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1982, pp. 347-350. https://doi.org/10.56577/FFC-33.347

in:

Albuquerque Country II, Wells, S. G.; Grambling, J. A.; Callender, J. F.; [eds.], New Mexico Geological Society 33 rd Annual Fall Field Conference Guidebook, 370 p. https://doi.org/10.56577/FFC-33

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PLEISTOCENE-HOLOCENE CLIMATE OF THE ESTANCIA BASIN, CENTRAL NEW MEXICO

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INTRODUCTION

The climatic significance of the shorelines of the ancient Lake Estancia, situated between the Pedernal Hills to the east and the Manzano Mountains to the west, was first recognized by Meinzer (1911). Hydrologic modeling, for the estimation of past climates in the western United States, began with Lake Estancia (Leopold, 1951). Since then, additional hydrologic models of Lake Estancia have been developed (Antevs, 1954; Harbour, 1958; Lyons, 1969; Galloway, 1970; Brackenridge, 1978). Also, additional shorelines have been recognized (Lyons, 1969; Titus, 1969; Bachhuber, 1971, this guidebook). Estimates of climate during high lake stands, based on these models, range from reduced temperature and precipitation to more than a doubling of present precipitation.

Previous modeling studies either did not have information about the elevation of the highest shorelines or did not know the probable age of the shorelines. These uncertainties have contributed to the wide range of climatic estimates. This article briefly describes the hydrologic system and its controls, summarizes shoreline information, examines previous estimates of climate, and presents revised climatic estimates based on a simple hydrologic model.

ESTANCIA BASIN

Estancia basin is a structural and topographic, north-trending asymmetrical graben. The basin floor averages 1,853 m (6,080 ft) in elevation. Drainage divides, in the 6,115 km' basin area, range from a topographic sill at 1,929 m (6,330 ft) (fig. 1) to 3,078 m (10,100 ft) at Manzano Peak. Only 10 percent of the surface area in the basin is above 2,130 m (6,990 ft) in elevation, mainly along the Manzano Mountains.

The Estancia drainage basin is underlain by east-dipping limestone, sandstone, and alluvial aquifers which intercept all of the runoff from the Manzano Mountains. Recharge from the eastern side of the basin is estimated at less than one-fifth of that of the western side (Titus, 1969). No surface water presently reaches the playas. All ground water originates from within the topographic divides of the basin and is diverted into alluvial aquifers confined by the lacustrine, clay-rich deposits. Leakage from the basin may be substantial along semi-confined aquifers to the north, but it has not been quantified (Titus, 1969).

Basin-fill consists of up to 120 m of alluvium related to Plio-Pleistocene through-flowing drainage, overlain by up to 37 m of Pleistocene and Holocene lacustrine and alluvial deposits (Titus, 1969). Two clay-rich lacustrine beds are separated by alluvium. The older lake bed and alluvium only occur in subcrop (fig. 1). The upper 60 percent of the younger lacustrine unit is exposed in blowouts and represents at least three episodes of lake stability (Bachhuber, 1971, this guidebook; Bachhuber and McClellan, 1977).

Shoreline features (baymouth bars, beaches, and wave-cut cliffs), representing shoreline stands, have been mapped at 1,856 m, 1,873 m, and from 1,878 to 1,896 m (6,090 ft, 6,145 ft, and from 6,160 to 6,220 ft; the "A," "B," and "C" levels, respectively, of Harbour, 1958; fig. 1). Lyons (1969) described a number of higher shorelines at the elevation of the present topographic sill (1,929 m; 6,330 ft) and postulated possible overflow of the lake system. Titus (1969) recognized a wave-cut cliff at 1,939 m (6,360 ft), 10 m above the elevation of the present sill. Bachhuber (1971) studied the sedimentology, paleontology, and stratigraphy of the lacustrine deposits exposed in the blown-out depressions in the central basin. Fossil trout were collected from two horizons, which are separated by sediments that suggest drying and partial lake

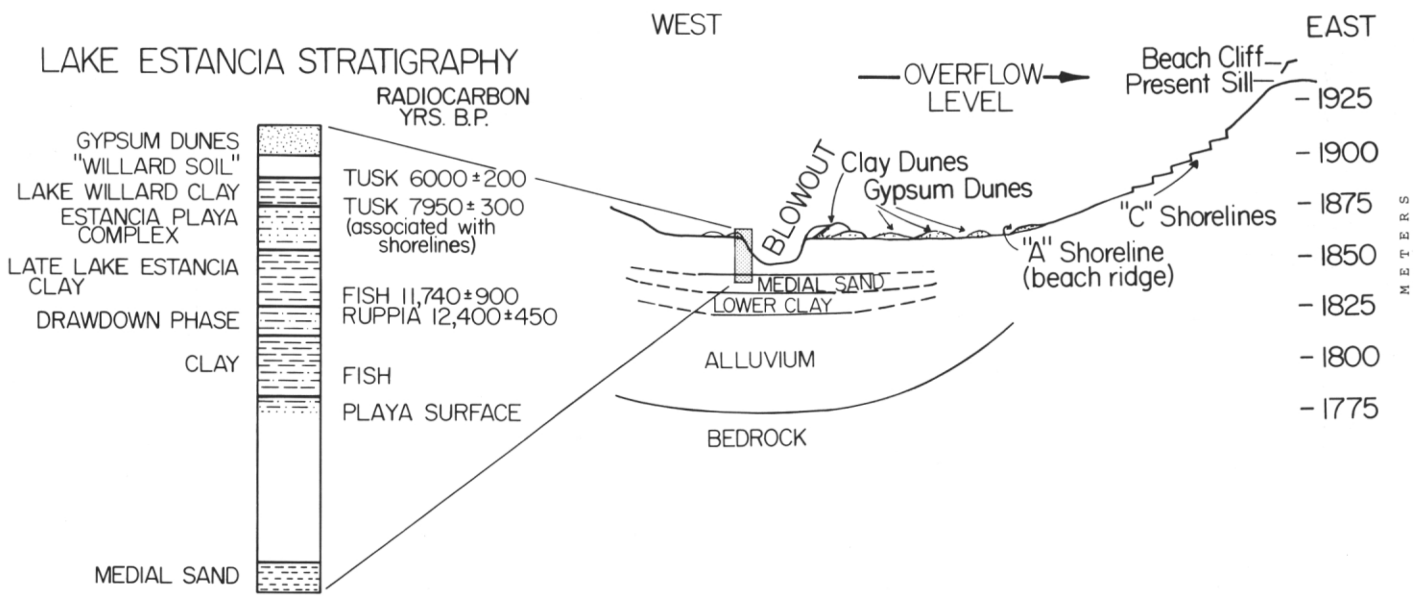

Figure 1. Profile of Estancia Lake basin showing elevation of sill, shorelines, lake floor, and blowouts. Stratigraphy adapted from Bachhuber (1971) and Titus (1969).

drawdown. Based on this evidence Bachhuber (1971) postulated overflow and drainage integration of Estancia basin with the Pecos River during at least two episodes. The upper lake bed, containing fish, was dated at approximately 12,000 years B.P. (fig. 1; Bachhuber, 1971), indicating that Lake Estancia reached an elevation of at least 1,929 m (6,330 ft) and overflowed at this time.

The lacustrine deposits are overlain by playa sediments which indicate desiccation following the 12,000 year B.P. high lake stand. Another lake-bed sequence, above the fish horizon and the playa sediments (Lake Willard), was deposited during a later, intermediate lake stand. This lake probably desiccated between 7,950 to 6,000 years B.P. (Bachhuber and McClellan, 1977). The highest lake stand of Lake Willard was probably responsible for the 13 "C" shorelines, although some of these ridges may have been formed during previous high stands. Subsequent lowering of Lake Willard left "B" and "A" shorelines, followed by an episode of "caliche" formation on top of the lacustrine deposits (Willard soil of Bachhuber and McClellan, 1977). Agypsum-dune field, in which the sand is relatively pure gypsum, migrated eastward over the lacustrine sediments and now rests on the calcrete horizon. Some of this sand is incorporated into a beach ridge formed during the latest stage of Lake Willard.

Nearly 100 deflation basins cut through the "caliche" and into the lacustrine sediments. The parabolic clay dunes derived from the blowouts overlap the gypsum dunes. Decrease in surface moisture during the Altithermal (6,000 to 4,000 years B.P.) and subsequent destabilization of the valley-floor allowed the deep deflation basins to develop as the water table lowered. The blowouts are now occupied by playa sediments that have filled in about I to 2.6 m of the depressions which formed during the Altithermal (Titus, 1969).

Present precipitation within the drainage basin is 36.6 cm per year, based on 7 to 53 years of data from recording stations at different elevations in the region. Sixty-five percent of the precipitation falls during the warm season, from April to September. The 43-year mean annual air temperature at Estancia is 10°C. Evaporation for a fresh-water lake under these conditions is estimated to be 152 cm per year (Meyers, 1962).

HYDROLOGIC MODEL

We have calculated the hydrologic balance in the closed-lake system required to stabilize the lake level at different elevations in the basin. A number of parameters from the basin, such as lake area and volume at selected elevations, are fixed. Others, such as present precipitation and evaporation, are approximately known. Parameters related to past conditions are based on empirical relationships and assumptions. Evaporation from a fresh-water lake is directly proportional to mean annual temperature. The temperature-evaporation relationship used here is that of Galloway (1970), corrected by a factor of 5/6 to accommodate the known present temperature and evaporation values for the Estancia valley.

Relationships between precipitation and water yield have not been determined specifically for the Estancia basin. Empirical curves have been developed, however, that relate temperature and precipitation to runoff (Langbein and others, 1949; Langbein, 1962; Schumm, 1965). These curves were constructed from instrumented drainage basins that were chosen to represent natural conditions, some of which are located in New Mexico. It must be assumed that they are generally applicable to the Estancia basin and that runoff equals water yield. We have made two additional assumptions that tend to estimate the amount of climatic change conservatively: (1) non-seasonally weighted mean-annual temperatures were used which predict up to 20 percent more runoff than Schumm's (1965) calculations, and (2) leakage and overflow from the basin is zero, even at high lake levels.

Calculations were based on the relationship:

$$Ve = P(R_t) - E_t$$

where Ve =equilibrium volume at a given elevation,

P= annual precipitation,

R_t = water yield at a given temperature (evaporation rate), and

E_t = evaporation from the lake surface at a given temperature.

A more accurate model could only be constructed with known water yield relationships. Also, it is difficult to assess such things as vegetation, snow cover, seasonality, and maximum and minimum values of the past. The simple relationships assumed here are supported by the fact that the model closely predicts the natural water table in the Estancia basin.

Calculations were done using a program that incorporates the areas and volumes of five lake levels; these measurements were made by planimeter (Table 1). The volume of lacustrine sediment was disregarded because this volume difference affects only the rate of elevation change and not the equilibrium shoreline level.

PALEOCLIMATE OF ESTANCIA BASIN

Previous Estimates

Previous climatic estimates have assumed or established a probable temperature reduction for full-glacial conditions and determined the corresponding amount of precipitation required to maintain the lake at the highest shoreline levels. Galloway (1970) cited periglacial conditions at low elevations elsewhere and assumed a mean-annual temperature reduction of 10.5°C. Our model shows that such a reduction would not overflow the sill without a slight increase in precipitation. However, modeling such extreme temperature reductions is of limited value because runoff under such conditions, probably involving permafrost in some of the basin, is not predicted by Schumm's and Langbein's studies. Galloway assumed that full-glacial temperatures produced the "C" shorelines in Estancia. However, Bachhuber (1971) showed that overflow occurred 12,000 years B.P., significantly after the last time of maximum glacial advance in the western U.S. (23,000-17,000 years B.P., after Madsen and Currey, 1979; Madole, 1980; Lajoie and Robinson, 1982).

Brackenridge (1978) presented arguments for a 7°-8°C temperature reduction during full-glacial conditions and cited a hydrologic balance at the high shorelines in Estancia as confirmation that full-glacial climate was no wetter than at present. His predicted climate matches the ternperature and precipitation values necessary to produce the "C" shorelines, which he believed to represent maximum-lake and full-glacial conditions (fig. 2). However, for this temperature reduction, a 40 percent increase in precipitation is required to bring the lake to overflow. Leopold's (1951) range of estimates for full-glacial climate satisfies the

Table 1. Elevations and areas of Lake Estancia used for calculations of hydrological budget. Equilibrium shoreline elevations were calculated using different combinations of precipitation and evaporation (temperature) values and the corresponding percent of runoff for these combinations. The relationship between equilibrium shoreline elevation and precipitation and temperature are plotted in Figure 2.

Elevation (m)	Area (km^2)
1,938.5	2,289
1,920.3	1,795
1,889.3	1,078
1,859.8	428
1,828.8	100
1,821.2	0

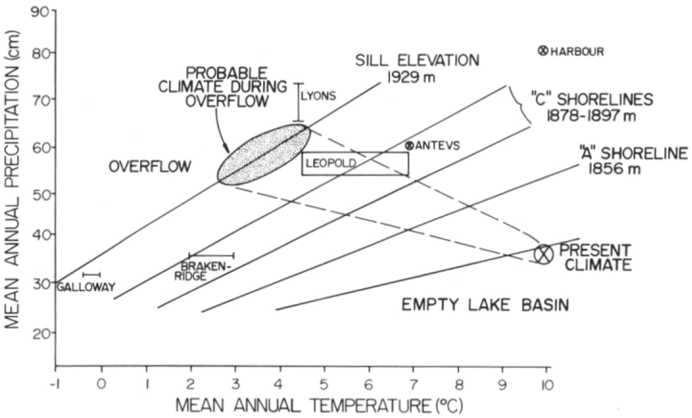

Figure 2. Graph showing climatic parameters possible for different shoreline elevations of Lake Estancia. Note the range of previous climatic estimates. Probable climate during last overflow (shaded area), about 12,000 years B.P., requires both reduced temperature and increased precipitation.

water budget to form "C" shorelines but falls short of achieving overflow. Antevs (1954) assumed a temperature reduction of about 3°C; this requires nearly a doubling of precipitation for the lake to reach even the "C" shorelines. Overflow would require nearly a tripling of precipitation, which is clearly unreasonable. Similarly, Harbour's (1958) assumption of no temperature change requires excessive moisture.

Probable Pleistocene Climate

Estimating the probable full-glacial and post-glacial climate of the Estancia basin depends upon the age relationships of the several shorelines and the last episode of overflow. The fossil fish, dated at 11,740 ± 900 years B.P., and subjacent *Ruppia,* dated at 12,400±450 450 years B.P., occur in lake clays underlain by sediments and organisms that indicate drawdown and desiccation (Bachhuber, 1971). This means that the last episode of overflow, which allowed the fish to populate the lake, occurred approximately 12,000 years B.P. If this relationship is correct, the dated high lake stand of Lake Estancia represents deglacial and not full-glacial conditions.

A high lake stand significantly lagging behind the initiation of glacial retreat has been documented in Lake Lahontan (Benson, 1978), Mono Basin (Lajoie and Robinson, 1982), and in an unglaciated basin in southeastern California (K. R. Lajoie, personal commun., 1982). The last, brief high stands (14,000-12,000 years B.P.) in the western Great Basin lakes do not correlate with the last glacial maximum (19,000-17,000 years B.P.); the glacial maximum for these lakes seems to coincide with intermediate lake elevations (Lajoie and Robinson, 1982). The last high stand of Lake Estancia has a similar chronology, with the highest lake stand occurring during the latest Pleistocene. This interpretation of increased precipitation during the time of deglaciation is supported by past vegetational associations at a similar latitude and elevation in the eastern Grand Canyon (Cole, 1982). There can be little question that there was a real increase in precipitation at this time because reduction in temperatures was probably not as great as during full-glacial conditions. The increase in precipitation required to make the lake overflow during times when temperature was reduced by 7°C, which is the full-glacial estimate based on relict cirques (Brackenridge, 1978), is about 40 percent. Late glacial temperature would presumably require even more precipitation.

Holocene Climate

The well-developed "C" shorelines, which were believed by some earlier investigators to represent full-glacial conditions, most likely correspond to the last episode of substantial lake development as recorded in the sediment column exposed in the blowouts. A radiocarbon date indicates that Lake Willard occurred some 8,000 years B.P. (Bachhuber and McClellan, 1977). Conceivably, some of the "C" shorelines may have been partially formed prior to Lake Willard, possibly even during full-glacial conditions. The simplest and most likely sequence of events, however, is that the "C" shorelines were preserved during the last fall of lake levels following overflow.

A reasonable interpretation, according to our model, is that the "C" shorelines represent a temperature reduction of about 4° to 5°C and about a 40 percent increase in precipitation, conditions not far different than postulated by Leopold (1951) and Antevs (1954), who considered the shorelines to be full glacial. Bachhuber and McClellan (1977) have postulated a 9.7°C temperature decrease to account for Lake Willard ("C" shoreline), based on occurrence of *Cribroelphidium selseyense* in the lake sediment. Such extreme conditions during the Holocene have not yet been observed elsewhere.

Other workers have documented a relatively moist early Holocene climate in the western U.S. Glacial deposits and bog stratigraphy in the Wasatch Mountains of Utah indicate a pause in deglaciation prior to 7,500 years B.P. and lower than average Holocene temperatures persisting until 8,000 years B.P. (Madsen and Currey, 1979). However, the glacier-fed Lake Bonneville has not been more than 18 m higher than the level of the present Great Salt Lake since about 11,000 years B.P. (Miller and others, 1980). Cole (1982) attributes a gradual transition to modern-dominant plant species during the early Holocene (up to 8,500 years B.P.), in the eastern Grand Canyon, to increased precipitation following the end of the Pleistocene.

The mid and late Holocene in Estancia basin is marked by continued desiccation, which is reflected in more weakly developed and obviously younger "B" and "A" shorelines. Lake stabilization at the "A" shoreline requires only about a 2°C lower temperature and a 20 percent increase in precipitation (fig. 2). Desiccation of the lake and subsequent blowing out of the basin-floor sediments during the Altithermal must have occurred in a climate significantly drier than present.

CONCLUSIONS

Viewed from high altitudes, the ancient shorelines of lakes in the Estancia, Pinos Wells, and Encino basins cover a vast area of central New Mexico. Significant climatic changes were involved in the flooding of such a large area. The large lake area compared to volume of water provided a system that was extremely sensitive to changes in precipitation and evaporation. This sensitivity is recorded as frequent changes from subaqueously deposited to playa-type sediments. Trout lived in this changeable environment only during and shortly after episodes of lake overflow, with the last such event occurring about 12,000 years B.P. Given the trout and the belief that such fish could not have survived the playa environment, it follows that deglaciation was a time of significantly increased precipitation in the southwestern U.S.

The idea that full-glacial "pluvial" conditions in the Great Basin and other parts of the southwestern U.S. were the result of a real increase in precipitation has been questioned (Brackenridge, 1978; Van Devender and Spaulding, 1979). The model used here suggests that even under full-glacial temperatures, some additional precipitation would be required to hold the lake at the well-developed shorelines which earlier workers believed to be full glacial in timing. Lake Estancia, however, is not a definitive test because full-glacial shorelines are not identifiable.

When the entire late-Pleistocene and Holocene record is considered, the relationship between temperature and precipitation changes with time. If the Altithermal and the intervals before and after are considered, increased temperatures are associated with falling lake levels and, according to the model, a real decrease in precipitation. Presumably, this is the climatic regimen that prevails today and that has been identified in the early Holocene of Colorado (Markgraf and Scott, 1981). However, as cited earlier, and based on higher shorelines in the late-glacial, warmer temperatures in the latest Pleistocene were times of increased real moisture compared to full-glacial conditions which were times of reduced moisture. These changes of temperature and moisture association with time probably reflect shifting patterns in the general atmospheric circulation that accompanied the withdrawal of glacial ice.

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