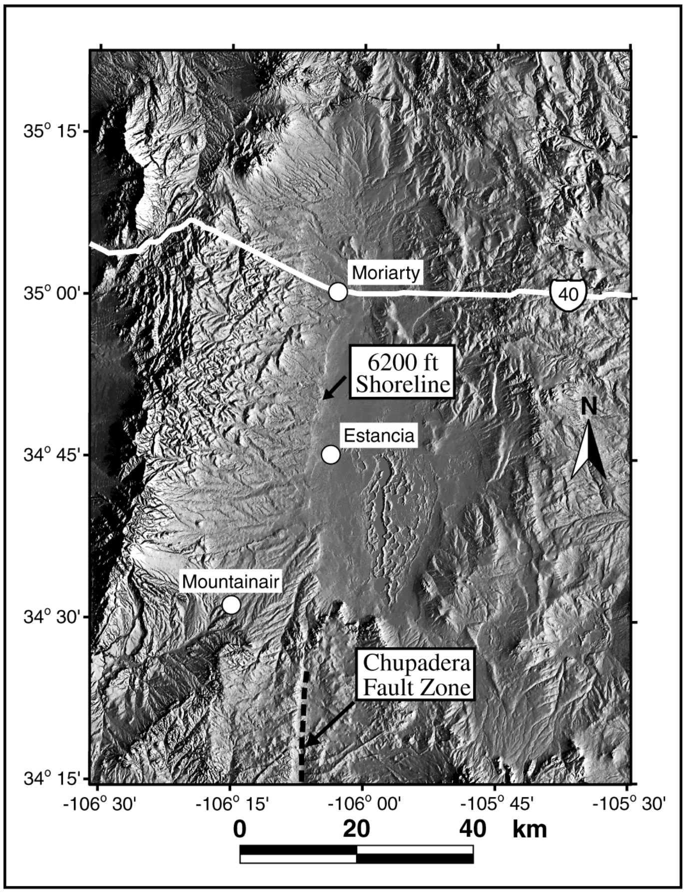

FIGURE 8. Shaded relief map of the Estancia basin and surrounding areas showing northern bedrock escarpment of the Chupadera fault (dashed line) and western shoreline escarpment of Lake Estancia. Repeated expansions of the lake to similar highstand elevations (~6200 ft) during the late Wisconsinan support a speculation that fractures and dissolution channels associated with the Chupadera structure provided conduits for enhanced leakage of groundwater from the basin during highstands of the lake.

DISCUSSION

An interesting feature of the Estancia lake-level reconstruction (Fig. 7) is that the lake expanded repeatedly to approximately the same 6200 ft elevation during the late Wisconsinan. A possible explanation for this apparent upper limit of lake level is that groundwater leakage from the basin played an increasingly important role in the water budget as the lake expanded to highstand elevations. The 6200 ft shoreline along the western side of the basin coincides with a notable escarpment that has generally been interpreted as a wave-cut cliff (e.g., Meinzer, 1911). This escarpment lines up to the south with a broad, down-to-the-east geologic structure (Chupadera fault and Claunch sag of Kelley and Thompson, 1964) that extends southward across Chupadera Mesa and into the northern Tularosa basin (Fig. 8). Considerable thicknesses of Permian evaporites are present beneath Chupadera Mesa, leading to a speculation that fractures and dissolution features associated with the Chupadera structural zone may have facilitated groundwater

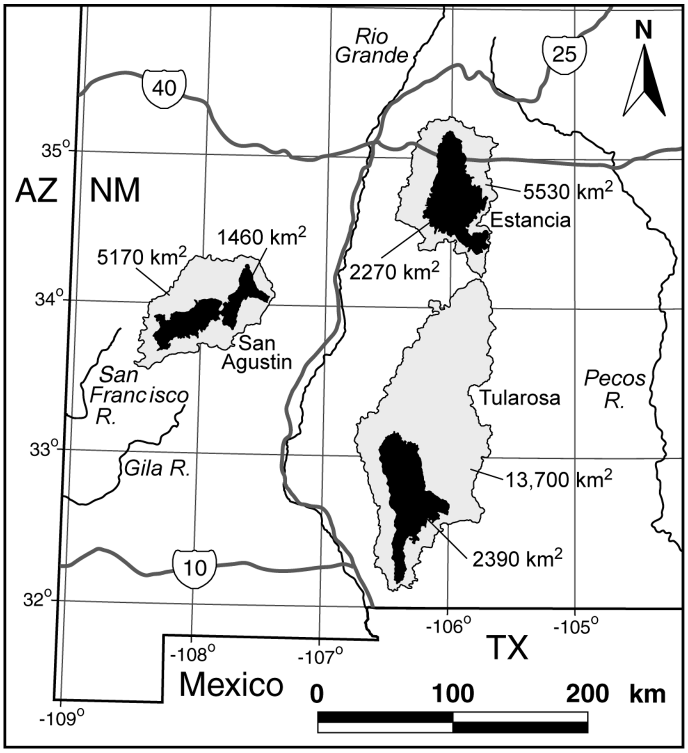

FIGURE 9. Extent of ice-age lakes corresponding to reported highstands in the Estancia (6335 ft highstand), San Agustin (7050 ft highstand), and Tularosa (4000 ft highstand) basins. In all three basins the larger lakes entail an increase in the size of the surrounding drainage basin. Lake area and drainage-basin area values (km^2) for each of the lake basins are indicated.

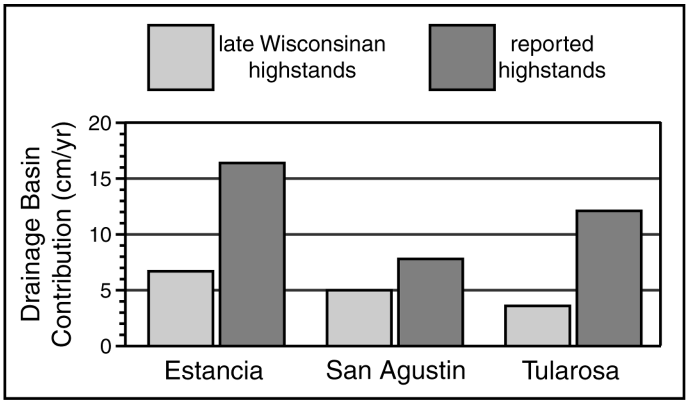

FIGURE 10. Histogram comparing water-budget requirements for documented (late Wisconsinan) and reported highstand lakes in the Estancia, San Agustin, and Tularosa basins (documented highstand lakes are depicted in Figure 1, reported highstand lakes in Figure 9). Values on the y-axis indicate the drainage-basin contribution (surface runoff plus groundwater discharge) needed to maintain the lakes at highstand elevations. The values of precipitation and evaporation used in the water-budget calculations are the same as used for the Figure 3 example.

leakage from the Estancia basin during times of higher regional water tables, thus limiting the size of the lake (Hawley, 1986; Hawley and Love, 1991). Repeated expansions of Lake Estancia to nearly the same elevation support this hypothesis.

Unambiguous shoreline features provide a basis for delineating the highstand lake elevations summarized in Hawley's (1993) compilation. Possible exceptions include the Pinos Wells basin, where Meinzer (1911) found little evidence for shorelines or basin-center lake beds. Hawley's tabulation of lake elevations also acknowledges reports that cite evidence for shoreline features significantly higher in elevation than the reasonably well-documented lakestands. For example, some investigators (e.g., Lyons, 1969; Titus, 1969; Bachhuber, 1971, 1989) have alluded to poorly preserved shoreline features above 6300 ft (1920 m) in the Estancia basin. In the San Agustin basin, shorelines have been reported at 7050 ft (2149 m) (Weber, 1994). In the Tularosa basin, shorelines at 3970 ft (1210 m) have been identified (Langford, 2002), and lacustrine deposits of Pleistocene age have been mapped near an elevation of 4000 ft (1219 m) (Seager et al., 1987). The surface extent of lakes in these basins, assuming that highstand elevations of 6335 ft (Estancia), 7050 ft (San Agustin), and 4000 ft (Tularosa) were attained, are depicted in Figure 9.

Hydrologic implications of greatly expanded lakes in these basins can be qualitatively assessed using the hydrologic-balance approach, as was done previously for each of the documented late Wisconsinan lakestands (Fig. 3). In comparison to the ratios listed in Table 1 for documented highstands, lake expansions to reported elevations in the Estancia and Tularosa basins entail substantial increases in the ratio of lake area to drainage-basin area. Consequently, the hydrologic requirements for maintaining reported highstands in these basins are much greater than for the documented lakes (Fig. 10). In contrast, expansion of Lake San Agustin to an elevation of 7050 ft does not appear to require large increases in surface runoff and groundwater discharge, because the increase in lake area is accompanied by a comparable increase in the size of the contributing drainage basin.

Questions regarding the maximum extent of the ice-age lakes in New Mexico underscore the need for additional field-based studies in all of the lake basins depicted in Figure 1. Early investigation of the basin-center lake deposits in the San Agustin basin (e.g., Clisby and Sears, 1956) sought to obtain a record of hydrologic changes spanning several glacial-interglacial cycles. At present, this goal of obtaining a long terrestrial record of climate from New Mexico has not been achieved, although the likelihood of obtaining such records from some of the closed basins (e.g., San Agustin, Tularosa) has not been ruled out.

The lacustrine sediments at Estancia may provide constraints on the timing and magnitude of structural events that resulted in topographic closure of that basin. Available borehole evidence suggests that the basin-center lake deposits at Estancia are only on the order of 30 m thick (e.g., Titus, 1969). Underlying alluvial deposits with a thickness of about 90 m indicate deposition in a valley with a through-flowing drainage system. The thinness of the lacustrine sequence suggests that topographic closure of the modern Estancia basin occurred recently in the geologic past, perhaps during middle Pleistocene time. The vertical relief between the base of the lacustrine sequence and the topographic sill at Estancia is on the order of 110 m. Information regarding the age of the base of the lacustrine sequence at Estancia would shed light on what appears to be a significant and relatively recent tectonic adjustment in the region.

In contrast to Estancia, Neogene basin-fill deposits in the Tularosa basin may be quite thick and could include mid-Pliocene to early Pleistocene lacustrine sediments that accumulated in a large complex of lakes (Lake Cabeza de Vaca of Strain, 1966) fed by the ancestral Rio Grande (Hawley, 1993). Thus, lacustrine sediments deposited in late Pleistocene Lake Otero represent the latest chapter in what might be a long history of lacustrine sedimentation in the basin. The geologic record of even the most recent pluvial episode in the Tularosa basin is poorly documented, however (Lucas and Hawley, 2002). Part of the problem in reconstructing the history of Lake Otero stems from the removal of significant amounts of the basin-center lacustrine sequence by deflation, and associated burial of adjoining areas beneath a layer of eolian sediment. Additional confusion arises over the term "Lake Otero" itself. Given that lacustrine deposits spanning the last 2 million years may be partially preserved around the margin of the lake basin, identification of all outcroppings of clayey or gypsiferous deposits as sediments of Lake Otero may be a simplification, especially if the term "Lake Otero" is to be reserved for the most recent (late Pleistocene) pluvial episode. As with most of the New Mexico lake basins, clarification awaits further field-based stratigraphic, geomorphic, and chronometric studies. The problem of documenting pre-Wisconsinan lake expansions in the ice-age lake basins is a topic that has received little attention in New Mexico (e.g., Gile, 2002).

Work also remains to be done in terms of quantifying the paleoclimatic implications of the large perennial lakes that existed in the Southwest during the ice ages. An hypothesis that accounts for increased precipitation in the Southwest despite cooler overall temperatures calls on the development of high atmospheric pressure over the Laurentide ice sheet and an overall southward displacement of the winter storm track and transport of Pacific moisture over the continent. Global circulation models using late Wisconsinan boundary conditions have successfully simulated this response of the atmospheric circulation to the northern hemisphere ice sheet (e.g., Kutzbach and Wright, 1985), and this hypothesis for increased winter precipitation in southwestern North America during the last glacial maximum appears to have gained general acceptance. Details of the hydrologic response of the ice-age lake basins are not directly addressed by this model, however. For example, the large, century- to millennial-scale fluctuations recorded by Lake Estancia (Fig. 7) suggest a manifestation of glacial-age climate that operated at much higher frequencies than the comparatively slow buildup and decay of the continental ice sheets. Considering the likely importance of summer evaporation on the hydrologic budget of the ice-age lakes, it also seems reasonable to inquire if there was an aspect of the atmospheric circulation that might have resulted in increased summer cloud cover and decreased summer evaporation in the Southwest. Evidence from the entire spectrum of paleoclimatic archives, including the records of ancient lake beds and shorelines, provide important clues to these and other questions regarding the large- and fine-scale structure of climate during the ice ages.

CONCLUSIONS

Morphometric characteristics of the ice-age lake basins in New Mexico suggest that contributions to the lakes from surrounding drainage basins (surface runoff and groundwater discharge) as well as elevational gradients in precipitation and evaporation played significant roles in the hydrologic response of the large, topographically closed basins to glacial climates. The geomorphic and stratigraphic record of Lake Estancia indicates substantial increases in effective moisture and major expansions of the lake between 24 and 12 kyrs B.P., with intervening century- to millennial-scale episodes of drier climate and lake drawdown. The observations presented in this report illustrate the wide range of research questions that may be directly or peripherally addressed by an understanding of the history of the ice-age lakes, and are intended to highlight the need for additional, field-based studies of the numerous lacustrine archives that are present in the American Southwest.

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