Geochronology and paleoenvironments of the glacial-age Tahoka Formation, Texas and New Mexico High Plains

Stephen A. Hall, Department of Geography, University of Texas, Austin, Texas 78712

Abstract

Radiocarbon ages on organic matter from the late Pleistocene Tahoka Formation at White Lake, Bailey County, Texas, provide a new chronology for playa lakes on the southern High Plains. Lacustrine muds at White Lake accumulated at least 20,000–17,000 ^{14}C yrs B.P. during the last glacial maximum. The basin at White Lake also contained standing water ca 37,000 ^{14}C yrs B.P. during the late middle Wisconsinan, a period of time that is poorly documented at other regional paleolakes. A thin bed of lacustrine dolomite and abundant phytoplankton at White Lake may indicate a brief phase of lake drying ca 16,500–17,000 ^{14}C yrs B.P. The timing of the final desiccation of the paleolake is not known, although a ^{14}C-based sedimentation rate extrapolated to the top of the lacustrine deposits indicates possible drying by ca 14,000 ^{14}C yrs B.P. The vegetation on the High Plains during the last glacial maximum and during the late middle Wisconsinan ca 37,000 ^{14}C yrs B.P. was a sagebrush grassland, as indicated by pollen analysis. Previous interpretations of a pine-spruce boreal forest on the High Plains were based on pollen assemblages that were weathered and altered by differential preservation.

Introduction

During the Pleistocene, many large playa basins on the southern High Plains of Texas and eastern New Mexico were filled with water. Streams, flowing eastward from basin to basin across the Llano Estacado, connected some of the larger playas and emptied into head-cut canyons on the edge of the Caprock Escarpment (Fig. 1). Late Pleistocene discharge through Yellowhouse Draw, the drainage connecting White Lake and other large playas, was sufficient to cut down through caliche caprock and into the Ogallala Formation. Postglacial climate warming and drying of the paleolakes, however, reduced discharge and resulted in a shift from erosion to deposition in the channels by 12,000 ^{14}C yrs B.P. Subsequently, from 12,000 ^{14}C yrs B.P. to the late Holocene, Yellowhouse Draw and other drainage channels across the High Plains slowly aggraded (Holliday, 1995).

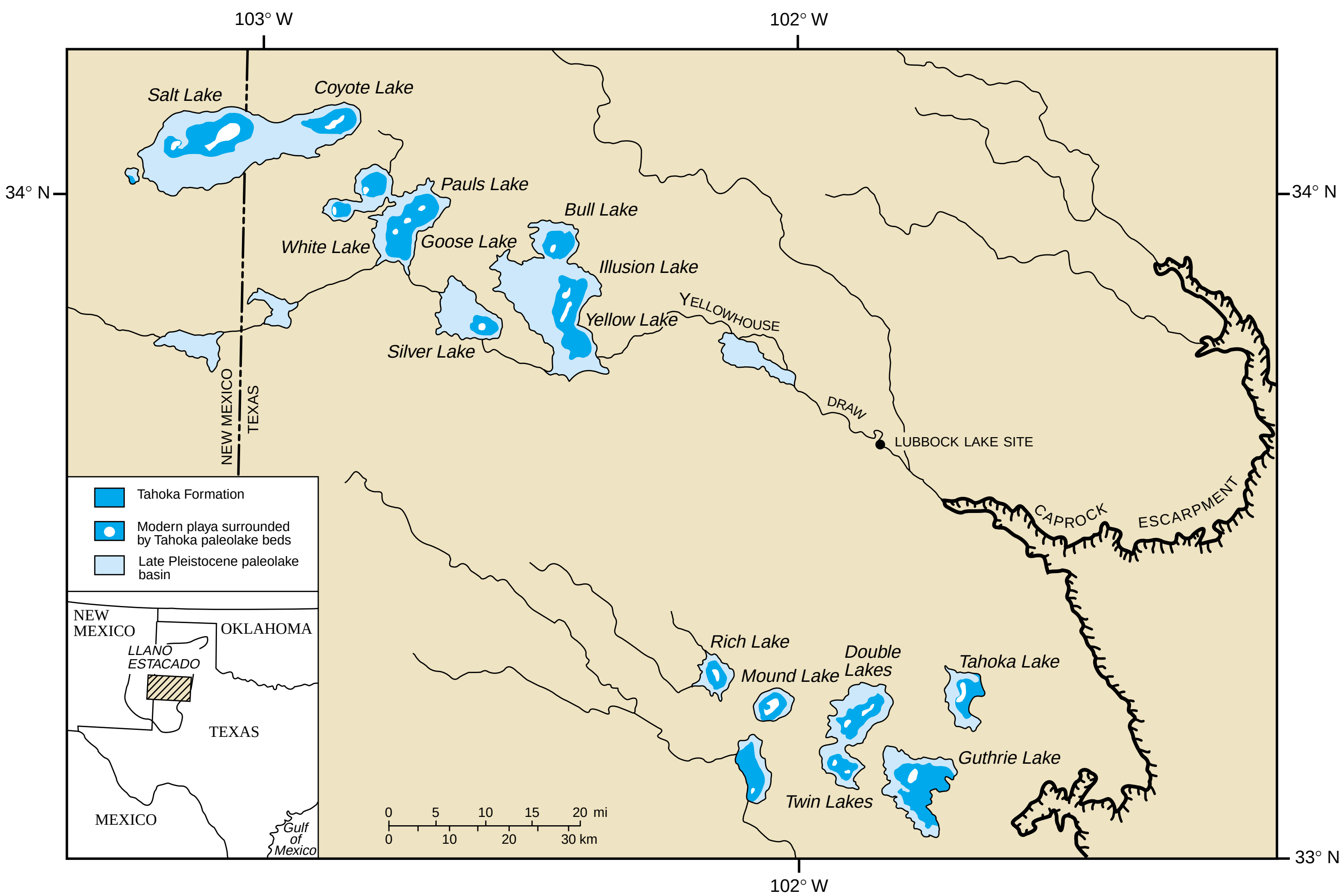

FIGURE 1—Large playa lake basins and the Tahoka Formation on the Llano Estacado, southern High Plains, Texas and eastern New Mexico (modified from Bureau of Economic Geology, 1967, 1968, 1974, 1978).

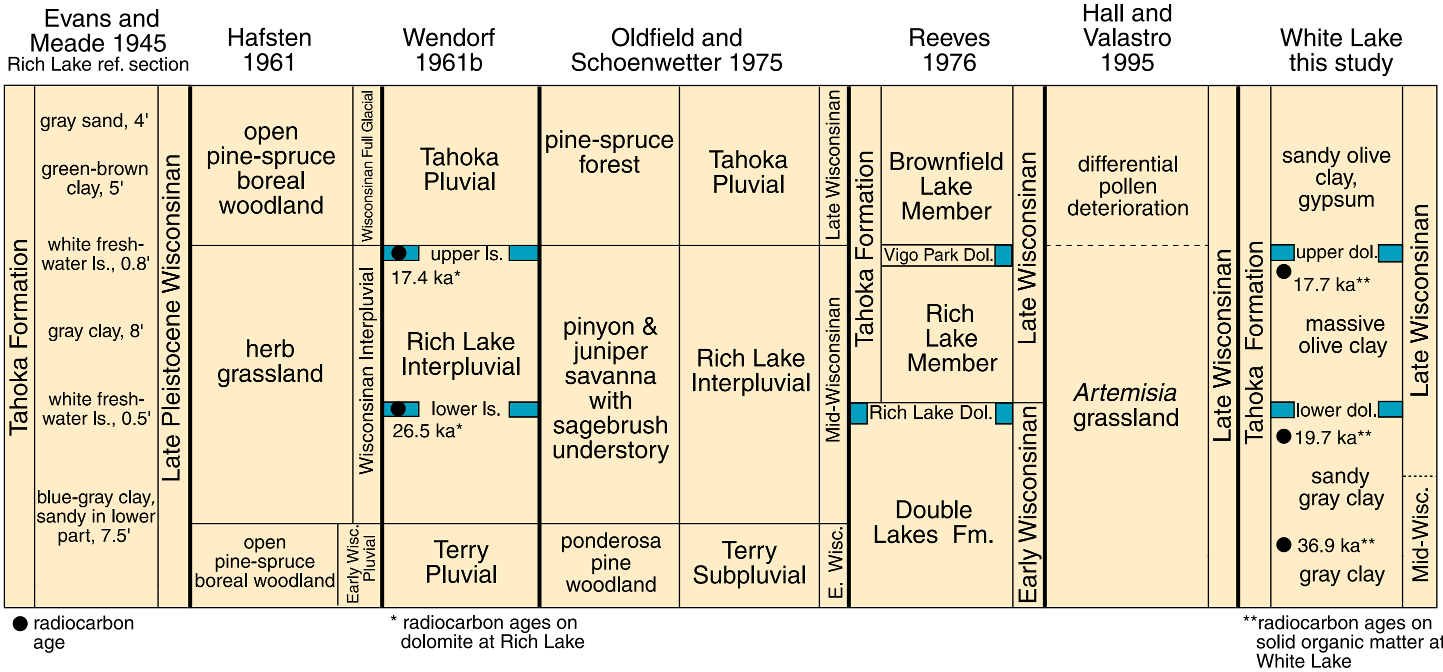

FIGURE 2—Correlation chart of the Tahoka Formation with associated pollen records and selected radiocarbon ages.

During the period of high lake levels, thick deposits of lacustrine mud accumulated in the playa basins. Evans and Meade (1945) named the paleolake deposits the "Tahoka clay" for the community of Tahoka, Lynn County, Texas. Near the town of Tahoka are Tahoka Lake, Guthrie Lake, Double Lakes, and other playa basins in which the Tahoka clay is exposed (Fig. 1). Whereas Evans and Meade (1945) and subsequent workers have regarded the Tahoka clay as late Wisconsinan, an accurate age of the Tahoka was never determined. The Tahoka playa basins are the easternmost playas in the United States, and a firm chronology for the Tahoka clays is essential in order to have a basis for correlation with western paleolakes as well as to establish a paleoclimatic record for the High Plains.

The nomenclatural history of the Tahoka clay, the complex problems associated with early attempts to correlate the Tahoka with late Quaternary time-stratigraphy (Richmond and Fullerton, 1986) using radiocarbon ages of carbonates, and new information on radiocarbon geochronology and paleoenvironments from one of the Tahoka playa basins are the issues discussed below.

Tahoka Formation

In the original description of the Tahoka clay, Evans and Meade (1945) recognized two basin-fill facies, one a sand-and-gravel-dominated sequence representing basin margin and fluvial-deltaic sediments and the other a clay-dominated lacustrine mud at the center of the basins. A Tahoka clay reference section of a lacustrine facies was established at Rich Lake, Lynn County, Texas (Evans and Meade, 1945), consisting of 8 m (26 ft) of gray sandy clay containing two thin layers of freshwater limestone (Fig. 2). They assigned a "late Pleistocene Wisconsin" age to the Tahoka based on associated extinct mammals, including *Mammuthus*, *Equus*, *Camelops*, *Glyptodon*, and *Bison taylori*. Evans and Meade (1945, p. 498) pointed out that the mammoth, horse, camel, and glyptodont remains are also found in older deposits, but that the presence of *Bison taylori* indicates a late Pleistocene age. Whereas the fossil bison material reported by Evans and Meade (1945) from the Tahoka and other fossil mammal localities from the High Plains have not survived in collections and their fossil quarries are no longer available for study (Dalquest and Schultz, 1992, pp. 70–71), the wide occurrence of *B. antiquus* (= *B. taylori*) at well-dated Paleoindian sites (Holliday, 1997) indicates that the late Wisconsinan age for the Tahoka clays based on the presence of *B. antiquus* is accurate from a present-day perspective.

The chart in Figure 2 illustrates 1) the different correlations that have been suggested for the Tahoka Formation, 2) other formation and member names that have been previously applied to the Tahoka clays, 3) some of the climatic intervals that have been used in connection with the Tahoka, and 4) the varied pollen-paleovegetational interpretations, as well as the findings of this study.

Correlations based on radiocarbon ages of carbonates

The two thin layers of freshwater limestone described by Evans and Meade (1945) at Rich Lake, later identified as dolomite (Reeves and Parry, 1965), have been observed at other paleolake deposits in the region; the dolomites serve as marker beds in correlating the Tahoka Formation across the Llano Estacado. One of the difficulties in determining the age of the Tahoka Formation, however, has been the lack of suitable materials for radiocarbon dating. In the absence of other materials, radiocarbon ages were obtained on the two thin dolomite beds at Rich Lake. The upper dolomite yielded an age of 17,400 ± 600 ^{14}C yrs B.P., and the lower dolomite yielded an age of 26,500 ± 800 ^{14}C yrs B.P. (Wendorf, 1961a). The radiocarbon chronology of the two dolomites led to the conclusion that the upper part of the Tahoka Formation correlated with the late Wisconsinan, that the middle Tahoka clay between the thin dolomite beds was middle Wisconsinan, and that the lower Tahoka was early Wisconsinan (Wendorf, 1961b), in spite of the fact that the bracketing ^{14}C ages indicated that the lacustrine clays between the thin dolomite beds were partially late Wisconsinan, as it was understood in the early 1960s (Frye et al., 1965).

One of the issues regarding the Tahoka clay is the uncertainty of the stratigraphy and chronology of the base of the formation (Evans and Meade, 1945, pp. 495–496). Reeves (1976) cored several playa basins and reported 8 m (26 ft) of olive-gray lacustrine sediments beneath the Tahoka Formation that he named the Double Lakes Formation (Fig. 2). Based largely on the radiocarbon ages from carbonates and "boreal forest" pollen results discussed below, the Tahoka Formation of Evans and Meade (1945) was redefined by Reeves (1976). In the redefinition, the upper and lower dolomites were named "Vigo Park

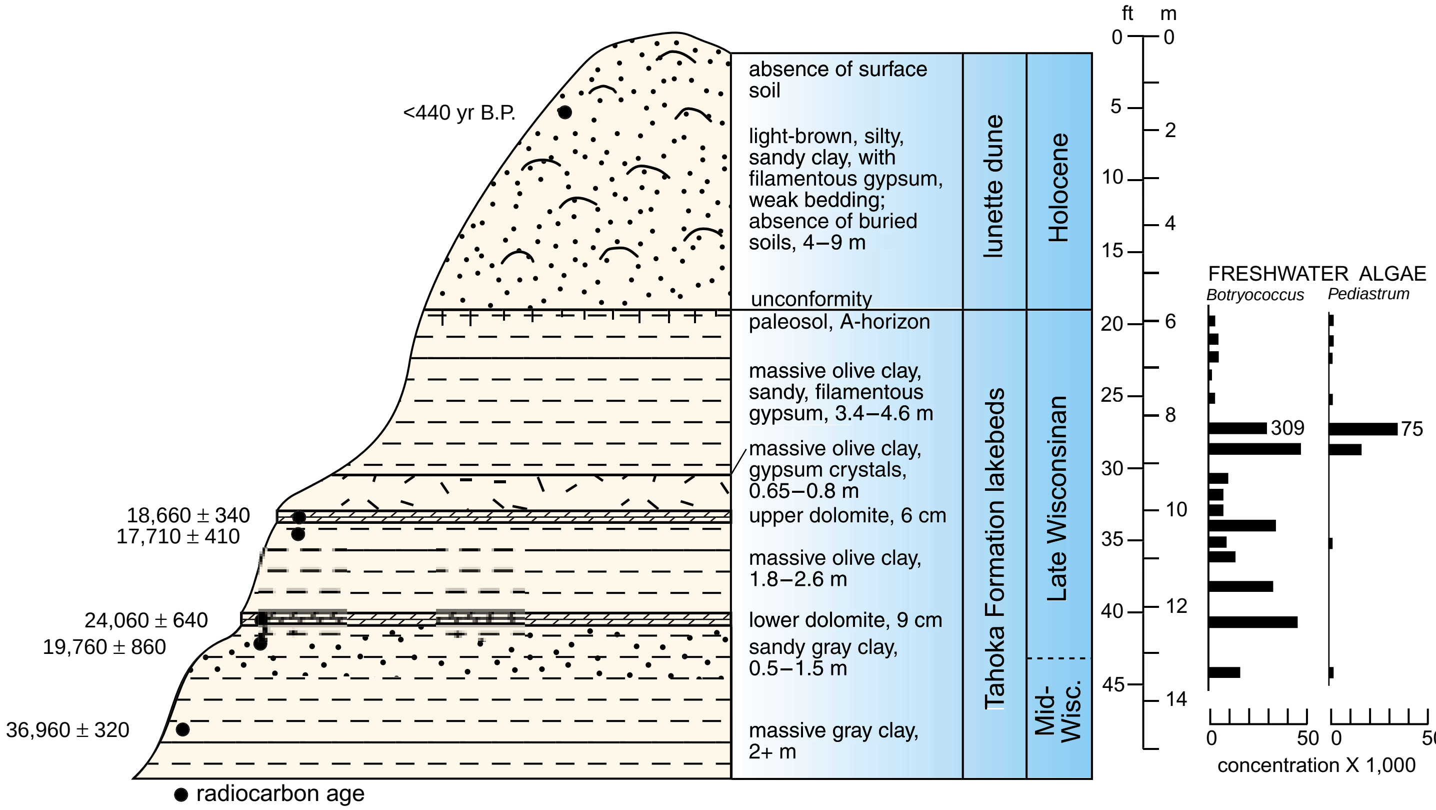

FIGURE 3—Stratigraphy of the Tahoka Formation and overlying lunette dune, measured at the northeast corner of White Lake Basin, Muleshoe National Wildlife Refuge, Bailey County, Texas. Radiocarbon ages are listed in Table 1. Also shown are freshwater green algae concentrations (colonies per gram of sediment processed) from Tahoka lakebeds (modified from Hall and Valastro, 1995, with new data).

Dolomite" and "Rich Lake Dolomite," respectively. Reeves' new "Tahoka" was restricted to the deposits above the lower dolomite; the clays between the dolomites were called the "Rich Lake Member," and the clays above the upper dolomite were called the "Brownfield Lake Member" of the new "Tahoka," all of which were correctly regarded as late Wisconsinan. The lower half of the Evans and Meade (1945) Tahoka Formation was renamed the "Double Lakes Formation"; the "Rich Lake Dolomite" was included in the "Double Lakes Formation" and was defined as the upper boundary of the new formation. Reeves (1976) interpreted the "Double Lakes Formation" to be early Wisconsinan, as he used a two-fold division of Wisconsinan time that excluded the middle Wisconsinan. Whereas Reeves (1976) correctly regarded the Tahoka Formation as representing lacustrine deposits from permanent lakes associated with the last glacial maximum, he was misled by the pollen record and by too early radiocarbon ages on the dolomites. Thus, he concluded that the lower part of the Tahoka Formation of Evans and Meade (1945) was pre-late Wisconsinan and assigned the lower beds to the new Double Lakes Formation. At present, the stratigraphy and chronology of the base of the Tahoka clay of Evans and Meade (1945) is not determined, and the relationship of the Tahoka to the subsurface Double Lakes Formation (Reeves, 1976) is yet unclear. Because of the circumstances discussed above and following, the writer recommends that the Evans and Meade (1945) definition of the Tahoka Formation be conserved and that Reeves' (1976) member names for the Tahoka Formation be abandoned.

Correlations based on "boreal forest" and "Tahoka Pluvial"

The interpretation of the pollen record from lacustrine clays of the Tahoka Formation reinforced the carbonate-based radiocarbon correlation. The upper part of the Tahoka Formation, above the upper dolomite at Rich Lake and Tahoka Lake, is characterized by high percentages of pine and spruce pollen that at the time were interpreted as a late Wisconsinan pine-spruce boreal woodland vegetation (Hafsten, 1961, 1964). The cool, wet climate supposedly represented by the pine-spruce pollen zone was called the "Tahoka Pluvial" (Fig. 2) climatic event (Wendorf, 1961b). Additional pollen studies from two other High Plains playas, White Lake and Illusion Lake, found similar records that seemed to support these paleovegetational reconstructions (Oldfield and Schoenwetter, 1964, 1975).

Pollen assemblages from the lake clays below the upper dolomite have been interpreted as an "herb grassland" (Hafsten, 1961) and a "pinyon and juniper savanna with sagebrush understory" (Oldfield and Schoenwetter, 1975). Regardless of these differences in interpretation, their strong contrast with the "pine-spruce boreal woodland" of the "Tahoka Pluvial" led to the conclusion that the lacustrine clays beneath the upper dolomite represented a different paleoclimatic regime that was significantly older and was middle Wisconsinan in age. The lacustrine beds beneath the upper dolomite were named the "Rich Lake Interpluvial" (Wendorf, 1961b).

Toward the base of the Tahoka Formation, slight increases in percentages of pine pollen were interpreted as an "open pine-spruce boreal woodland" (Hafsten, 1961) and a "ponderosa pine woodland" (Oldfield and Schoenwetter, 1975). Again, the contrast of these pollen assemblages with those higher in the sections led to the conclusion that the basal Tahoka clays represented a cooler, wetter early Wisconsinan climate; the pollen zone was referred to as the "Terry Pluvial" (Wendorf, 1961b) and later the "Terry Subpluvial" (Oldfield and Schoenwetter, 1975).

White Lake

White Lake is one of three playas formed in a single large basin at Muleshoe

TABLE 1—Radiocarbon ages from Tahoka Formation and lunette dune, White Lake, Bailey County, Texas.

Lab no.	Material dated	Measured depth (cm)†	^{14}C age (yrs. B.P.)ƒ	δ^{13}C (‰)	^{13}C corrected ^{14}C age (yrs. B.P.)
I-11,514	*Bison* bone	155	<185	–10.9	<440
I-11,269	dolomite	995–1,005	18,660 ± 340	—	—
Tx-7055	organic matter	1,010–1,020	17,650 ± 410	–21.3	17,710 ± 410
I-11,515	dolomite	1,210–1,220	24,060 ± 640	—	—
Tx-7056	organic matter	1,230–1,240	19,710 ± 850	–21.7	19,760 ± 860
Beta-126921*	organic matter	1,380–1,385	36,860 ± 320	–19.2	36,960 ± 320

*AMS-based age, all other conventional; Libby half-life 5,568 ± 30 yrs.
†From measured section, northeast edge of White Lake Basin, Fig. 3.
ƒ1-sigma standard deviation.

National Wildlife Refuge, Bailey County, Texas. The White Lake sequence of paleolake deposits (Fig. 3, page 73) is one of the more complete in the region and is similar to that described by Evans and Meade (1945) at Rich Lake. Evans and Meade (1945) mapped the extent of the Tahoka clay at White Lake from an aerial photograph, and the geology of the playa basin was noted by Harbour (1975) in conjunction with a pollen investigation (Oldfield and Schoenwetter, 1975). An 8-ft-deep (2.4-m-deep) core was taken from near the outcrop of the Tahoka clay at White Lake. Coring stopped at an "indurated pebbly sandstone" that was thought to be Cretaceous, outcrops of which are found at the basin margin nearby (Harbour, 1975, p. 41). Thus, at White Lake, the Tahoka clay could be 32 ft (9.7 m) thick (Harbour, 1975), although the base of the Tahoka is not exposed. The top of the Tahoka clay is characterized by a moderately developed A-horizon paleosol. A lunette dune on the east side of the playa originated by deflation of the dry lakebed and overlies the Tahoka clay (Fig. 3). The lunette dune may be late Holocene. A limb bone of *Bison* from near the top of the dune yielded an age of < 440 ^{14}C yrs B.P.

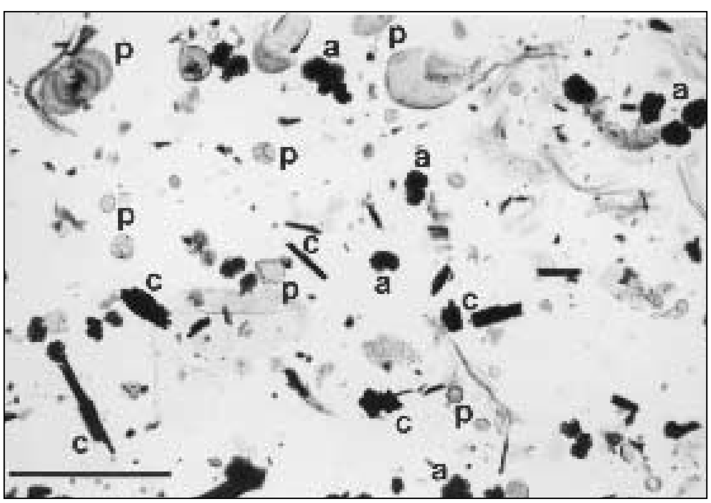

FIGURE 4—Photomicrograph of organic detritus AMS-dated 36,960 ± 320 ^{14}C yrs B.P.; **a** = algal colony, **c** = charcoal, **p** = pollen grain; bar scale = 100 micrometers.

Radiocarbon ages from organic matter versus carbonates

Methods

Solid organic matter (humus or detritus) was extracted for radiocarbon dating from White Lake sediments by two methods. The organics from below the dolomites were extracted from 10–15 kg (24–37 lb) of lacustrine clays by washing the material through sieves, discarding the >150 µm fraction, and pretreating the fine fraction with 10% HCl to remove carbonates and 2% NaOH to remove the soluble humic-acid fraction. The remaining organic residue was dated by conventional methodology (Bowman, 1990). The sample for accelerator mass spectrometry- (AMS) ^{14}C determination was processed by palynologic methods to extract particulate organic matter from sediment. Approximately 100 g (3.5 oz) of clay was washed in 10% HCl to remove carbonates and 30% HF to remove silicates; heavy liquid separation in $ZnCl_2$ was used to remove remaining mineral matter and to concentrate organics, then a second HF treatment was used to remove remaining fine silicates, and finally a 2% NaOH wash was used to remove soluble humates. The use of chemicals containing carbon, such as acetic acid, was avoided.

The detrital organic matter extracted from Tahoka lake muds for radiocarbon dating consists of small fragments (< 150 µm) of charcoal, colonies of freshwater algae, pollen grains, and unidentifiable organic detritus, all numbering in the tens of thousands of particles per gram of clay (Fig. 4). The origin of the pollen grains and charcoal is from atmospheric transport to the playa basin from the surrounding terrain; the algal colonies originate from the water column. During the last glacial maximum, organic detritus would have also entered the basin by fluvial transport. Other organic matter is transported to the playa by overland flow. There is little doubt that some old or "dead" carbon is incorporated into the lake mud, although the amount of old carbon is likely minuscule. However, unlike old carbon that can readily re-enter the environment by deflation or dissolution of caliche or bedrock that is enriched in carbonate, organic matter in old rocks is oxidized and destroyed with time and is less likely to be a source of error in radiocarbon ages of organic matter from lake sediments.

In this study, the organic residues were inspected for possible presence of pre-Quaternary palynomorphs, and none were observed. Nearby Cretaceous sandstone and shale that crop out in the White Lake Basin are weathered and do not contain palynomorphs or organic matter that could be a source of dead carbon. For sediments of late Wisconsinan age, contamination with young or modern carbon is potentially a much greater source of error in radiocarbon ages than contamination that comes from dead carbon (Bowman, 1990). In this study, fresh unweathered clays were collected for radiocarbon assay and pretreated with HCl and NaOH washes to remove any recent carbonate or soluble organic contaminants. Bulk samples of dolomite were submitted for radiocarbon analysis.

Radiocarbon ages from carbonates

Dual samples from dolomites and organic matter from clays directly beneath the dolomites show that the radiocarbon age of the upper dolomite is ca 900 yrs too old and the radiocarbon age of the lower dolomite is ca 4,300 yrs too old (Table 1). A previous radiocarbon assay of the White Lake upper dolomite is 19,275 ± 560 ^{14}C yrs B.P. (Reeves and Parry, 1965), an age that is apparently ca 1,500 yrs too old, if the age of the organic matter is accurate. Inorganic carbonates are generally avoided as a source of radiocarbon-based chronologies because of the uncertainty of the origin of the carbon in precipitated calcite or dolomite. Old or radioactive dead carbon can be introduced into the environment as atmospheric dust or through ground water. Studies of paired radiocarbon ages on soil and lacustrine carbonates versus organic matter invariably show that the carbonate ages are thousands of years too old (Gile et al., 1981, p. 77; Monger and Buck, 1995, p. 31; Winsborough et al., 1996).

New radiocarbon chronology of the Tahoka

The Tahoka Formation paleolake deposits at White Lake, both the lacustrine clays and dolomites, are late Wisconsinan. The age of the clay immediately beneath the upper dolomite is 17,710 ± 410 ^{14}C yrs B.P., and the age of the sandy clay below the lower dolomite is 19,760 ± 860 ^{14}C yrs B.P. Furthermore, the age of lacustrine clay from near the base of the exposed Tahoka is 36,960 ± 320 yrs B.P., indicating that the basal Tahoka clay, at least at White Lake, is late middle Wisconsinan (Table 1). However, the ca 37,000 ^{14}C yrs B.P. age is from an isolated exposure of lake clays at White Lake where the stratigraphic relationships with the rest of the Tahoka are unclear; the ca 37,000 ^{14}C yrs B.P. lake clay may be below an unconformity in the Tahoka clay.

Radiocarbon dating of the upper part of the Tahoka Formation at White Lake was not attempted. Palynologic analysis has shown that the clays above the upper dolomite exhibit strong loss of pollen and other organic detritus due to weathering. It is not known what the effects of weathering of the lacustrine clays and partial loss of organic matter would have on their radiocarbon age, although weathering of Holocene alluvium can result in slightly younger ages (Haas et al., 1986).

FIGURE 5—Detail of a mural at the Lubbock Lake State Landmark, Lubbock, Texas, depicting the late glacial landscape of the High Plains. Mammals pictured above include black-tailed prairie dog (*Cynomys ludovicianus*), flat-headed peccary (*Platygonus compressus*), yesterdays camel (*Camelops hesternus*), dire wolf (*Canis dirus*), giant short-faced bear (*Arctodus simus*), Columbian mammoth (*Mammuthus columbi*), extinct bison (*Bison antiquus*), and pronghorn antelope (*Capromeryx* or *Antilocapra*); avian species are burrowing owl (*Athene cunicularia)* and wild turkey (*Meleagris gallopavo*); the tortoise, now extinct, is *Hesperotestudo wilsoni*. Painting by Nola Davis, courtesy of Texas Parks and Wildlife, Interpretation and Exhibits Branch.

Reinterpretation of the pollen record

Even though the pollen data from the High Plains Tahoka Formation lake beds were carefully collected and properly presented by experienced researchers, their interpretations were mistaken by not taking into account the significance of poorly preserved pollen assemblages from the upper part of the Tahoka deposits. At the time of the initial pollen work in the late 1950s and early 1960s, the presence of a boreal forest on the modern-day prairies was dramatic news that subsequently has been cited as fact for many years. It has been shown now that the high percentages of pine and spruce pollen, upon which the interpretations of a "pine-spruce boreal forest" and the "Tahoka Pluvial" were founded, are artifacts of poor pollen preservation. The chemistry of conifer pollen allows these grains to persist in weathered sediments after non-conifer pollen grains are destroyed, thereby resulting in differential preservation and artificially high percentages of conifer pollen (Hall, 1981; Hall and Valastro, 1995). Differential pollen preservation was also documented by Bachhuber (1971) in late Pleistocene lakebeds in the Estancia Basin.

The weathering and differential preservation of pollen assemblages at White Lake, Rich Lake, and Illusion Lake are generally restricted to the Tahoka Formation paleolake clays immediately above the upper dolomite (Hafsten, 1961; Oldfield and Schoenwetter, 1975; Hall and Valastro, 1995). The upper dolomite evidently acted as a barrier to infiltrating water fronts that, with time, oxidize pollen and other organic matter. The pattern of differentially preserved pollen assemblages, above the upper dolomite, dominated by oxidation-resistant pine and spruce, and the presence of well-preserved pollen assemblages below the dolomite, dominated by pollen from sagebrush and prairie plants, was repeated from basin to basin. What appeared to earlier workers as a pattern of vegetation change was in fact a pattern of pollen grain oxidation and differential preservation related to the presence of a dolomite bed.

The new pollen and radiocarbon results from White Lake show that the vegetation on the High Plains during the late Wisconsinan was treeless sagebrush grassland (Fig. 5; Hall and Valastro, 1995). Pollen analysis of the late middle Wisconsinan deposits, based on one AMS radiocarbon age, 36,960 ± 320 ^{14}C yrs B.P., also indicates treeless, sagebrush-grassland vegetation on the High Plains (Fig. 6). Inspection of the pollen diagram shows a total of ca 20% tree pollen, such as pine (*Pinus*), spruce (*Picea*), oak (*Quercus*), and juniper (*Juniperus*). However, pollen grains of these tree taxa are carried great distances by winds, and their presence in small amounts in grassland vegetation constitutes only a background rain. For example, a study of pollen deposition at a series of pollen traps extending from the southern Rockies into the High Plains prairies of Texas shows that the above tree taxa can account for 12–32% of the total pollen influx in the modern grasslands at a distance of 225 km (140 mi) from mountain forests (Hall, 1990).

The single pollen assemblage from the middle-Wisconsinan lake clay contrasts with the late-Wisconsinan pollen assemblages by having comparatively lower percentages of sagebrush (*Artemisia*) and a higher amount of grasses (*Poaceae*). The middle Wisconsinan pollen spectrum also matches the next higher one, suggesting that, if an unconformity is present in the poorly exposed lower Tahoka lake deposits, the unconformity may be just below the 19,760 ± 860 ^{14}C yrs B.P.-age clay.

Pollen analysis of late Pleistocene deposits in the region indicates further that the late Wisconsinan vegetation was sagebrush grassland throughout the western plains and much of the Southwest. Although plant macrofossils from woodrat middens document the presence of trees along escarpments in the Southwest, pollen analysis consistently shows that the regional late Wisconsinan vegetation was dominated by shrub grassland, not coniferous woodland (Hall, 1985, 1997, 2000).

Paleolake levels on the Llano Estacado

The playa lakes on the southern High Plains are the easternmost large "pluvial" lakes in the United States. The pre-Wisconsinan history of these large lake basins on the High Plains has not been determined, and their late Pleistocene his-

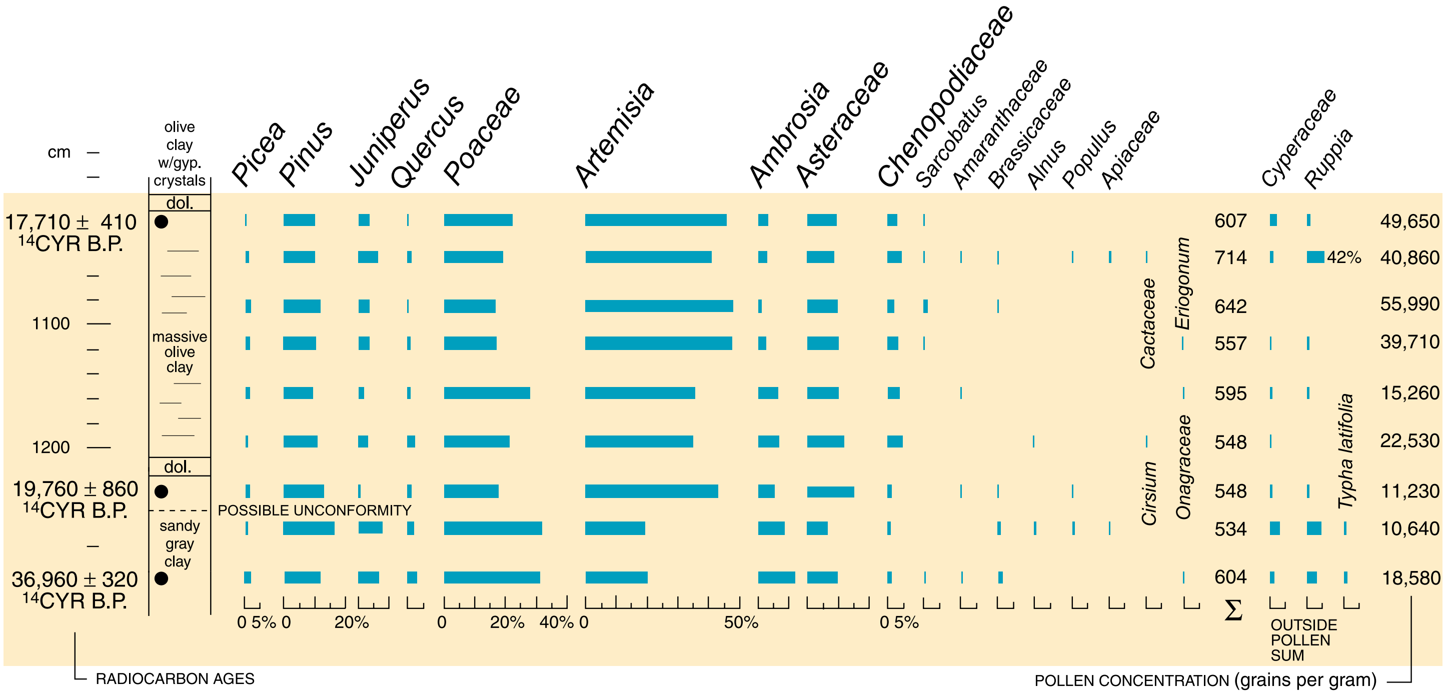

FIGURE 6—Pollen percentage diagram, White Lake, Bailey County, Texas; modified from Hall and Valastro (1995) with new pollen data from late-middle Wisconsinan lacustrine clay.

tory is only poorly known. However, as indicated by the radiocarbon ages of Tahoka Formation lacustrine clays at White Lake, greater-than-present playa lake levels existed on the southern High Plains at ca 37,000 ^{14}C yrs B.P. Because the Tahoka lakebeds at White Lake accumulated during the late Wisconsinan, based on two radiocarbon ages, the other large lake basins on the High Plains were likely at a high stand between ca 20,000 and 17,000 ^{14}C yrs B.P. as well, correlating with the last glacial maximum period of high stands generally observed in playa basins throughout the western United States (Smith and Street-Perrott, 1983). Sedimentation rates based on the two younger radiocarbon ages at White Lake indicate that deposition of the lacustrine facies of the Tahoka Formation ended ca 14,000 ^{14}C yrs B.P.

The Estancia Basin of central New Mexico has the most complete late Wisconsinan lacustrine sequence described in the region (Bachhuber, 1992; Allen and Anderson, 1993; Anderson and Allen, 1999) and is compared with the White Lake sequence. A major freshwater phase of high lake levels occurred there between ca 20,000 and 15,000 ^{14}C yrs B.P., followed by a period of low lake levels ca 15,000–13,700 ^{14}C yrs B.P., and shifting back again to a brief interval of permanent lake levels from ca 13,700 to after 12,400 ^{14}C yrs B.P. (Anderson and Allen, 1999). Whereas the age of the lakebeds at White Lake corresponds to the period of high lake levels at Estancia Basin, the White Lake Basin may have been dry after ca 14,000 ^{14}C yrs B.P. at a time when a permanent lake was forming again at Estancia Basin. Pre-Wisconsinan lake sediments have been documented at Estancia Basin (Bachhuber, 1992), but comparisons with White Lake are unclear. In order to establish patterns and correlate paleolake sequences, the Tahoka Formation lakebed deposits require a higher-resolution age control.

Warm episodes during late Wisconsinan?

The two dolomite beds in the Tahoka Formation may indicate episodes of climatic drying on the High Plains during the last glacial maximum. The precipitation of high-Mg calcite and dolomite in playa lakes is commonly associated with high ratios of Mg/Ca, high salinity, and shallow water (Last, 1990; Friedman, 1966; Reeves and Parry, 1965; Hussain and Warren, 1988). These conditions suggest that the lake in the White Lake Basin may have partly dried during the late Wisconsinan. Resting on the upper dolomite is a 65–80 cm (25.5–31.5 inches) thick, massive, dense olive clay with crystals of gypsum as much as 30 mm (1.18 inches) long, probably secondary in origin. The dense olive clay also contains an abundance of freshwater green algae *Botryococcus* and *Pediastrum*, with concentrations as high as 309,000 and 75,000 colonies per gram of clay, respectively (Fig. 3). The abundance of green algae indicates massive algal blooms in the lake, perhaps associated with a period of eutrophication coinciding with the deposition of dolomite. The algal blooms were probably a response to low lake levels when the dolomite was formed. Sedimentation rates from the two radiocarbon ages indicate that the algae-bearing olive clay accumulated over a period of about 500 yrs. Although speculative, an episode of drying and local decline in lake levels may have occurred on the southern High Plains for a short time from about 17,000–16,500 ^{14}C yrs B.P. The lower dolomite, however, is not associated with an increase in phytoplankton, thus may represent only a brief drying event. The two dolomites have been documented at Rich Lake, Tahoka Lake, White Lake, Goose Lake, and Illusion Lake (Evans and Meade, 1945; Hafsten, 1961; Harbour, 1975). Because the thin dolomites are found in several large playas in the southern High Plains, the paleoenvironmental conditions that produced them likely affected a broad region. If the ages of the dolomites and associated clays at White Lake are accurate, the dolomites formed at a time when the paleolake at Estancia Basin was at a high stand—the Estancia and White Lake Basins apparently out of phase with each other, at least at a fine scale.

Conclusions

The Tahoka Formation lakebeds of the southern High Plains have yielded ^{14}C ages of 19,760 ± 860 and 17,710 ± 410 ^{14}C yrs B.P. and were deposited during the late Wisconsinan. The lowest exposed lacustrine clays of the Tahoka Formation at White Lake yielded an AMS radiocarbon age of 36,960 ± 320 ^{14}C yrs B.P. and are late-middle Wisconsinan. Sedimentation rates based on the two younger radiocarbon ages indicate that the Tahoka paleolake dried by ca 14,000 ^{14}C yrs B.P. The age of the Tahoka is synchronous with freshwater lake deposits in the Estancia Basin in central New Mexico, although these preliminary results indicate that the paleolake basin at White Lake may have dried 1,500 yrs before the desiccation of the playa lake at Estancia, and that two episodes of dolomite accumulation, indicating drying at White Lake, occurred during a high stand at Estancia Basin. Overall, the High Plains paleolakes and the Estancia Basin paleolakes may exhibit a similar history of high lake stands related to regional climate across which are superimposed short-term events that are apparently out of phase and are related to differences in local weather, topography, and ground water. Pollen analysis of the middle and late Wisconsinan lake clays indicates the dominance of sagebrush-grassland vegetation on the High Plains.

Acknowledgments. I thank Don Clapp of Muleshoe National Wildlife Refuge for permission to work at White Lake. I thank Dr. Bruce Allen and Dr. Steven Reneau for their helpful comments on the manuscript. This work was partially funded by a grant from the University of Texas at Austin. Dr. Gary S. Morgan identified the animals in the mural on page 75.

References

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, pp. 1920–1923.

Anderson, R. Y., and Allen, B. D., 1999, Geomorphic and hydrologic response in Estancia Basin to late Pleistocene and Holocene climate change; *in* Pazzaglia, F. J., and Lucas, S. G. (eds.), Albuquerque geology: New Mexico Geological Society, Guidebook 50, pp. 75–82.

Bachhuber, F. W., 1971, Paleolimnology of Lake Estancia and the Quaternary history of the Estancia Valley, central New Mexico: Unpublished Ph.D. dissertation, University of New Mexico, 238 pp.

Bachhuber, F. W., 1992, A pre-late Wisconsin paleolimnologic record from the Estancia Valley, central New Mexico; *in* Clark, P. U., and Lea, P. D. (eds.), The last interglacial-glacial transition in North America: Geological Society of America, Special Paper 270, pp. 289–307.

Bowman, S., 1990, Radiocarbon dating: University of California Press, Berkeley, 64 pp.

Bureau of Economic Geology, 1967, Lubbock sheet: University of Texas (Austin), Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Bureau of Economic Geology, 1968, Plainview sheet: University of Texas (Austin), Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Bureau of Economic Geology, 1974, Brownfield sheet: University of Texas (Austin), Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Bureau of Economic Geology, 1978, Clovis sheet: University of Texas (Austin), Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Dalquest, W. W., and Schultz, G. E., 1992, Ice Age mammals of northwestern Texas: Midwestern State University Press, Wichita Falls, TX, 309 pp.

Evans, G. L., and Meade, G. E., 1945, Quaternary of the Texas High Plains: University of Texas (Austin), Publication 4401, pp. 485–507.

Friedman, G. M., 1966, Occurrence and origin of Quaternary dolomite of Salt Flat, west Texas: Journal of Sedimentary Petrology, v. 36, pp. 263–267.

Frye, J. C., Willman, H. B., and Black, R. F., 1965, Outline of glacial geology of Illinois and Wisconsin; *in* Wright, H. E., Jr., and Frey, D. G. (eds.), The Quaternary of the United States: Yale University Press, Princeton, pp. 43–61.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 pp.

Haas, H., Holliday, V., and Stuckenrath, R., 1986, Dating of Holocene stratigraphy with soluble and insoluble organic fractions at the Lubbock Lake archaeological site, Texas—an ideal case study: Radiocarbon, v. 28, pp. 473–485.

Hafsten, U., 1961, Pleistocene development of vegetation and climate in the southern High Plains as evidenced by pollen analysis; *in* Wendorf, F. (ed.), Paleoecology of the Llano Estacado: Museum of New Mexico Press, Fort Burgwin Research Center, Publication no. 1, pp. 59–91.

Hafsten, U., 1964, A standard pollen diagram for the southern High Plains, USA, covering the period back to the early Wisconsin glaciation: International Quaternary Congress VI, Warsaw, Report 2, pp. 407–420.

Hall, S. A., 1981, Deteriorated pollen grains and the interpretation of Quaternary pollen diagrams: Review of Palaeobotany and Palynology, v. 32, pp. 193–206.

Hall, S. A., 1985, Quaternary pollen analysis and vegetation history of the Southwest; *in* Bryant, V. M., Jr., and Holloway, R. G. (eds.), Pollen records of late-Quaternary North American sediments: American Association of Stratigraphic Palynologists Foundation, pp. 95–123.

Hall, S. A., 1990, Pollen deposition and vegetation in the southern Rocky Mountains and southwest Plains, USA: Grana, v. 29, pp. 47–61.

Hall, S. A., 1997, Pollen analysis and woodrat middens—re-evaluation of Quaternary vegetational history in the American Southwest: Southwestern Geographer, v. 1, pp. 25–43.

Hall, S. A., 2000, Was the High Plains a pine-spruce forest?: Rangelands, v. 22, pp. 3–5.

Hall, S. A., and Valastro, S., Jr., 1995, Grassland vegetation in the southern Great Plains during the last glacial maximum: Quaternary Research, v. 44, pp. 237–245.

Harbour, J., 1975, General stratigraphy; *in* Wendorf, F., and Hester, J. J. (eds.), Late Pleistocene environments of the southern High Plains: Fort Burgwin Research Center, Publication no. 9, pp. 33–56.

Holliday, V. T., 1995, Stratigraphy and paleoenvironments of late Quaternary valley fills on the southern High Plains: Geological Society of America, Memoir 186, 136 pp.

Holliday, V. T., 1997, Paleoindian geoarchaeology of the southern High Plains: University of Texas Press, Austin, 297 pp.

Hussain, M., and Warren, J. K., 1988, Dolomitization in a sulfate-rich environment—modern example from Salt Flat sabkha (dried playa lake) in west Texas and New Mexico: Carbonates and Evaporites, v. 3, pp. 164–173.

Last, W. M., 1990, Lacustrine dolomite—an overview of modern, Holocene, and Pleistocene occurrences: Earth-Science Reviews, v. 27, pp. 221–263.

Monger, H. C., and Buck, B. J., 1995, Eolian evolution and paleoenvironmental changes during the late Quaternary in the Fort Bliss maneuver areas and vicinity: New Mexico State University, Las Cruces, 131 pp.

Oldfield, F., and Schoenwetter, J., 1964, Late Quaternary environments and early man on the southern High Plains: Antiquity, v. 38, pp. 226–229.

Oldfield, F., and Schoenwetter, J., 1975, Discussion of the pollen analytical evidence; *in* Wendorf, F., and Hester, J. J. (eds.), Late Pleistocene environments of the southern High Plains: Fort Burgwin Research Center, Publication no. 9, pp. 149–177.

Reeves, C. C., Jr., 1976, Quaternary stratigraphy and geologic history of southern High Plains, Texas and New Mexico; *in* Mahaney, W. C. (ed.), Quaternary stratigraphy of North America: Dowden, Hutchinson, and Ross, Stroudsburg, PA, pp. 213–234.

Reeves, C. C., Jr., and Parry, W. T., 1965, Geology of west Texas pluvial lake carbonates: American Journal of Science, v. 263, pp. 606–615.

Richmond, G. M., and Fullerton, D. S., 1986, Introduction to Quaternary glaciations in the United States of America: Quaternary Science Reviews, v. 5, pp. 3–10.

Smith, G. I., and Street-Perrott, F. A., 1983, Pluvial lakes of the western United States; *in* Porter, S. C. (ed.), Late-Quaternary environments of the United States, v. 1, The late Pleistocene: University of Minnesota Press, Minneapolis, pp. 190–212.

Wendorf, F., 1961a, A listing of radiocarbon dates; *in* Wendorf, F. (ed.), Paleoecology of the Llano Estacado: Museum of New Mexico Press, Fort Burgwin Research Center, Publication no. 1, pp. 134–136.

Wendorf, F., 1961b, An interpretation of late Pleistocene environments of the Llano Estacado; *in* Wendorf, F. (ed.), Paleoecology of the Llano Estacado: Museum of New Mexico Press, Fort Burgwin Research Center, Publication no. 1, pp. 115–133.

Winsborough, B. M., Caran, S. C., Neely, J. A., and Valastro, S., Jr., 1996, Calcified microbial mats date prehistoric canals—radiocarbon assay of organic extracts from travertine: Geoarchaeology, v. 11, pp. 37–50.