GEOMORPHIC SETTING AND LATE QUATERNARY HISTORY OF PLUVIAL-LAKE BASINS IN THE SOUTHERN NEW MEXICO REGION

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INTRODUCTION

This paper on the geomorphic setting and late Quaternary history of pluvial-lake basins in the southern New Mexico region is extracted from a longer report (in progress) on the Quaternary and Pliocene geology of the southeastern Basin and Range province. The latter effort, scheduled for completion in 1995, is an attempt to synthesize more than 30 years of field observations on alluvial and lacustrine basins in the western U. S. and northern Mexico. Review papers and guidebooks that I have previously authored or coauthored on the subject include Hawley and Wilson (1965), Hawley (1969), Hawley and Kottlowski (1969), Hawley and others (1976), Hawley (1978), Gile and others (1981), Seager and others (1984), Sandor and others (1990), and Hawley and Love (1991).

Most of my work has been sponsored by the U. S. Soil Conservation Service (Soil Survey Investigations Division - 1962 to 1977), and the New Mexico Bureau of Mines and Mineral Resources (1974 to present). Much of it has been done in basins of the Rio Grande rift structural province between Española, New Mexico and El Paso, Texas; and, over the years, it has involved many collaborators. Major coworkers include G. O. Bachman, L H. Gile, W. E. King, F. E. Kottlowski, D. W. Love, R. P. Lozinsky, M. N. Machette, A. L. Metcalf, H. C. Monger, J. A. Sandor, and W. R. Seager.

In this paper I emphasize aspects of my geological investigations that relate most directly to ongoing archaeological and paleoenvironmental research in the Fort Bliss - McGregor Range area near Orogrande. The major geomorphic features of the area are the very extensive floors of intermontane basins (bolsons), contiguous piedmont slopes (bajadas and pediments), and upland areas including both mountain ranges and high plateaus with steep bounding escarpments. Basin floors are now characterized by discontinuous ephemeral drainageways, widespread eolian deposits, and numerous closed depressions with ephemeral lakes (playas). In the recent (geologic) past, however, central basin plains were occupied by extensive perennial lakes and/or large fluvial systems. The late Quaternary stratigraphic record, now well-documented at Pendejo Cave, must be evaluated in the context of these changing basin landscapes and related climate-driven geomorphic processes. Environmental change in nearby upland areas, including the Sacramento-Sierra Blanca highlands and Diablo Plateau (Otero Mesa), must also be considered. During the past 150,000 years, for example, we know that this area has been affected by climate and geomorphic-process regimes that include a full glacial and early interglacial interval about 150,000 to 120,000 years ago (marine-oxygen-isotope stages 6 and 5e) when environments were probably similar to the late Wisconsin-Holocene period that started about 25,000 to 30,000 years ago (O-isotope stages 2 and 1). Intervening time included the later stages of the last interglacial (late Sangamon) and early parts of the Wisconsin glacial-pluvial stage.

Before discussing the evolution of pluvial lake basins of the region, I will briefly describe the regional geomorphic setting and review existing paleoenvironmental interpretations, because there is always a need to better define 1) <u>what we now know</u>, 2) <u>what we think we know</u>, and 3) <u>what we wish we knew</u> about late Quaternary history. The broader region of interest comprises most of the southeastern Basin and Range province (Mexico highland and Sacramento sections) and contiguous parts of the "Transition Zone" between the Colorado Plateau and the Basin and Range provinces. It extends from eastern Arizona, across southern and central New Mexico into northern Chihuahua and Trans-Pecos Texas (Fig. 1). See Morrison (1991a) for recent reviews of Quaternary geologic research from national, as well as a regional perspective.

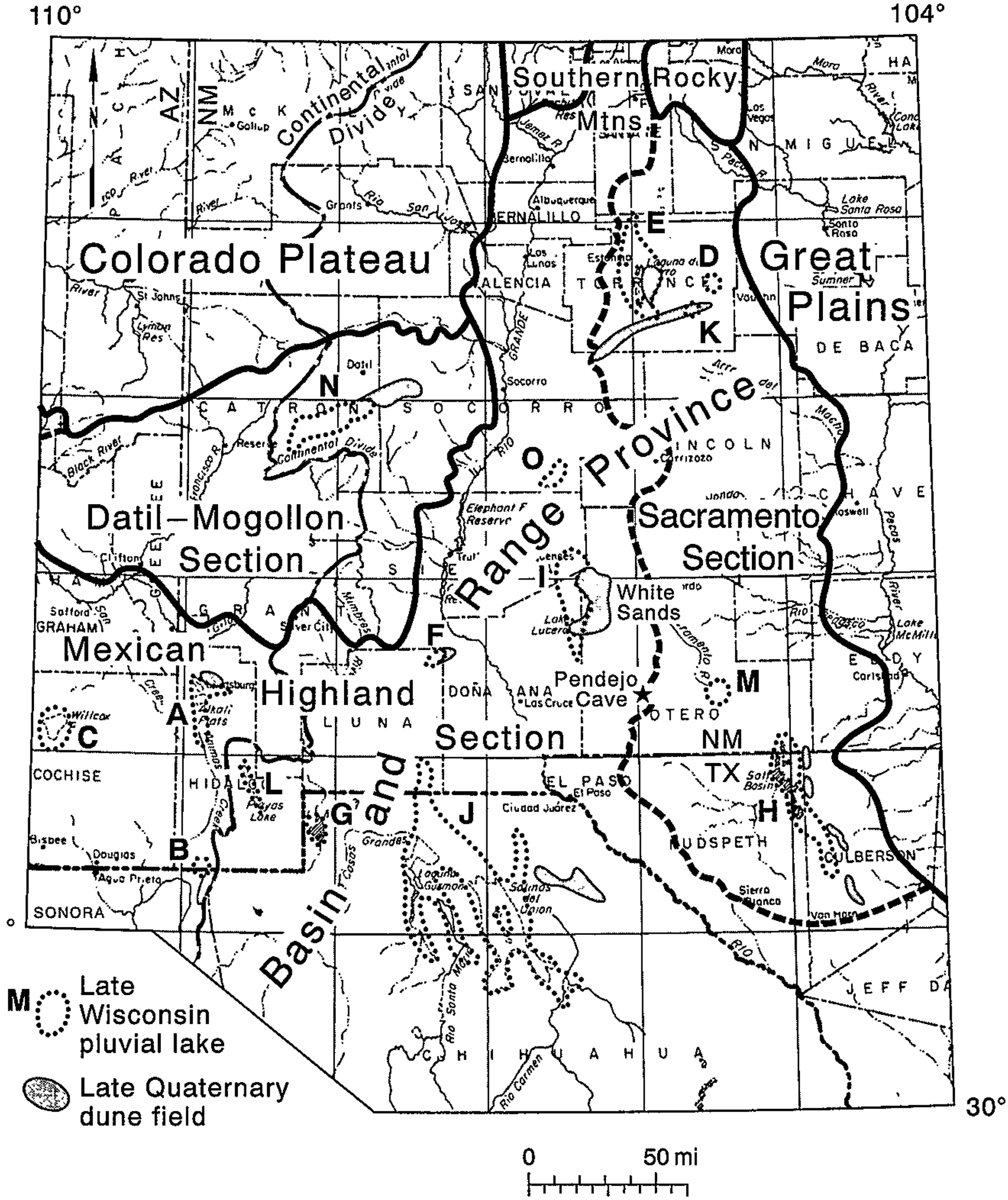

FIGURE 1. Locations of Late Quaternary pluvial lakes in the southern New Mexico region and major physiographic subdivisions of the southeastern Basin and Range province.

REGIONAL GEOMORPHIC SETTING

Physiographic concepts and terminology used herein (Fig. 1) are based primarily on Fenneman's (1931) classification. Recent advances in geographic information systems and understanding of regional geomorphology, however, have resulted in much better definition of subdivisions, placement of boundaries, and recognition of "transition" areas between provinces. The following summary descriptions of the Datil-Mogollon, Mexican Highland, and Sacramento sections are based on Hawley (1986a). Current quantitative studies of major landform classes in the region (Dikau and others, 1991) will probably require minor changes in some of the boundaries shown in Figure 1.

The Datil-Mogollon Section

The Datil-Mogollon section is an eastern extension of the Transition Zone province of central Arizona (Peirce, 1985), which is located between the Colorado Plateau and Basin and Range provinces. The section essentially coincides with the Mogollon-Datil volcanic field in west-central New Mexico, and it is bounded on the northwest by the White Mountains in eastern Arizona. Highlands of the Transition Zone and Datil-Mogollon region, with the exception of the internally-drained San Agustin basin, are the source of the few perennial streams that cross or enter the Mexican Highland and Sonoran Desert sections to the south and west (upper Gila, Mimbres, and Salt River systems).

The Datil-Mogollon section includes many remnants of mid-Tertiary calderas and volcanoes. It is characterized by high plateaus, scattered block-faulted basins and ranges, and deeply entrenched stream valleys. Alpine valleys on Mount Baldy and Mount Ord in the White Mountains (max. elev. 3476 m) were glaciated in middle and late Pleistocene time (Merrill and Péwé, 1977; Péwé and others, 1984). The San Agustin Plains in the north-central part of the section form the floor of a high-level basin with thick upper Cenozoic fill. Much of the Plains surface (minimum elevation, 2065 m) was flooded by pluvial lake San Agustin during Wisconsin and pre-Wisconsin glaciations (Table 1). The paleoclimatic record from this basin (Markgraf, 1983, 1984; Phillips and others, 1992), which is about 900 m above lake plains of the Chihuahuan Desert region, is discussed in a following section.

The Mexican Highland Section

The Mexican Highland section occupies most of southeastern Arizona, southern and central New Mexico, western Trans-Pecos Texas, and Chihuahua, Mexico (Figure 1). Basin areas below about 1524 m (5000 ft) form the bulk of the Chihuahuan Desert region. Broad intermontane basins occupy 60 to 80 percent of the area, and the intervening complex range blocks include a wide variety of rock units of Precambrian, Paleozoic, late Mesozoic, and Cenozoic age. Continental clastic, volcanic, and plutonic units of Tertiary age are widespread (Hawley and others, 1976; Morrison, 1985, 1991b).

Western Mexican Highland. Intermontane basins of the Mexican Highland section between the Rio Grande and the San Pedro Valley of southeastern Arizona are characterized by large areas of internal drainage (bolsons of Hill, 1900). Only the western and northern border zones of the region (upper Gila and Salt River basins) have deep valleys and well integrated drainage systems. The Continental Divide in southwestern New Mexico is along the highest of a series of surface-drainage divides (1347 to 3051 m) that separate a number of closed basins.

TABLE 1. SELECTED DATA ON LATE QUATERNARY LAKES IN THE SOUTHEASTERN BASIN AND RANGE PROVINCE
ARIZONA, NEW MEXICO, TEXAS (USA), AND CHIHUAHUA (MEXICO)

Map Unit Fig. 1	Lake Name	Late Wisconsin Pluvial Lake Features						Pre-Wisconsin Lake?	Remarks Lake Named by:
		Location Lat. N Long. W	Lake Area km² (mi²)	Max. Lake Elev. m (ft)	Basin Floor Elev. m (ft)	Sill Elev. m (ft)	Over-flow?	Elev. m (ft)	Major Sources of Information: Playa Name(s) and elevations:
A	Animas	32° 15′ 108° 45′	388L (150)	1,279* (4,195)	1,259L (4,130)	1,292L (4,240)	No **	Yes	<u>Schwennesen (1918)</u> Fleischhauer and Stone (1982) Alkali Flats - 1,259 m
B	Cloverdale	31° 30′ 108° 45′	104ME (40)	1,576M* (4,170)	1,561M (5,120)	1,578M (5,176)	No **	Yes?	<u>Schwennesen (1918)</u>
C	Cochise	32° 15′ 110° 00′	310L (120)	1,274L* (4,180)	1,260L (4,135)	1,298L (4,260)	No	Yes 1,290L (4,230)	<u>Meinzer and Kelton (1913)</u> Long (1966), Schreiber and others (1970) Schreiber (1978), Waters (1989) Wilcox Playa - 1,260 m
D	Encino	34° 30′	47L (18)	1,882L* (6,175)	1,859M (6,100)	1,908LM (6,260)	No **	Yes	<u>Meinzer (1911)</u> Kelley (1972), Kelley and Kelley (1972) Titus (1973) Bachhuber (1982, 1989)
E	Estancia	34° 45′ 106° 00′	1,114L (430)	1,890L* (6,200)	1,856M (6,090)	1,933M (6,342)	No **	Yes 1,893L (6,210)	<u>Meinzer (1911)</u> Bachhuber (1971, 1989, 1990) Lyons (1969), Titus (1973) Smith and Anderson (1982) Laguna del Perro - 1,841 m
F	Goodsight	32° 30′ 107° 30′	39L (15)	1,372LM* (4,500)	1,358LM (4,456)	1,375LM (4,510)	No **	Yes	<u>Hawley (1965)</u> Clemons (1979)
G	Hachita	31° 30′ 108° 00′	150M (58)	1,262M* (4,140)	1,250ME (4,100)	1,262- 1,273M (4,140- 4,177)	? (to J) **	Yes?	<u>Schwennesen (1918)</u> Brand (1937), Hawley (1969), Morrison (1969), Axtell (1978), Miller (1981) Laguna de los Moscos - 1,250 m
H	King	32° 00′ 105° 00′	900LM (350)	1,116LE (3,660)	1,103L 1,097M (3,620- 3,600)	---- ----	No **	Yes	<u>Miller (1981)</u> King (1948), Boyd and Kreitler (1986) Hussain et al. (1988) Kreitler et al. (1990) Salt Flat - 1,097 m

TABLE 1. CONTINUED

Map Unit Fig. 1	Lake Name	Location Lat. N Long. W	Lake Area km² (mi²)	Max. Lake Elev. m (ft)	Basin Floor Elev. m (ft)	Sill Elev. m (ft)	Over-flow?	Pre-Wisconsin Lake? Elev. m (ft)	Remarks Lake Named by: Major Sources of Information: Playa Name(s) and elevations:
		Late Wisconsin Pluvial Lake Features							
I	Otero	32° 45' 106° 30'	466LM (180)	1,204ME (3,950)	1,184- 1,189M (3,885- 3,900)	1,220M (4,003)	No **	Yes	<u>Herrick (1904)</u> Hawley (1983), Seager et al. (1987) Johnson et al. (1989) Lake Lucero - 1,184 m Alkali Flat - 1,189 m
J	Palomas	31° 00' 107° 00'	7,770L (3,000)	1,225LE (4,018)	1,150- 1,175M (3,773- 3,855)	1,225- 1,250M (4,018- 4,100)	No **	Yes	<u>Reeves (1969)</u> Laguna Tildio - 1,150 m Laguna Guzman - 1,170 m Laguna Santa Maria - 1,150 m Salinas de Union - 1,175 m
K	Pinos Wells??	34° 30' 105° 30'	52ME (20)	1,859LE (6,100)	1,829LM (6,000)	1,902LM (6,240)	No **	Yes?	<u>Lyons (1969), Titus (1969)</u> Meinzer (1911) Bachhuber (1971, 1982, 1986) Kelley (1972), Titus (1973)
L	Playas	31° 45' 108° 30'	65M (25)	1,311LME (4,300)	1,303M (4,275)	1,314M (4,312)	? (to G) **	Yes?	<u>Schwennesen (1918)</u> Axtell (1978)
M	Sacramento	32° 45' 10° 30'	72M (28)	1,347M* (4,418)	1,308M (4,290)	1,347M (4,418)	(to H?) **	Yes	<u>This Paper</u> John O. Flat - 1,308 m
N	San Agustin	34° 00' 108° 00'	780L (300)	2,115L* (6,940)	2,065L (6,775)	2,158M (7,078)	No **	Yes 2,135L (7,005)	<u>Powers (1939)</u> Weber (1980), Stearns (1962) Markgraf and others (1984) Phillips et al (1992) San Agustin Playa - 2,065 m C-N Playa - 2,101 m
O	Trinity	33° 30' 106° 45'	199L (77)	1,431LE (4,695)	1,425L (4,675)	1,440M (4,725)	No **	Yes	<u>Neal and others (1983)</u>

Note that drainage-basin areas (ground- and surface-water) are still not well documented in many of these lake basins

L Data from cited literature. See remarks, and Williams and Bedinger (1984)
M Estimates from maps and aerial photographs, 1:24,000 to 1:100,000 scales
E Estimates not well documented, need field verification
* Well-defined shoreline features mark high stands
** Ground-water outflow important discharge mechnism
?? Late Wisconsin lake may not have formed

Broad alluvial plains that drain to playa lake depressions are the dominant landscape feature (Fig. 1). Basins with large playas (Animas, Cloverdale, Los Moscos, Playas, Los Muertos, and Wilcox) were sites of permanent lakes during pluvial intervals of the late Quaternary and earlier Pleistocene time (Table 1). The largest pluvial lake in the region, Lake Palomas (Reeves, 1969), is located in the Bolson de los Muertos of north-central Chihuahua (Fig. 1). This complex of deep structural basins includes the distal parts of the Casas Grande, Santa Maria and Carmen river systems that head in the Sierra Madre Occidental, as well as the Rio Mimbers basin of New Mexico. It was also the "sink" for part of the ancestral upper Rio Grande in Pliocene to early Pleistocene time.

Eastern Mexican Highland and Rio Grande Rift. The eastern part of the Mexican Highland section generally coincides with the central and southern Rio Grande rift structural province (Hawley, 1978; Seager and others, 1984; Chapin, 1988). The area includes the narrow, entrenched valleys of the middle Rio Grande and its major tributaries; however, extensive parts of broad intermontane basins are internally drained and undissected. As noted in the Mexican Highland areas west of the Rio Grande, basin (bolson) floors are dotted with numerous playas. Evidence of large pluvial lakes (Otero, and Trinity) has been found in the west-central Tularosa and northern Jornada del Muerto Basins (Table 1). The largest dune field in New Mexico (White Sands), and the Holocene Carrizozo basalt flow also occupy large areas of the Tularosa Basin.

Sacramento Section

The Sacramento section, extending from east-central New Mexico into northern Trans-Pecos Texas, is another transitional physiographic unit (Hawley, 1986). It is bounded on the east by, and is structurally part of, the Pecos Valley section of the Great Plains. The Sacramento section is characterized by high tablelands, cuesta-form mountains with east-tilted dipslopes and west-facing escarpments, and widely scattered structural basins. Broad summit plains and dipslopes are underlain by upper Paleozoic carbonate rocks and sandstones, commonly with gypsum interbeds. Karst depressions, including large solution-subsidence basins, are widespread and primarily related to dissolution of gypsum. Extensive cave systems have formed in carbonate terranes of the Guadalupe Mountain and Capitan areas. Late Cenozoic evolution of Carlsbad Caverns on the east slope of the Guadalupe Mountains is described by Hill (1987).

Sierra Blanca Peak (altitude 3658 m), an erosion remnant of a huge mid-Tertiary volcano in the central part of the Sacramento section, is the site of the southernmost Pleistocene glaciation in the Continental United States (Richmond, 1986). Extensive lacustrine and eolian deposits associated with late Quaternary lakes and playas are well preserved in the Estancia Valley and Salt Basin structural depressions (pluvial Lakes Estancia and King; Fig. 1, Table 1). The Estancia basin (Hawley and Love, 1991, p. 130-133), with a relatively thin fill compared to other basins, exhibits considerable amount of Miocene-Pleistocene erosion and solution-subsidence. Smaller pluvial lakes were present in at least two other basins (Encino and Sacramento; Fig. 1, Table 1). These basins, as well as the Pinos Wells basin, which also may have been the site of a pluvial lake, appear to have been significantly affected by late Cenozoic solution-subsidence.

LATE QUATERNARY PALEOENVIRONMENTS

Paleoclimates characterized by greater effective moisture and cooler temperature dominated the last glacial stage (marine-O-isotope stages 2 to 5d) in the southeastern Basin and Range - Colorado Plateau region. During the late Wisconsin full-glacial interval (stage 2, ~ 10-25 ka B.P.), small glaciers formed in isolated alpine areas of the White Mountains and Sierra Blanca (Merrill and Péwé 1977; Péwé and others 1984; Richmond, 1986). Larger alpine glaciers occurred in higher parts of the Southern Rockies (McCalpin, 1983; Porter and others, 1983; Wesling and McFadden, 1986). Late Wisconsin rock glaciers in the mountains of central New Mexico are described by Blagbrough (1984, 1986, 1991). Short-lived, perennial lakes formed in at least 14 of the region's closed basins during the same interval, as well as earlier in Pleistocene time (Fig. 1, Table 1).

Paleoclimatic inferences from the glacial-periglacial and pluvial-lake depositional record in central New Mexico indicate that at least part of the last full glacial was characterized by climates significantly colder that the present, with or without significant increases in precipitation (Allen, 1991; Smith and Anderson, 1982; Smith and Street-Perrott, 1983; Markgraf and others, 1983, 1984; Phillips and others, 1992; Waters, 1989). Blagbrough (1984, 1991) shows that late Wisconsin temperatures in mountains of the central Sacramento section (about 34° N) were cold enough to form rock-glaciers with interstial ice at elevations as low as 2360 m on northwest-facing slopes. This was about 1130 m below the accumulation of exposed glacial ice on nearby northern slopes of Sierra Blanca Peak (elev. 3658 m).

Consideration of the combined glacial, periglacial, lacustrine, and paleobotanical record has led some workers to infer that full-glacial climates in the Southwest were from 7 to 10°C colder and as dry or drier than present (Galloway, 1970, 1983; Brackenridge, 1978). They have also rejected the term "pluvial" when referring to perennial lakes of the late Wisconsin. Recent studies by paleobiologists, on the other hand, suggest that the late Wisconsin - early Holocene climate was characterized by cooler summers (with or without monsoon intervals), relatively mild winters, and increased winter precipitation in comparison mid - to late Holocene conditions (Metcalf, 1967, 1977; Harris, 1985a, b, 1988, 1989; Wells, 1979; Spaulding and others, 1983; Van Devender and others, 1984; Van Devender, 1985, 1986, 1990; Neilson, 1986; Ashbaugh and Metcalf, 1986; Spaulding and Graumlich, 1986). Vegetation-cover regimes during the late Wisconsin in the northern Chihuahuan Desert region probably included steppe grass or shrub communities as well as the juniper-oak and pinon-juniper woodlands that have been documented by the packrat-midden record (Betancourt and others, 1990).

Recent investigations of ground-water isotopic composition in the Colorado Plateau area of northwestern New Mexico (Phillips and others, 1986a) indicate that Late Wisconsin climate in the American Southwest was moderately cooler (5° to 7°C) than today, with drier summers and wetter winters. They suggest that the time of maximum effective precipitation and minimum temperature occurred between 24 and 21 ka. They also infer that sometime between 20 and 17 ka there was a short period of relatively high temperature and low effective precipitation when temperatures were about 3°C warmer than the remainder of the late Wisconsin. After an episode of cool-moist conditions about 17,000 yrs ago, the climate remained cold but became progressively drier throughout the early Holocene. Their interpretation of ground-water isotopic data agrees most closely with the regional model of late Wisconsin paleoclimates for the American Southwest proposed by Spaulding and others (1983). These paleoclimatic interpretations are also supported by recent assessments of the late Quaternary paleoenvironmental record at San Agustin Plains in west-central New Mexico

(Markgraf and others, 1983, 1984; Phillips and others, 1992) that are further discussed in this paper.

Late Pleistocene climates prior to the last full glacial (O-isotope stages 3 to 5d) are not yet well documented. However, it seems reasonable to assume that early and middle Wisconsin climates were relatively mild, cool and moist in comparison to either the hot-dry conditions of the present or the cold-moist to dry climates inferred for the last full glacial (Harris, 1987). The last interglacial (O-isotope stage 5e, about 120 to 130 ka) probably included a warm (monsoonal?) period that was as warm as the middle to late Holocene interval.

The emerging picture of Late Pleistocene and Holocene environments of the Southwest is considerably more complex that what is portrayed in much of the earlier literature on the subject (compare Antevs, 1955, Leopold, 1951, and Martin and Mehringer, 1965, with Spaulding and others, 1983, Hall, 1985, and Waters, 1985, 1989). Compositions and ranges of plant and animal communities in the late Quaternary cannot be explained by simple altitudinal shifts in life zones (Van Devender and Spaulding, 1979; Spaulding and others, 1983; Van Devender and Toolin, 1983; Spaulding, 1984; Van Devender, 1985, 1990; Harris, 1987, 1988, 1989; Betancourt and others, 1990). We definitely need more well-dated and well-documented records of biological communities and associated biochemical and soil-geomorphic processes in various climatic settings (e.g. Gile and others, 1981; Machette, 1985; McGrath and Hawley, 1987; Monger and others, 1991; Peterjohn and Schlesinger, 1991). More paleohydrologic, geochemical, and biochemical research that emphasize the isotope chemistry of various types of precipitates in aqueous environments and soils, relict components of ground-water flow systems, and fossil organic material is clearly needed (e.g. Cerling, 1984; Neilson, 1986; Phillips and others, 1986a, b; Cerling and others, 1989; Quade and others, 1989).

PLUVIAL-LAKE BASINS OF THE SOUTHEASTERN BASIN AND RANGE PROVINCE

Introduction

The Quaternary depositional records in major playa-lake basins of the southeastern Basin and Range province are briefly discussed in following sections of this report. Location of major features discussed are shown on Figure 1. Selected data on Late Quaternary pluvial lakes in 15 internally-drained basins of the region (including the Datil-Mogollon section of the Transition Zone) are given in Table 1. The table includes my interpretations of the highest possible lake levels during the late Wisconsin (~10 to 25 Ka), possible outflow mechanisms, and some inferences on the presence of pre-Wisconsin lakes. Table 1 also illustrates the great range in surface area and variety of geographic settings of the individual pluvial-lake plains. It does not contain information on critical paleohydrologic factors such as climate and vegetative cover, watershed area-altitude relationships, surface- and ground-water budgets, erosion-sedimentation patterns, and soil-geomorphic relationships.

Comparison of recent reviews on evolution of pluvial lakes of the Southwest with information on lake area, shoreline, and inflow-outflow characteristics in this report illustrates the opportunity for fruitful research in all of the lake basins in the region (Hubbs and Miller, 1948; Hendrickson and others 1980; Miller, 1981; Smith and Street-Perrott, 1983; Williams and Bedinger, 1984; Taylor, 1985; Minckley and others, 1986; Smith and Miller, 1986). For example, published models of paleoclimates based on recent interpretations of very high Wisconsin lake levels, with or without spillout, of the San Agustin-White Lake and Estancia-Encino basin complexes should be viewed with caution (Weber, 1980, 1982; Bachhuber, 1982, 1989, 1990; Smith and Anderson, 1982; Behnke and Platts, 1990; Allen, 1991; Hawley and Love, 1991, p. 131-132).

Fills of internally-drained structural basins (bolsons) form the bulk of the Quaternary/Pliocene depositional record in the region. Except for through-going streams in the valleys of the upper Rio Grande and Gila systems, surface drainage and some ground water discharge is to closed-basin "sinks" presently occupied by ephemeral-lake plains (playas). Alluvial deposits are by far the largest component of the basin fill; and coalescent-fan piedmonts (bajadas) and basin-floor alluvial plains form extensive constructional surfaces of middle and late Quaternary age. Thick lacustrine sequences are major constituents of the basin-floor facies assemblage at many localities; and sandy eolian deposits are locally extensive. The latter sedimentary facies occurs in both basin-floor and piedmont settings downwind from major fluvial and lacustrine plains. Closure of lake basins has been produced by several mechanisms. Structural subsidence of a basin segment relative to adjacent range-and-basin blocks is the ultimate formative process; but closure is usually enhanced by a combination of 1) alluvial damming of basin-floor segments by fan progradation; 2) deflation of former lake plains with resultant accentuation of playa depressions and downwind construction of "climbing" dune fields; and 3) solution subsidence in areas underlain by gypsum and carbonate rocks.

Recent large-area geologic maps and cross sections by Seager and others (1982, 1987) and Drewes and others (1985) give a general, but reasonably accurate overview of Pliocene and Quaternary units. They also serve as comprehensive indexes of detailed mapping in the area. Middle Miocene to middle Pleistocene basin fill is included in either the Gila Group (Conglomerate) in basins west of the Rio Grande rift, or the Santa Fe Group within the rift zone itself (Chapin, 1988). Neotectonic features include mid- to late-Quaternary fault scarps that occur near the margins of (and locally within) many of the region's structural basins (Seager, 1980; Machette, 1987). Other Quaternary-Pliocene units not discussed in this section include 1) locally extensive basalts of the San Bernadino-Animas, Potrillo-Palomas, and Carrizozo volcanic fields; and 2) cave deposits of late Quaternary age that usually contain significant paleoenvironmental and archaeological records (Harris, 1985a, b, 1987, 1988, 1989; other symposia papers).

Lake Basins West of the Rio Grande

The southwestern New Mexico-southeastern Arizona (Mexican Highland) area includes seven of the late Quaternary pluvial lakes listed in Table 1 (Animas, Cloverdale, Cochise, Goodsight, Hachita, Palomas and Playas; Fig. 1: A, B, C, F, G, J, L). The basin of Lake San Agustin (Fig. 1: N) is also located adjacent to the Continental Divide in the Datil-Mogollon section of west-central New Mexico. The area contains the largest (Palomas, 7770 km^2) and six of the smaller lakes (Animas, Cloverdale, Cochise, Goodsight, Los Moscos and Playas -- 39 to 150 km^2) of the region. Lakes Palomas and Hachita (Los Moscos), located in northwestern Chihuahua, expanded to or extended a short distance across the International Boundary during their very highest stages. The small area inundated by *Lake Cloverdale* ($\sim$95 km^2, 1577 m level) occupies parts of New Mexico, Chihuahua, and Sonora at the south end of Animas (San Luis) Valley. Ground-water discharge is both northward into the Lake Animas-upper Gila basin (Reeder, 1957; O'Brien and Stone, 1984) and southward into the Rio Yaqui system (Hendrickson and others, 1980; Minckley and others, 1986). Fleischhauer and Stone (1982) describe the surficial deposits and soils in the shoreline zone of *Lake Animas* (Fig. 1, A) and discuss late Wisconsin and Holocene environments in that pluvial-lake basin.

Detailed research on the subsurface character of lake and playa deposits has only been done in the northern Sulphur Springs Valley (Lake Cochise -- Waters, 1989) and at Lake San Agustin (Markgraf and others, 1983, 1984; Phillips and others, 1992). This work is summarized in the following sections. The *Lake Goodsight* basin has been mapped by Clemons (1979), but detailed studies of lake deposits (first described by Hawley, 1965) have not been done. Reconnaissance investigations on pluvial *Lake Palomas* in Bolson de los Muertos and the major contributing drainage basins of Rios Casas Grandes, Santa Maria, and Carmen in Chihuahua are discussed by Reeves (1969), Morrison (1969), and Hawley (1969). These large fluvial systems head in subhumid to semiarid highlands in or adjacent to the Sierra Madre Occidental. Only about one-fifth of the Lake Palomas basin is in the United States (primarily the Mimbres River basin). Lakes and playas in the extensive "bolsones" of the Chihuahuan Desert region in Mexico are not described in this report. See Blásquez (1959), Hawley (1969), Axtell (1978), Miller (1981), Minckley and others (1986), Smith and Miller (1986), and Taylor (1985) for information on these basins.

The drainage basins of *Lakes Cloverdale*, *Hachita*, and *Playas* (Fig. 1, B, G, L) have received little attention since early studies by Schwennessen (1918), and detailed topographic maps (1:24,000 and 1:50,000) have only recently become available. Now, for the first time, reasonably accurate mapping of lake deposits and measurement of watershed area and altitude is possible. Much of the current information on these lakes (Table 1) still needs to be field checked and will be subject to some revision. Local alluvial damming of valley floors appears to have played a major role in forming the present Playas and Los Moscos basins; and episodic discharge from Lake Playas to Lake Palomas via the lower Hachita (Los Moscos) and Rio Casas Grandes Valleys has possibly occurred in mid- to late Quaternary time (Table 1). Recent shifts in sites of basin-floor aggradation at the confluence of upper Playas and Hachita Valleys have apparently allowed surface flow from the southern Playas Valley to alternately discharge into the Playas Lake and Laguna de los Moscos (playa) depressions. Furthermore, distributaries of the Rio Casas Grandes in the Ascencion subbasin south and east of Laguna de Los Moscos may have been able to contribute to or receive discharge from the Hachita-Los Moscos subbasin depending on subtle shifts in basin floor aggradation.

Sulphur Springs Valley, Arizona and Pluvial Lake Cochise. Meinzer's early work on the hydrogeology of Sulphur Spring Valley, Arizona (Meinzer and Kelton, 1913) has also served as an important guide for subsequent field research on lake and playa features. Meinzer's studies included mapping relict shoreline and surficial deposits of Lake Cochise (Table 1, L), documentation of the late Pleistocene high-lake stand at about 1475 m (4180 ft), and recognition of probable older lake beds in water wells of the Wilcox basin. In addition, ground-water studies have demonstrated that this basin is one of the few truly closed geohydrologic systems in the region (Langer and others, 1984).

Modern studies of Wilcox Playa and Lake Cochise (Schreiber, 1978; Waters, 1989) have concentrated on the sedimentology, paleobiology (pollen and ostracodes), and geochemistry of alluvial, eolian, playa, and relict lacustrine facies, both at the surface and in the shallow subsurface. Subsurface deposits of middle to late Quaternary age have been sampled in backhoe trenches, auger holes (as deep as 7 m) and one 42-m core hole. Water well records cited by Schrieber (1978; Schreiber and others, 1972) indicate that lake and playa sediments (organic-rich clays and mud) can be as thick as 146 m beneath the basin of Lake Cochise. The lower part of the lacustrine sequence could be as old as early Pleistocene; and this unit is in turn underlain by coarser-grained basin fill that locally extends to depths of more than 1000 m (Drewes and others, 1985).

The 42-m core hole was drilled near the center of Wilcox Playa (elev. 1260 m) in 1961 and it penetrated about 39 m of black mud below a 3-m-thick surficial layer of brown, oxidized mud (Martin, 1963; Schreiber and others, 1972). Long's (1966) radiocarbon dating of organic zones from the upper 2.5 m of the cored section yielded 14C ages of about 22 to 23 ka. Paleoenvironmental interpretations by Martin (1963) and Cameron (1971), respectively, of pollen and ostracode assemblages in the core samples indicate that lake-floor sediments deposited since the last interglacial (O-stage 5e?) could be as thick as 23 to 25 m. Martin (1963) suggested that deposits of highly-saline temporary lakes characterize a "Sangamon" interval cored between 23 to 27 m, and that deposits below 27 m are of Illinoian age (O-stage 6?). On the other hand, Cameron (1971) inferred from the ostracode record that the 25 to 42-m interval represented only interglacial conditions. Her studies indicated that a permanent lake was present during deposition of the upper 15 m of the cored section and that intermittent basin flooding occurred during deposition of the 15-25 m interval.

General chronological control for the uppermost lacustrine deposits is furnished by radiocarbon ages of organic matter (including charcoal) and secondary carbonates sampled within 3 m of the modern surface (Long, 1966; Waters, 1989). According to Long's (1966, p. 82) interpretation of mid- to late-Wisconsin history, pluvial conditions existed from before 30 to about 13 ka, when the lake was significantly higher than the 1274-m beach ridge. Long (1966) also suggested that there was a major drop in lake level between 13 and 11.5 ka, which was followed by an episode of lake expansion between 11.5 and 10.5 ka to near the 1,274-m beach-ridge level. Playa conditions are presumed to have existed throughout the Holocene (Long, 1966), with as much as 1.5 m of deflation of the ancient lake floor near the core-hole site (Schreiber and others, 1972).

Water's (1989) detailed stratigraphic studies of Lake Cochise deposits in a series of backhoe trenches extending basinward from the 1274-m shoreline provide a much more detailed picture of the pluvial lake record in latest Quaternary time. Documentation includes 19 new radiocarbon ages, mostly for humates and organic carbon extracted from marls, but also including seven charcoal dates. According to Waters (1989, p. 10):

> The lacustrine sequence of Lake Cochise provides independent confirmation that two periods of pluvial climates influenced southern Arizona, and the American Southwest in general, on during late-glacial time (ca. 13,750-13,400 yr B.P.0 and the other during the early Holocene (ca. 8900 yr B.P. or before). The late-glacial pluvial, characterized by cooler temperatures and greater winter precipitation (Spaulding et al., 1983; COHMAP Members, 1988), led to the formation of the 1274-m shoreline and deposition of unit B. The early Holocene pluvial, characterized by warmer temperatures, greater than modern precipitation resulting apparently from enhanced monsoonal circulation (Spaulding and Graumlich, 1986), appears to have led to the rise of Lake Cochise during the early Holocene when water filled the basin to an elevation slightly below the late Pleistocene maximum stand at 1274 m. In addition, the potential moisture from large tropical storms must also be considered in the hydrologic budget of Lake Cochise. No lakes were present in the Wilcox basin during the Altithermal, and two additional lake stands appear to have occurred during the alter part of the middle Holocene, perhaps as a result of more mesic conditions at the end of the Altithermal. Only shallow lakes have intermittently existed in the Wilcox Playa since the middle Holocene.

The late Quaternary alluvial stratigraphy of Whitewater Draw in southern Sulphur Springs Valley (Elfrida basin) has also been described by Waters (1983, 1985). His research area was in the Agua Prieta-Douglas segment of the Rio Yaqui basin and includes the Double Adobe archaeological site. Whitewater Draw occupies a broad shallow valley cut in both Plio-Pleistocene basin fill and other Pleistocene valley fill, here composed of terrace alluvium and marl. Primary age control on upper quaternary deposits is provided by 33 dates on charcoal (Waters, 1985). The basal unit of the valley fill exposed in the modern arroyo system is an upward-fining sequence of braided channel gravels and sand to clay deposits, which date from about 15 to 8 ka. Overlying cienega sediments of early mid-Holocene age were cut to a depth of 4.3 m sometime between 6.75 and 5.5 ka, and this large channel was filled by a fining-upward, gravel to clay sequence. Cienega sediments deposited during the past 5.5 ka form much of the youngest valley fill along Whitewater Draw, and Waters (1983) has identified six subcycles of cienega formation separated by minor erosional episodes up to about 750 yrs B.P. The modern arroyo was cut between A.D. 1885 and 1910, following an interval of cutting and filling of small draws, and shortly after widespread deposition of "flood silt."

Waters (1985) also compares the late Quaternary evolution of Whitewater Draw with the "classic" alluvial chronology at the nearby Lehner and Murray Springs sites (Haynes, 1968a, b, 1981, 1982). He shows that well-dated depositional units and erosion surfaces record: 1) a major interval of mid- to late-Wisconsin valley deepening and widening; 2) late Wisconsin to early mid-Holocene valley filling by fluvial channel, floodplain, and marsh (cienega) deposits; 3) middle Holocene arroyo cutting and backfilling, from ~7 to 5.5 ka at Whitewater Draw and ~7 to 4 ka at Murray Springs; and 4) widespread, but episodic aggradation of valley floors until incision of the modern arroyo system during the past century.

These major geomorphic events broadly correlate with changes in late Quaternary environmental conditions and shifts in climate-controlled geomorphic processes noted throughout the southeastern Basin and Range region. However, Waters (1985) clearly demonstrates that the fine details of a local "alluvial chronology" cannot be correlated from locality to locality, even in the same climate-process setting, because of complex responses to local geomorphic conditions. He further emphasizes "that intervalley correlation of late Quaternary alluvial deposits without absolute dating control is problematic" (Waters, 1985, p. 708).

Lake San Agustin Basin. The prominent relict shorelines and lake-plain deposits of the San Agustin Plains have long attracted the attention of Quaternary specialists (Powers, 1939; Foreman and others, 1959). This is one of the few lake basins in the region (Fig. 1, Table 1, N) where shorelines and related surficial deposits have been mapped in detail (Powers, 1939; Stearns, 1962; Weber, 1980, and available unpublished maps). Shoreline features of Pleistocene Lake Agustin include wave-cut notches, beaches, bars and spits. They are best expressed at elevations between 2073 m and 2115 m (the highest shoreline noted by Powers and Stearns). Subsequent work by Weber (1980) demonstrates the presence of a less distinct and discontinuous group of shorelines at higher elevations. The highest shoreline features occur between 2135 and 2150 m (Weber, 1982), but their record is quite fragmentary. Tectonic deformation of shorelines has not been observed, and there is no evidence of lake overflow across the 2158-m sill at the east end of the basin. However, it is possible that lake discharge could occur via the regional groundwater system (Brady and others, 1984).

There are distinct differences in the degree of soil development above and below the prominent 2115-m shoreline. Weakly developed soils characterize the landscape at and below 2115 m, while above that elevation soils that have very well-developed argillic horizons and strong calcic horizons are locally present. Weber (1980, 1982) suggests that Lake San Agustin expanded to at least the 2135 m level during late Wisconsin time (O-isotope stage 2). However, my interpretation (Table 1) limits the late Wisconsin lake to the 2115-m shoreline. Lake San Agustin may have expanded to at least the 2135-m level in the middle Pleistocene but additional work is needed to establish earlier shoreline chronologies.

Two long cores (Oberlin 1-200 m, Oberlin 2-600 m) taken in 1955 and 1958-59 from the deepest part of the San Agustin Basin (Foreman and others, 1959; Martin and Mehringer, 1965; Markgraf and others, 1983, 1984) have stimulated a long-term interest in the stratigraphy of this basin's fill. Early interpretations of the sedimentologic and pollen record indicated that predominantly fine-grained, unconsolidated Quaternary deposits extend to depths of about 290 m and that poorly consolidated, conglomeratic fill of late Tertiary age is below 326 m (Foreman and others, 1959). Numerous radiocarbon dates from the upper 9 m of the Oberlin cores (11-32 ka range) indicate that the uppermost basin fill is of mid- to late-Wisconsin age (Foreman and others, 1959; Markgraf and others, 1983).

Recent paleomagnetic analyses of the 164 to 327-m portion of the 600-m (Oberlin 2) core support general placement of the Plio-Pleistocene boundary (top of the Olduvai normal subchron, 1.6-1.7 Ma) at depths of 268 to 305 m below the basin floor (Markgraf and others, 1984). Interpretations of the paleomagnetic-polarity log further suggest that the Brunhes-Matuyama (~7.5 Ma) reversal is within a thick silty clay interval at depths of either 186 or 252 m.

The paleoenvironmental assessment of the subsurface record by Markgraf and others (1983, 1984) included analysis of samples from the upper 2.2 m of central basin sediments in order to better evaluate conditions existing over the past 18,000 years. Their work involved study of pollen, ostracodes, diatoms and other algae, as well as amino acid racemization analyses and new 14 C age determinations. Preliminary results form this very significant study suggests that Lake San Agustin was a large freshwater body, with depth of at least 50 m, during the last full glacial (~18 ka). Shoreline levels at that time could have been at or near the 2115-m high stand. "Palynological and other paleolimnological information combined suggest that the climate at about 18,000 yr BP was characterized by long, cool, wet winters and shorter than modern, but dry, warm summers" (Markgraf and others, 1984, p. 341).

The shallow subsurface record also contains evidence of 1) drier, but still cool paleoclimates between 16 and 11 ka that resulted in low levels and increased salinity of Lake San Agustin; and 2) wetter and warmer paleoclimates between 11 and 8 ka that resulted in decreased lake salinity. The latter conditions may indicate a shift from winter- to summer-dominant precipitation pattern. According to Markgraf and others (1983, 1984), essentially modern playa environments were established on the San Agustin Plains by 5 ka, with the preceding early-middle Holocene (8-5 ka) interval being characterized by presence of shallow saline lakes and local fresh-water marshes on the basin floor.

Phillips and others (1992) have developed a new model of late Wisconsin paleohydrologic and paleoclimatic conditions in the San Agustin that is primarily based on ^{18}O variation in ostracode shells. An additional report based on recent thesis research by Peggy S. Johnson is in preparation. Phillips and others (1992) report that a cold and relatively wet full glacial maximum 21.8 to 20.6 ky B.P. marked the culmination of a long glacial-pluvial interval beginning about 26 ky B.P.. This cold period was characterized by high ground- and surface-water inflow and low evaporation that produced the highest Wisconsin stand of Lake San Agustin at the 2115 m level. The 35 to 26 ka interval (late mid-Wisconsin) was dominated by very low lake levels produced by dry but still relatively cold paleoclimatic conditions. The glacial maximum was followed by a period of climate instability distinguished by rapid fluctuations in both temperature and moisture regimes. High lake stands with progressively lower peaks occurred at about 19, 17, and 14 ka. The late Wisconsin isotopic data of Phillips and others (1992) support a model of synchronous fluctuations in the water balance of the entire Basin and Range - Southern Rocky Mountain region. They suggest, however, that there was a progressive south-to-north latitudinal shift in maximum precipitation.

Pluvial Lake Basins East of the Rio Grande

The eastern Mexican Highland area of south-central New Mexico includes two of the late Quaternary pluvial lakes listed in Table 1 (Otero and Trinity; Fig. 1: I,O). The basins of Lakes Estancia, Encino, Pinos Wells, Sacramento and King are located near the Rio Grande-Pecos divide in the Sacramento section, which extends southward from central New Mexico to Trans-Pecos Texas (Fig. 1: D, E, H, K, M). All lake basins in this area have several important features in common. Ground-water inflow and outflow played an important role in basin paleohydrology, and evaporite (mainly gypsum) dissolution-precipitation and solution-subsidence phenomena are widespread (Allen, 1991; Allmendinger and Titus, 1973; Bedinger and others, 1989; Boyd and Kreitler, 1986; Hawley and Love, 1991, p. 130-133; Neal and others, 1983; Titus, 1973). Only the Lake Estancia and Sacramento basins definitely contained deep freshwater bodies during the late Wisconsin. These conditions possibly also occurred for short periods in the Encino and Pinos Wells basins. Lakes King, Otero, and Trinity were probably always at least slightly saline and were very shallow, although Lakes King and Otero flooded very large areas (Table 1).

As in southwestern New Mexico, detailed topographic maps (1:24,000) of much of the area have only recently become available, and much better characterization of lake deposits and watershed features is now possible. Detailed research on upper Quaternary lake and playa deposits has only been done in the Estancia Valley (Bachhuber, 1989; Allen, 1991) and is summarized in a following section of this paper.

Pluvial Lakes of the Jornada and Tularosa Basins (Trinity and Otero; Plate 1, I, O). The floors of intermontane basins flanking the San Andres Range of south-central New Mexico, the Jornada del Muerto and Tularosa Basins, are the present sites of numerous playa-lake depressions and extensive alkali (mostly gypsum) flats (Allmendinger and Titus, 1973; Hawley, 1983; Meinzer and Hare, 1915; Neal and others, 1983; Weir, 1965).

During middle? Pliocene to early Pleistocene time large basin-floor areas were occupied by aggrading distributaries of the ancestral upper Rio Grande (Hawley, 1975, fig. 2; Gile and others, 1981, fig. 5). One system of distributaries emptied into a closed segment of the northern Jornada del Muerto Basin and terminated in a large depression now partly "flooded" by the early to middle Pleistocene Jornada basalt flow (Hawley, 1978, p. 94-97). The middle to late Quaternary basin of *Lake Trinity* (Neal and others, 1983) is located just east of this flow. Extensive and thick bedded gypsum deposits exposed near the Red Lake depression south of the Jornada flow may be remnants of the fill of a larger, pre-basalt lake basin of Plio-Pleistocene age.

The other major system of fluvial distributaries mark the terminus of the ancestral upper Rio Grande in the bolson plains (Mesilla, Los Muertos, Hueco and Tularosa) of the Chihuahua-New Mexico-Texas border region. The mid-Pliocene to early Pleistocene complex of lakes that was fed by this fluvial system has been designated Lake Cabeza de Vaca by Strain (1966). This complex includes basin floors presently occupied by the playa remnants of (late Pleistocene) Lakes Goodsight and Palomas (Fig. 1: F, J) as well as the relict plain of pluvial Lake Otero (Fig. 1: I) in the Tularosa Basin and western part of the White Sands (gypsum) dune field (Weber and Kottlowski, 1959).

Eastern distributaries of the ancestral Rio Grande, which fanned out from the gap between the Organ and Franklin Mountains (Fillmore Pass), constructed an extensive fluvial-deltaic plain that still forms the floor of much to the southern Tularosa Basin and northern Hueco Bolson south and west of Orogrande (Seager and others, 1987). Eolian activity and local playa deposition have been the dominant geomorphic processes in this area since the early Pleistocene (Blair and others, 1990). A low sill (elev. ~1220 m, 4003 ft) near the headquarters of White Sands Missile Range separates this ancient fluvial plain from the area of Tularosa Basin flooded by mid- to late-Pleistocene Lake Otero (Herrick, 1904; Meinzer and Hare, 1915).

Lake Otero was primarily fed by local streams heading in the flanking San Andres-Oscura (west) and Jarilla-Sierra Blanca-Sacramento (east) mountain ranges. The major stream system that once fed Lake Otero has recently (mid- to late Holocene) been "dammed" off by the Carrizozo basalt flow (Hawley, 1983). Its headwaters are in the northern Sierra Blanca to Jarilla Mountain area. I also suggest here that there has been a secondary, but probably very significant contribution by regional ground-water flow derived from an area that possibly extended as far north as the Estancia Basin. This flow system definitely included a large part of Chupadera Mesa (see Hawley and Love, 1991, p. 130-133).

An unnamed complex of large playas and downwind eolian-sand ridges (lunettes) is located north of the Jarilla Mountains in the area adjacent to the Tres Hermanos hills (west of Escondido railroad siding and U.S. 54). The rim of these playa-lake depressions have elevations slightly below 1219 m (4000 ft), and their floors have minimum elevations of about 1210 m (3970 ft). This area occupies a southeastern structural subbasin of the Tularosa Basin. It lies between the Sacramento Mountain block and a bedrock high extending northward from the Jarilla Mountains (Seager and other, 1987). The playa-lake complex near Tres Hermanos marks the highest level of basin-floor flooding during mid- to late Quaternary time.

Deep ground-water levels in the Tularosa-Hueco basin area south of Lake Lucero playa (~1184 m, 3885 ft), the lowest depression of the floor of the Lake Otero plain, reflect a regional flow system graded to the entrenched El Paso Valley segment of the Rio Grande (Bedinger and others, 1989). Deep valley incision in the Las Cruces-El Paso area and partial draining of adjacent basin fills occurred sometime in the middle Pleistocene, at least 250 ka (Gile and others, 1981; Seager and others, 1984).

Basins of the Sacramento Section (Estancia, Encino, Pinos Wells, Sacramento and King; Figure 1: E, D, K, M, H). Basins in the Sacramento section where pluvial lakes have been reported are associated with carbonate and gypsiferous bedrock terranes of Pennsylvanian and Permian age (primarily the Madera Group, and San Andres and Yeso Formations). Solution-subsidence possibly played as great a role in basin formation as block faulting in the Estancia Valley area. Regional ground-water flow was definitely a major factor in the expansion and contraction of these pluvial lakes. The present positions of surface-water and shallow ground-water divides should not be considered as permanent hydrographic features. Much more work needs to be done in each basin to better establish ground-water inflow and outflow components of paleohydrologic systems, particularly in deeper parts of regional carbonate aquifers whose boundaries may extend well beyond the surface watersheds of individual lake basins.

Lake Sacramento (Fig. 1: M) is a newly recognized pluvial lake, at least 40 m deep, that formed in a structural basin at the terminus of the Sacramento River system (Derr, 1981; Sheet 31). The geohydrology of this part of New Mexico has never been properly documented (Bjorklund, 1957) and previous workers have erroneously considered that the Sacramento River flowed directly into the Salt Basin (Miller, 1981, p. 60; Boyd and Kreitler, 1986, p. 7). The Sacramento watershed includes the summit area of the southern Sacramento Mountains, with highest elevations at about 2900 m. The lake basin is bounded on the southwest by the Diablo Plateau and on the northeast by a prominent fault-block escarpment, which is a southeastward extension of the Sacramento fault zone of Bates (1961). A prominent relict shoreline (Fig. 2), marked by gravelly beach ridges at about 1340 to 1347 m, occurs at the southern and eastern margin of the basin. A sill on the southeastern basin rim at about the same elevation as the high shoreline shows no evidence of erosion by a major overflow event. Any surface or subsurface outflow would have to continue through or beneath a large internally-drained basin (site of Van Winkle Playa) before draining to the Dell City (Texas) area of the Salt Basin via Four Mile Draw (Crow Flat, 1:100,000 topographic sheet).

Lake King (Fig. 1: H), recently named by Miller (1981), flooded much of the northern Salt Basin floor. This deep structural basin lies between the Guadalupe and Delaware Mountains (east) and the Diablo Plateau (west), and straddles the Texas-New Mexico boundary in the Crow Flats area northeast of Dell City (Nielson and Sharp, 1989). Lake and playa features and associated gypsiferous dune deposits were originally mapped by P. B. King (1948). No additional detailed work has been done on near-shore deposits or shoreline features (Table 1). Recent work (Boyd and Kreitler, 1986; Kreitler and others, 1990) has concentrated on the hydrogeology and geochemistry of gypsiferous playa deposits and on the development of a regional ground-water flow model. One playa (Zimpleman Salt Lake) in the central part of the northern Salt Basin contains economic deposits of halite (Boyd and Kreitler, 1986, Hussain et al, 1988). Ground-water in the basin has a shallow, surface-discharging component characterized by active precipitation of gypsum. The deeper ground-water flow system,

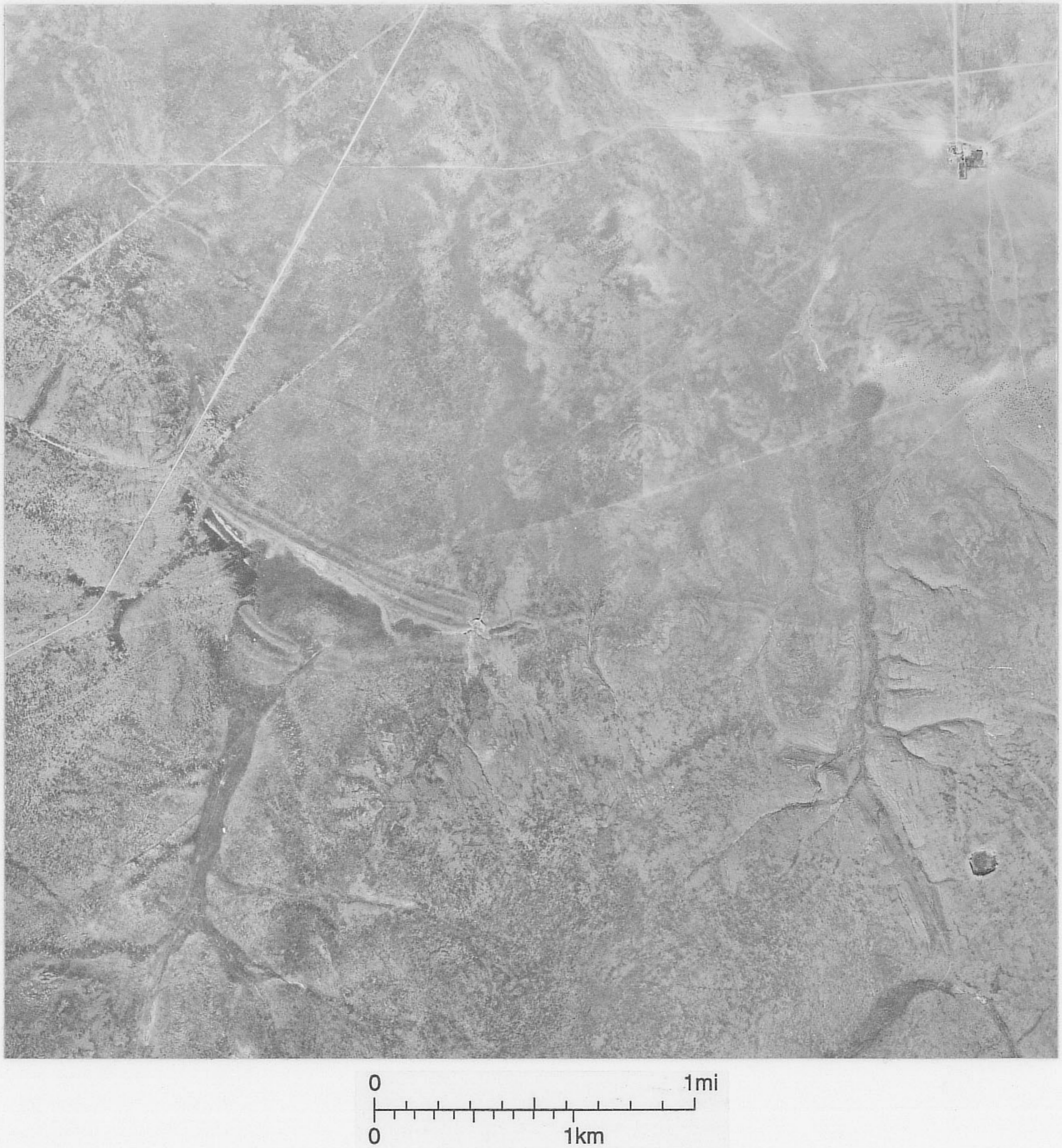

FIGURE 2. High-shoreline features of pluvial Lake Sacramento, southeastern Otero County, New Mexico. Baymouth gravel-bar complex (left center) at an elevation of 1340 to 1347 m (4395-4418 ft) marks the deepest stage of the lake. When these features were formed in late Wisconsin time, the lake flooded an area of about 72 km^2 (28 m^2) and was at least 40 m (130 ft) deep. "John O. (Stevens) Flat" (elev. ~1308 m), the central playa of the almost circular lake basin is located about two miles to the north of the upper edge of the photo. Location is in the southwestern corner of Cleones Tank (7 1/2') Quadrangle (105° 30'W, 32° 15'N). La Heeta Harvey (Stevens) Ranch Hq. is in the upper right hand corner of the photo. Note large sinkhole in limestone of the San Andres Formation at the lower right. Aerial photograph taken on January 12, 1974 (1339, 111699, 1-101, H15000, GS-UDJO).

however, may ultimately discharge at Balmorhea Springs in the lower Pecos River basin (Sharp, 1989; Kreitler and others, 1990).

The basins of pluvial Lakes Estancia, Encino and Pinos Wells (Fig. 1: E, D, K) are located in the northern part of the Sacramento section in central New Mexico. Meinzer (1911) originally mapped the area and recognized the prominent high shoreline features preserved in the Estancia and Encino basins (respective elevations of about 1890 m and 1882 m, Table 1). He did not, however, recognize any shorelines in the Pinos Wells depression; and presence of a major pluvial lake of the late Wisconsin age in that basin has still not been documented. Later workers, notably Bachhuber (1971, 1982) and Titus (1973), have suggested that the Estancia-Pinos Wells-Encino system formed a late Wisconsin chain of lakes that spilled into Pecos River tributaries northeast of Encino.

Bachhuber (1989) has recently discussed the occurrence and paleolimnological significance of cutthroat trout (Oncorhynchus clarki) in pluvial lakes of the Estancia Valley. According to his interpretation, Lake Estancia last expanded to a spillway level (1933 m sill elevation, Table 1) in Illinoian or pre-Illinoian time (O-isotope stage 6 or earlier). During major periods of lake discharge surface flow would then have continued to the Pecos River via an integrated drainage system that passed through deep lakes in the Pinos Wells and Encino basins. Bachhuber suggests that cutthroat trout were introduced to Lake Estancia at such times. There is no field evidence for such overflow events, however, and other mechanisms must be invoked for introduction of trout to Lake Estancia (see discussion of Bachhuber's 1989 paper by Behnke and Platts, 1990; and Hawley and Love, 1991, p. 131-133, Stop E-1). In addition, Kelley (1972, p. 47) demonstrated that Bachhuber's (1971, 1982) proposed Encino-Canyon Pintada spillway route could not have provided a surface outlet for Lake Estancia.

My own recent field studies and ongoing work by Bruce Allen (1991) have found no evidence of high-lake stages in the Estancia Basin that exceeded 1893 m in middle to late Pleistocene time. The highest shoreline elevation is 40 m below the lowest possible sill elevation(1933 m) on the southeastern basin rim near Cedarvale. During the highest stages Lake Estancia appears to have discharged southward through a solution-enlarged fracture zone developed in carbonate and gypsiferous bedrock beneath Chupadera Mesa (Hawley, 1986b). This ground-water flow system would have ultimately drained into the northern Tularosa Basin.

There is general agreement on the late Wisconsin history of "late" Lake Estancia (Bachhuber, 1989; Allen, 1991). The chronology that has been developed is based on radiocarbon dating of organic remains and very detailed (outcrop and core hole) studies of basin-fill stratigraphy and sedimentology. Bachhuber (1989) dates the initial freshwater phase of the pluvial lake, associated with the onset of cold/moist conditions, at 24,300 yrs B.P.. He also finds evidence for a long preceding interval of warm/dry (interpluvial) and cold/dry (sub-pluvial) conditions, which he correlates with the Sangamon to middle Wisconsin period. Two subsequent freshwater stages occurred before and after 20 ka, the latter probably representing the deepest lake. Freshwater stages were separated by warmer and drier partial drawdown phases characterized by saline lake waters. According to Bachhuber (1989), the lake freshened for the final time about 12,500 yrs ago (his Lake Willard) and trout migrated back in the lake through tributaries that headed in local mountain uplands. Warm/dry conditions of the early Holocene resulted in complete desiccation of "Lake Willard". The prominent deflation basins and large dunes of the Laguna del Perro area developed in the middle Holocene.

Allen (1991; work in progress) has concentrated on depositional sequences in both central-lake basin and shoreline settings. He recognizes two major sedimentary facies in a lacustrine sequence (up to 10-m thick) exposed in the walls of deep deflational (playa-lake) basins. Two radiocarbon-dated, bioturbated-clay intervals (with trout), between 15 and 20 ka and near 13 ka, represent sedimentation during lake high stands. The lower unit probably marks the highest (1890 m) Wisconsin lake stage between ~18 and 15.6 ka according to Allen (1991). Laminated gypsum-clay (varved) facies were deposited during low stands of Lake Estancia that preceded, occurred between, and followed the deep-lake intervals. Significant desiccation of Lake Estancia occurred between 12 and 11 ka; however, a minor subsequent rise in lake level formed a prominent gypsum beach bar at 1860 m. The final desiccation phase of the pluvial lake was apparently underway by about 10 ka. Allen (1991) agrees with Bachhuber (and other workers) that the time of maximum deflation of playa-lake depressions (and ground-water drawdown) occurred in the mid-Holocene, about 4000 years ago.

The detail of Allen's current field studies allows him to recognize cycles of climatic change at three different scales in the sedimentary record: millennial, centennial, and decadal. He also recognizes the very significant role that ground-water processes have played in Estancia Basin paleohydrology. Paleohydrologic models (Meinzer, 1922; Leopold, 1951; Antevs, 1954; Galloway, 1970; Brackenridge, 1978; Smith and Anderson, 1982) that neglect ground-water-surface-water linkages cannot explain many of the lacustrine and playa-basin features observed in the Estancia Valley area, as well as in the other lacustrine basin of the region.

CONCLUSION

My brief review of pluvial-lake basins and paleoenvironmental reconstructions in the southern New Mexico region illustrates the great amount of high-quality research that has already been completed. The information in Table 1 on fifteen lake basins of the region and the interpretations presented in this report are based on long-term field observations and relatively complete literature reviews. These interpretations appear to be quite reasonable, at least at the present time. The report, however, also clearly indicates the large amount of work that still needs to be done. This is a really exciting time to be a Quaternary geologist and geomorphologist. Certainly, as the excellent stratigraphic records at Pendejo Cave and the other sites discussed by participants at this conference are deciphered, there will be a "quantum jump" in our excitement and productivity levels. Let's hope that there is still more to environmental geology than locating hazardous-waste dumps in the "deserts" (Bedinger et al., 1989; Hawley and Longmire, 1992).

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