New Mexico Bureau of Mines and Mineral Resources

Open-file Report 69

Hydrogeologic Evolution of Estancia Valley, a Closed Basin in Central New Mexico

by

Frank B. Titus

Socorro, 1973

CONTENTS

FIGURES

PREFACE

This project was completed with the considerable help of many individuals and with information and data provided by several agencies. The New Mexico State Engineer District Office in Albuquerque provided logs of many water wells in the area and also provided copies of several maps that are the result of their administrative work in Estancia Valley. J. T. Everheart, geohydrologist with that office, was always available to discuss hydrologic phenomena in the basin and to provide conclusions that have resulted from his analyses of considerable data.

Personnel of the U.S. Geological Survey in Albuquerque analyzed the water samples for the project; funding for the analyses was provided by the New Mexico Bureau of Mines & Mineral Resources under a cooperative agreement between the two agencies. Lynn Brandvold and R. W. Foster, with the New Mexico Bureau of Mines and Mineral Resources, provided chemical and X-ray analyses respectively of sediment samples.

B. E. DeBrine, graduate assistant at New Mexico Institute of Mining and Technology, worked long and irregular hours collecting data for the project. He, along with R. G. Haubold and J. C. Halepaska, did most of the test-hole drilling and well construction on which are based the subsurface stratigraphic correlations and hydrologic interpretations. Bore-hole logs were run in the test holes by J. D. Hudson of the U.S. Geological Survey.

Financial support covering travel, part of the drilling costs, and a significant part of salaries for two years was provided by the Office of Water Resources Research, Department of Interior, through the New Mexico Water Resources Research Institute under grant number B005-WRI-151.

S. A. Wengerd, V. C. Kelley, and R. Y. Anderson reviewed an early version script and offered at that time many helpful technical and editorial suggestions. John Hawley critically reviewed the final manuscript.

The aid and assistance of these agencies and individuals, and many other unnamed individuals, is most gratefully acknowledged. The conclusions presented are the author's own, and do not necessarily coincide with those of all cooperators or reviewers.

Frank B. Titus
Ebasco Corp.
New York, New York

April 1, 1973

ABSTRACT

Estancia Valley, a 2,000-square-mile closed basin in central New Mexico, has since late Pliocene (?) been sequentially the site of a) accumulation of several hundred feet of alluvium in a structurally subsiding river valley, b) two successive late Pleistocene lakes and one shallow Holocene lake, and c) several score steep-walled depressions 20 to 40 ft deep, each of which now contains a perennially moist playa. The alluvial unit is here named the Estancia Valley Formation. Above it is 100 ft of mostly lacustrine sediment here named the Dog Lake Formation.

The Pliocene (?) and early Pleistocene Estancia River may have flowed to the Portales Valley on the Llano Estacado. Early Lake Estancia is correlated with the Terry Pluvial, and Late Lake Estancia with Tahoka and San Jon of the Llano Estacado. The early lake overflowed the basin at a sill in the elevated river valley. The late lake had no outflow, and was probably chemically stratified.

The playa depressions on the former lake floor were formed mainly by deflation, with the sediment being blown onto great dunes east of each depression. Playa-depression sites were initially controlled by ground-water solution of gypsum in the Yeso Formation beneath 400 ft of valley fill. Subsidence extending upward through the hydrologic confining beds of the Dog Lake Formation also created permeability paths through which water in the underlying Estancia Valley Formation discharged upward to the playas to evaporate.

Prior to heavy pumping for irrigation, natural discharge was by a) evaporation from the playas, b) evapo-transpiration from springs and marshes west of the edge of the lacustrine strata, and c) deep subsurface leakage to the north through pre-Tertiary strata. Pumping has dried the springs and marshes.

INTRODUCTION

Estancia Valley in central New Mexico has long been recognized as the site of a Pleistocene lake (Keyes, 1903). Early recognition of its lacustrine history was based on the topographic closure of the basin and the obvious beach remnants that ring the lower parts of the basin sides. While the general nature of the bedrock geology, structure, and hydrology has been presented in the literature, there are no published detailed studies of the geology of unconsolidated sediment in the valley.

Purpose and Scope

The geology of the valley fill and geomorphology of the basin are presented in terms of two important shaping forces—water and wind. This requires a) a systematic classification of the materials that have been deposited in the central part of the basin, b) description of the surface and subsurface features that have been developed by the two fluids, and c) the establishment of a chronology of events from basin origin to the present.

In contrast to most studies of Pleistocene lakes, which deal mainly with the effects of surface water, this study includes consideration of the geologic effects of ground water. The effects of flowing ground water did not cease with the disappearance of the lake, and significant modifications of the floor of the basin have taken place since the lake evaporated.

The study is limited to phenomena of physical geology and qualitative physical and chemical hydrology. No attempt was made during field work to collect paleontologic data, but the work of others, particularly Bachhuber, has been invaluable in dating late Pleistocene and Holocene events.

Location and Geography

Estancia Valley is a topographically closed basin lying in the central part of New Mexico, and containing approximately 2,000 square miles within its perimeter (fig. 1). It is approximately bisected by longitude 106°W., and by latitude 34°45' N. The valley is about 55 miles long and 35 miles wide. The town of Moriarty, in the north-central part of the valley, is about 40 miles east of Albuquerque. The town of Estancia, the county seat for Torrance County, is near the west side of the nearly flat valley floor.

Economically, Estancia Valley is almost totally dependent on farming and ranching. Irrigated farms were first established in 1941, and since then have expanded in area until 1965 when the U.S. Geological Survey estimated that 22,000 acres were under irrigation, and that annual pumpage of ground water was about 25,000 acre-ft (Busch and Hudson, 1967, p. 72). The remainder of the valley is grazing land or, at higher elevations, pinon forest. During the first half of this century dry farming without irrigation was common at intermediate and higher elevations, but this activity, involving mainly pinto bean fields, has nearly ceased.

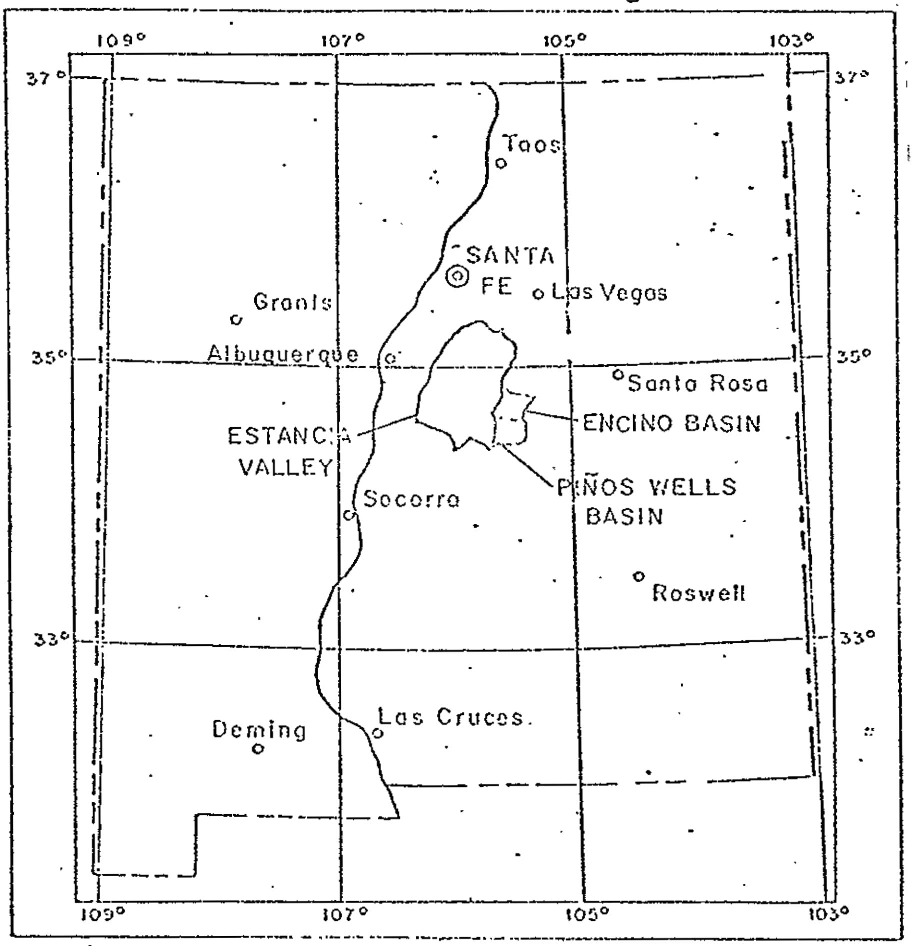


FIGURE 1 — Index map showing location of Estancia valley, Pinos Wells Basin, and Encino Basin.

Artificial discharge of ground water by pumping is drastically modifying the natural hydrologic pattern. The intensively pumped area is on the west side of the valley floor and on lower slopes of the west side and north end of the valley.

The climate is mild and semiarid. Annual temperatures at Estancia, in the central part of the valley, average 50°F. January temperature averages about 30°F, while July averages about 70°F. The average maximum daytime temperature in July is about 86°F (U.S. Weather Bureau, 1968). Precipitation in the central part of the valley is about 12 inches annually, with the months of heaviest rainfall being July, August, and September (New Mexico State Engineer Office, 1956). Annual precipitation on the highest parts of the Manzano Mountains to the west is more than 30 inches. Only on rare occasions do heavy rainstorms cause runoff that reaches the valley floor.

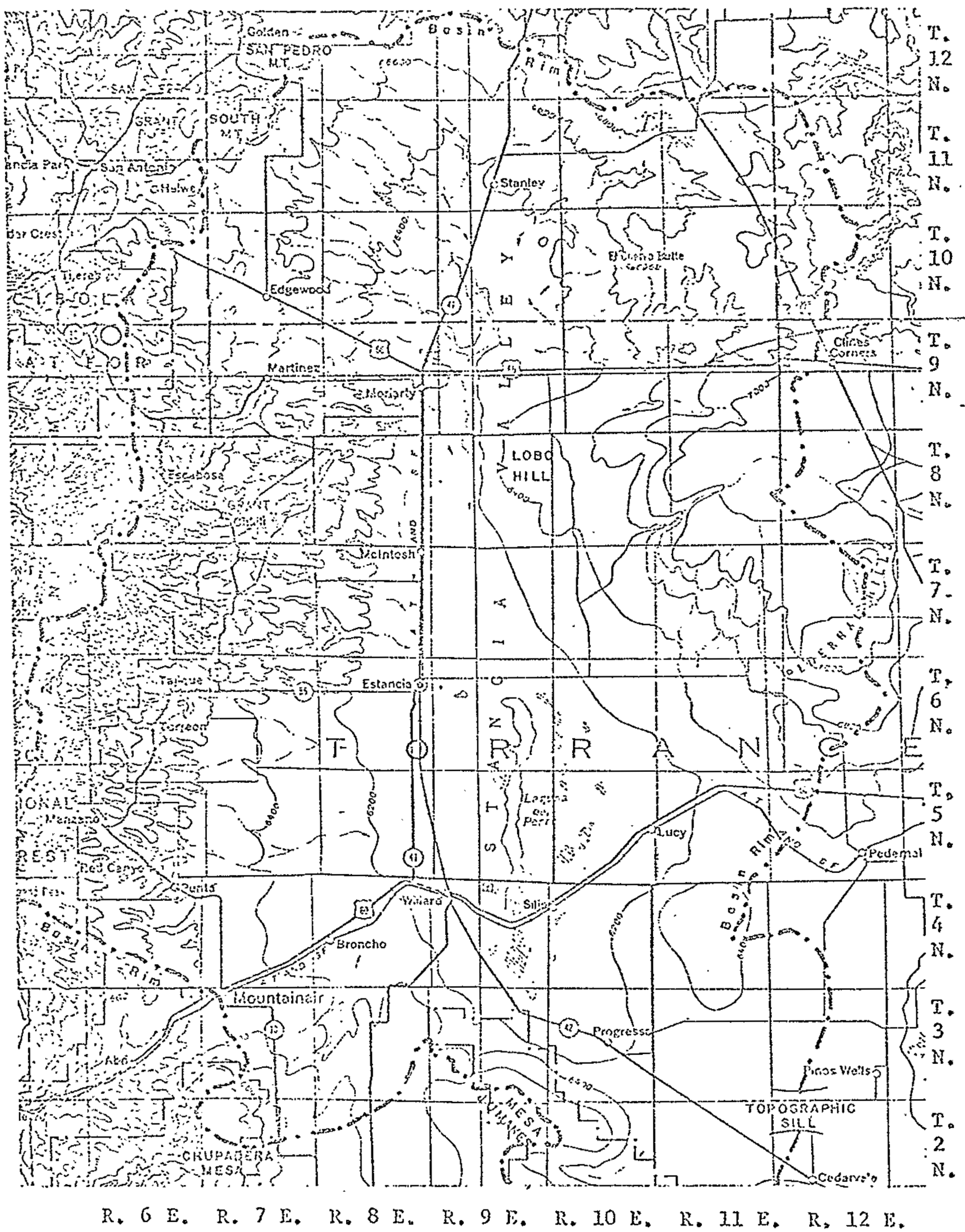
Wind velocities and directions were recorded continuously at a height of 6 ft above a playa surface in the central part of the valley. During the months of March through May, strong west-southwest winds regularly sweep across the valley. The wind blows nearly continuously during this period, but is generally strongest in the afternoon. Average velocities of from 30 to 37 miles per hour (mph) were commonly measured. The instrument does not record velocities of individual gusts. Average weekly velocities of more than 13 mph are not uncommon. During the rest of the year strong winds are sporadic, and the directions from which they blow are more variable. From June through October, occasional winds having average velocities of up to 25 mph blow from the southwest and southeast. From November through February the strongest winds are out of the west-northwest to north-northeast with velocities of up to 30 mph.

Topography of the Valley

The valley floor is an elliptical area, comprising about 450 square miles, enclosed within the 6,200-ft contour line of topographic maps (fig. 2). Average altitude is 6,100 ft. The generally flat configuration of the floor is interrupted in the south-central and central parts by numerous irregularly shaped 20-ft to 40-ft depressions that range from a fraction of a square mile to 7.5 square miles in area. Most of these steep-walled depressions contain saline playas. Closely associated with the depressions are dunes that stand as high as 130 ft above the general valley floor. The dunes, where the spatial relations are clear, lie to the east of the playa depressions.

Surrounding the valley floor, at elevations between about 6,100 and 6,225 ft, are the easily recognized lacustrine beach remnants. The beaches at most places form a series of topographic steps 4 to 8 ft high. The lower beaches are broad and much less distinct than those in the middle and upper parts of the beach range.

Westward from the valley floor, and above the beach



shown as Interstate 40

FIGURE 2 — Topographic map of Estancia Valley (from U.S. Geological Survey State Topographic map)

remnants, the slopes rise at about 40 ft per mile on a stream-dissected surface toward the mountains that form the west rim of the basin. Eastward from the floor, the initial slope above the beach remnants is steeper, averaging nearly 100 ft per mile, rising toward the low, maturely eroded Pedernal Hills and associated uplands that form the east rim of the basin.

The Manzano Mountains, rising to peak altitudes in the southern part of the range of more than 10,000 ft, from the west rim of the basin. The northern part of the range, called by some the Manzanita Mountains, has somewhat lower crestal altitudes, ranging between 7,000 and 8,000 ft.

Northeastward from the Manzano Mountains the rim of the basin lies along the crests of South Mountain and San Pedro Mountain. The Sandia Mountains to the west are drained by streams that flow toward the Rio Grande. At the north end of Estancia Valley, headward erosion by tributaries of Galisteo Arroyo, which also flows to the Rio Grande, is actively reducing the area of Estancia drainage. Here, the rim of the basin trends eastward along the divide, with steep slopes to the north toward Galisteo Arroyo, and more gentle slopes of 60 to 80 ft to the mile southward into Estancia Valley. The altitude of the rim is 6,600 to 6,700 ft.

The rim along the east side of the basin follows the crest of a broad drainage divide between Estancia Valley and tributaries of the Pecos River. The highest point on the east rim, about 7,600, is in the Pedernal Hills, which lie south of US-40. From here southward the altitude of the rim decreases steadily to its lowest point a few miles north of Cedarvale. This low point, here called the topographic sill, lies east of the south end of Estancia Valley at an altitude of about 6,350 ft. East and northeast of the sill are the small closed basins of Pinos Wells and Encino (fig. 1).

At the south end of Estancia Valley, the land surface rises abruptly to the top of Mesa Jumanes and the north end of Chupadera Mesa. The south topographic rim lies near the top of this mesa complex at an altitude of 6,700 ft to more than 7,000 ft. The valley of westward flowing Abo Arroyo separates Chupadera Mesa from the south end of the Manzano Mountains. The town of Mountainair, at an altitude of 6,540 ft, is on the drainage divide.

Regional Topographic Setting

Estancia Valley is an elongate bowl-shaped basin lying between the valleys of the Rio Grande on the west and the Pecos River on the east. The floor, at about 6,100 ft, is higher than either the Rio Grande or Pecos drainages at the same latitudes. The Rio Grande at Albuquerque has an elevation of 4,950 ft; at Bernardo, 50 miles west of the south end of Estancia Valley, the river is at 4,725 ft. The Pecos River at Santa Rosa, 75 miles east of the north end of the valley, is at 4,530 ft; and at Fort Sumner, 100 miles east of the south end of the valley, is at 4,000 ft. The relative elevations of Estancia Valley and the 2 main rivers of New Mexico that lie to either side is important because of the possibility of subterranean ground-water leakage from the basin.

Previous Work

Keyes (1903), in a paper on ephemeral lakes, commented briefly on the existence of an ancient lake in Estancia Valley. His statement is quoted in its entirety.

> There are some of the bolson plains in which limited deposits occur giving undoubted evidences of the existence of old lakes. The Sandoval bolson, south of Santa Fe, contains traces of a comparatively recent lake of considerable size. At present time the remnants are found in a group as small salt ponds, the chief of which is Laguna del Perro.

Meinzer (1911) published a general description of the geology and water resources of Estancia Valley after a 6-week field study made in 1909. This was the first, and remains one of the most informative, descriptions of Quarternary geology and the lake remnants. In this publication appeared the first analysis of the lacustrine and post-lacustrine conditions that resulted in the formation of the beaches, bars, dunes, and playa depressions so prominent in the valley. Meinzer correctly concluded that the playas were important sites of natural evaporative discharge of water from the valley. Although several modifications are now necessary, most of Meinzer's conclusions were valid, and this paper will add to, rather than negate, the important contribution that he made.

Bryan and McCann (1950) prepared a manuscript, which was never published, ascribing present 400+-ft topographic closure of the basin to solution of underlying gypsum beds and transportation of clastic and dissolved sediment out of the basin through underground rivers. Information now available does not support this mechanism.

Leopold (1951) analyzed Pleistocene climatic conditions in Estancia Valley, concluding that a large lake required both increased precipitation and lower temperature than afforded by present-day climate. Based on an assumed perennial snow line 1,500 meters (about 4,900 ft) below that of the present, he suggested that the average July temperature was lower by about 16°F than that of today, and that the annual precipitation necessary to maintain the lake was about 21 inches.

Antevs (1954) elaborated on the late Pleistocene climatic conditions in New Mexico, basing his conclusions for Estancia Valley on the same evidence that had been used by Leopold. Antevs postulated a June-September temperature 10°F lower than present, and precipitation on the order of 23 inches.

R. Smith (1957) reported on the availability and suitability of ground water for agricultural, municipal, and domestic use in Torrance County, which includes all but the northern end of Estancia Valley, and also includes Pinos Wells and Encino Basins. Smith was not concerned with geomorphic features left by the Pleistocene lake, and did not add significantly to knowledge of these features. The geology of the valley fill was taken from Meinzer's report for the most part. Smith suggested (p. 46) that the playa depressions had formed because of solution of gypsum in the underlying Yeso Formation and were not the work of wind alone as Meinzer had thought.

Harbour (1958) prepared a master's thesis for the University of New Mexico on the geology of the Lucy early-man site, which was also being studied by the Anthropology Department. Harbour described in considerable detail the stratigraphy of what were thought to be pond deposits at the site in the southeasternmost part of the valley. The site is about 260 ft topographically above the floor of the valley, which places it near the altitude of the topographic sill 10 miles to the southeast. Harbour also mapped and described the beaches 100 to 200 ft lower on the sloping sides of the basin.

Lyons (1969) collected a large amount of archaeological data on and from Estancia Valley, and produced a complete account of the prehistory. Bachhuber (1971) prepared a doctoral dissertation on the paleolimnology of Pleistocene Lake Estancia, which has been extremely helpful in establishing the chronology of events as well as adding substantially to my earlier work in the valley (1969), which was also a dissertation. I will note here that while Bachhuber and I agree on many aspects of basin history, we have some important areas of disagreement, particularly in relation to times during which the lake overtopped its basin. Readers interested in this information should read Bachhuber's account.

Galloway (1970) developed a model of the full-glacial climate for the Lake Estancia Basin that contrasts markedly with the models developed by Leopold (1951) and Antevs (1954). He suggested that major decreases in mean temperature (10-11°C) and evaporation alone could account for formation and maintenance of a perennial lake. Galloway proposed that precipitation during the last full glaciation in the Southwest (Pinedale Stadial) was from 80 to 90 percent of present amounts, but that the runoff percentage was greatly increased. In reviews of Galloway's model, Dury (1973) and Reeves (1973) question his assumptions on precipitation-runoff relationships. Reeves (1973), based on detailed studies of Texas High Plains playa depressions, considers that increased precipitation was required to maintain pluvial lake levels, even under much cooler conditions.

Finally, Kelley (1972) has mapped the geology of the Fort Sumner Sheet, which shows important geological relationships in the area east of Estancia Valley through which flowed the early surface streams that drained the valley while much of the valley fill was accumulating.

In January 1950, the New Mexico State Engineer declared the "Estancia Underground Water Basin" to be a ground-water basin subject to control under State law. The area declared by the State Engineer included essentially all the basin that is underlain by significant thickness of unconsolidated valley fill. Since then the area has been extended to the west and south to include part of the pre-Tertiary terrane that contributes ground water to the central part of the valley. The basin was not then, and has not since, been closed to development of new water rights, but there have been certain restrictions placed on such development. The State Engineer Office is actively involved in various studies of ground water and geologic conditions that have a bearing on administration of water rights.

The U.S. Geological Survey, as part of a cooperative program with the New Mexico State Engineer, makes regular water-level measurements in observation wells in the valley. These measurements are published regularly as State Engineer reports (Ballance, 1965; Busch, 1966; Busch and Hudson, 1967-1970; Hudson, 1971). The Geological Survey also has made numerous chemical analyses of ground water from the valley, and is a repository for these data.

Salt Harvest from the Playas

Salt has been harvested from the playas for many centuries, and Northrop (1959, p. 276) summarized the Spaniards' early interest in the deposits:

The deposits were visited by Rodriguez and Chamuscado in 1581, and by Onate in 1598; they were cited by Zarate-Salmeron in 1629 and by Benavides in 1630. As early as 1660 salt was being transported 700 miles to the silver mines in southern Chihuahua, Mexico. Spanish archives indicate that between 1716 and 1742, at least, there were numerous military escorts provided from Galisteo to the salt lakes.

Alden C. Hayes, Supervisory Archeologist with the National Park Service, provided 27 samples of salt collected during excavation of ruins of the village of Las Jumanes at Gran Quivira (Salinas) National ~~Park~~ Monument. Las Jumanes was occupied from about 1300 to 1672 A.D. (Hayes, written communication, 1967). The salt specimens indicate the reliance of the Indians of the so-called "Saline Pueblos" on salt from the playas for their own use, and suggests that during the time of occupancy of the pueblos salt may have been used for trade.

According to Talmadge and Wootton (1937, p. 146-147), Laguna Salina salt precipitate was worked commercially starting in 1915. In 1933 production amounted to 700 tons, and prices were 30 to 40 cents per 100 pounds. Three grades, 85, 92, and 98 percent pure, were separated in harvesting. In early production, the salt crust was scraped from the surface of the playa after it had precipitated to sufficient thickness. Later, shallow evaporation vats were constructed, and brine was pumped into the vats until sufficient thickness of salt accumulated. The best season for harvesting was from April to July, before the summer rains. A 30-minute rain reportedly would dissolve all of the salt on the lake surface and recrystallization required about 5 days of sunshine. Commercial production ceased in 1939 (R. Smith, 1957, p. 16).

PRE-LACUSTRINE GEOLOGY

The valley floor and most of the lower slopes on the valley sides are underlain by unconsolidated to poorly consolidated sediment comprising the valley fill (fig. 3). Precambrian, Paleozoic, and Mesozoic rocks crop out higher on the valley sides, and underlie the surface on which the valley fill rests.

Distribution of Pre-Tertiary Rocks

Precambrian rocks crop out in the west face of the Manzano Mountains, mostly outside the drainage area of Estancia Valley, and in a small area on the basin rim north of the Manzanos (fig. 3). On the east side of the valley the Precambrian crops out in the southern part of the rim and in a group of hills in T.4 N., Rs. 10 and 11 E.

Thin Sandia Formation and the thick Madera Limestone overlie Precambrian rocks on the west side. The Madera forms the surface on most of the west slopes of the valley; its subcrop extends as much as 10 miles toward the center of the valley beneath a wedge of valley fill. Farther east, subcrops of the Permian Abo and Yeso Formations form broad bands running the length of the valley and connecting with outcrops at the north and south ends. In the northern and central parts of the valley the Glorieta and San Andres Formations, and undifferentiated Triassic rocks, are in subcrop contact with the base of the valley fill. Undifferentiated Cretaceous rocks underlie the valley fill at the north end.

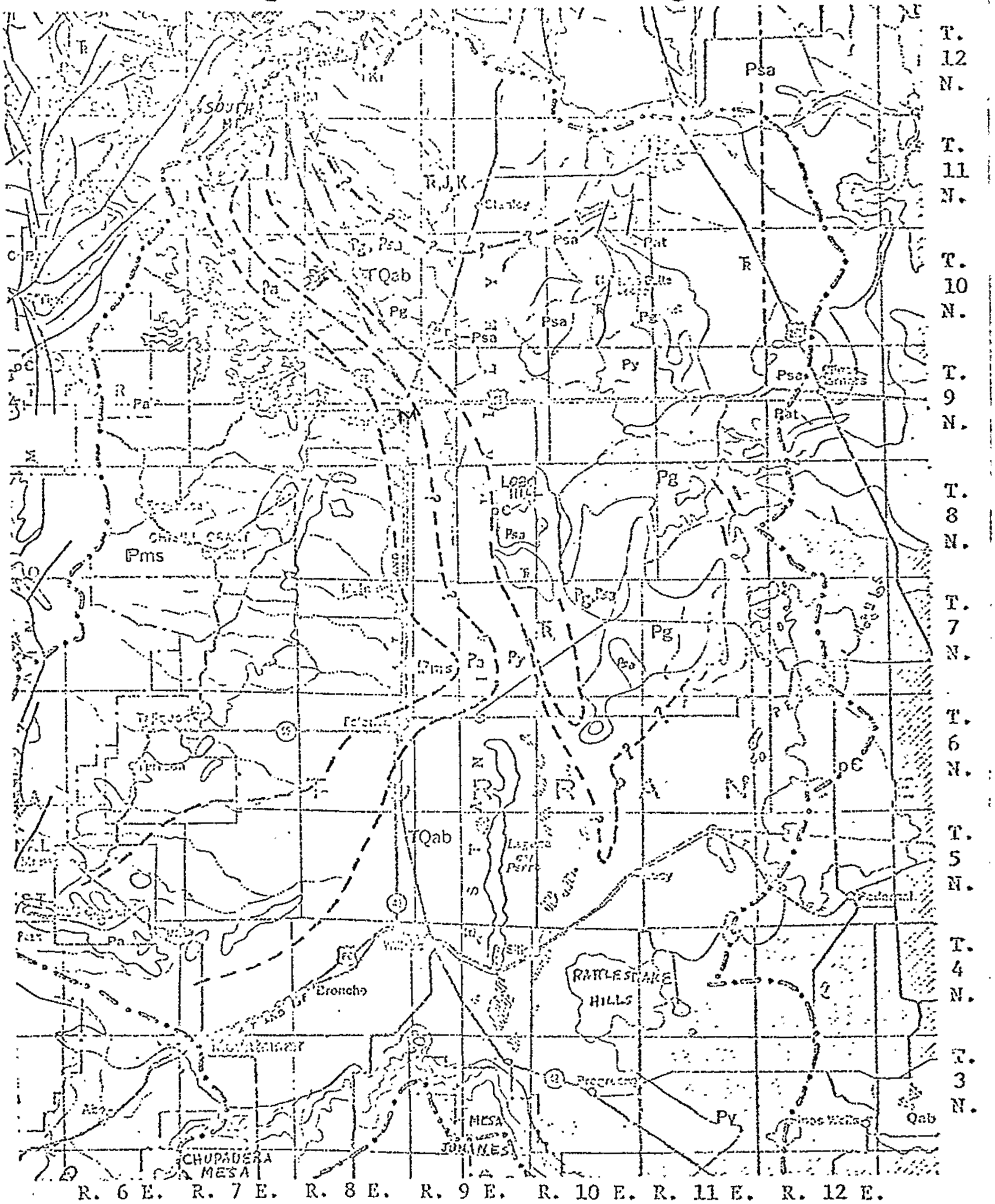


FIGURE 3 — Geologic map of Estancia Valley showing outcrops (modified from Dane and Bachman, 1965), and suggested location of buried contacts.

In the vicinity of the east half of T.8 N., R.9 E., the small but prominent conical peak of Lobo Hill, and a flat upland surface several square miles in area at its base, stand above the floor of the valley. Lobo Hill is composed of Precambrian quartzite, surrounded by limestone of the San Andres Formation. Triassic rocks crop out in the valley floor, and extend southward in subcrop 6 to 8 miles from Lobo Hill. In the southwest corner of T. 10 N., R. 9 E. highly fractured rocks of the Glorieta and San Andres Formations project through the valley fill.

In the south part of the east rim area, a relatively thin section of the Yeso Formation (Permian), resting directly on Precambrian rocks, forms the outcrops. Northward the Glorieta and San Andres Formations crop out on the rim and in the east slopes of the valley, and farther north Triassic rocks are at the surface.

The geologic map accompanying this report (fig. 3) is reproduced from the Geologic Map of New Mexico (Dane and Bachman, 1965); it has been modified in 2 areas on the basis of field work for this project. The Geologic Map of New Mexico shows Yeso outcrops projecting several miles into the basin in a broad area between Mountainair and Willard at the south end of the valley. More than 100 ft of alluvium underlies the surface here, and this published error is corrected on fig. 3. The other area is on the upland surface associated with Lobo Hill (E½ T. 8 N., R. 9 E.), where sinkholes and depressions indicate that the

Precambrian outcrop of Lobo Hill is surrounded by soluble limestone of the San Andres Formation.

Formation contacts underlying the valley fill shown on fig. 3 were modified from those on a map published by R. Smith (1957, pl. 1). The several sources of information used in the modification included: a) oil test strip logs, sample descriptions, and bore-hole logs; b) outcrop information from field observation, along with geologic maps of R. Smith (1957), Read and others (1944), Geologic Map of New Mexico (Dane and Bachman, 1965); c) water-well drillers' logs; and d) analysis of hydrologic patterns in the basin. Most of the modifications are slight. One major change is in the vicinity of TPs. 5 and 6 N., R. 10 E., where, on the basis of a small Glorieta outcrop in sec. 26, T. 6 N., R. 10 E., the Yeso-Glorieta subcrop contact is projected northeastward to connect with an outcrop contact in T. 7 N., R. 11 E. Smith, with limited information available, projected the contact southeastward across the southern part of T. 6 N., R. 11 E., but could not connect it with the contact in outcrop.

Smith's work was supplemented by adding the Abo-Yeso concealed contact, based on strip logs and electrical logs from oil tests such as the Eidal-Mitchell in sec. 33, T. 4 N., R. 8 E., the Murphree and Bond-Berkshire test in sec. 19, T. 6 N., R. 9 E., and the Olsen-Means test in sec. 27, T. 7 N., R. 10 E. Water-well drillers' logs were also used, but because of the presence of rarely distinguishable red beds in both the Abo and Yeso Formations, the information could only supplement data from the oil test holes. The trace of the contact from T. 7 N., R. 9 E. through the vicinity of Moriarty was chosen mainly by parallelism to the more reliably picked Madera-Abo and Yeso-Glorieta contacts.

The subcrop tongue of Triassic rocks shown on fig. 3 to extend southward from Lobo Hill 6 to 8 miles modifies Smith's interpretation that the subcrop in this area is Yeso and San Andres, and that the principal aquifer is in the Yeso (R. Smith, 1957, pl. 1, 2). Several water wells in the western part of T. 7 N., R. 10 E. were drilled through the valley fill, penetrated a thin section of Triassic red beds and sandstone, and apparently bottomed in the San Andres Formation. The log of one such well, in the NE¼NW¼NW¼ sec. 19, T. 7 N., R. 10 E., is included in Appendix A.

Subcrop contacts in the north end of the basin were located on the basis of logs from water wells that penetrated bedrock, and from the positions of scattered closed depressions in the terrain, which suggest ground-water solution of limestone strata in the Madera. Such depressions are notable on the U.S. Geological Survey topographic map for Edgewood Quadrangle in sec. 3, T. 10 N., R. 7 E. and in sec. 33, T. 11 N., R. 7 E. Other closed depressions on this map, for example in secs. 18 and 19, T. 11 N., R. 9 E., are shoreline phenomena related to a high stand of Pleistocene Lake Estancia, and should not be confused with the inferred Madera subcrop. The positions of the subcrop contacts were also controlled by outcrops on either side of the basin. A detailed geologic map by Kelley (1963) was used on the west side, and a reconnaissance map by Read and others (1944) on the east side, as bases for projecting the subcrops.

The Triassic, Jurassic, and Cretaceous rocks were not differentiated in the subsurface because of the paucity of well data. The log of a well in the SW¼ sec. 32, T. 11 N., R. 9 E. indicates that the valley fill here is underlain by Triassic rock. A log from the SE¼ sec. 3, T. 11 N., R. 8 E. indicates that bedrock at this location is Cretaceous rock (Appendix A).

The positions of the subsurface contacts are highly generalized in the northern part of the basin, and somewhat less generalized elsewhere. The general pattern of contact between bedrock formations and the base of the valley fill is important in considering the possibility of leakage from the basin, and in interpreting hydrologic and geomorphologic phenomena in the southern part of the valley.

Stratigraphy and Hydrologic Properties of Pre-Tertiary Rocks

Precambrian

The Precambrian rocks consist predominantly of granite, schist, gneiss, and quartzite, and their hydrologic properties are known only in a general way. Widely spaced springs and seeps in the west face of the Manzano Mountains discharge a fraction of a gallon per minute to a few gallons per minute. The Precambrian rocks have been drilled for water only in the southern part of the east rim, where they crop out or are directly overlain by up to several hundred feet of Yeso strata.

Porosity and permeability are controlled by fracturing and amount of weathering. R. Smith (1957, table 14) tabulated data on a number of ranch wells that pump water from the Precambrian rocks on the southeast side of the basin. Most of the wells are 150 to 300 ft deep and yield a fraction of a gallon per minute to a few gallons per minute. Many dry holes have been drilled that are not tabulated by Smith. These well data indicate that permeability and porosity are very low, and it is expected that both decrease with increasing depth.

R. Smith (1957, p. 24, table 14) reported a single, relatively large-yield well in Precambrian rock drilled in 1930 by the Santa Fe Railroad. The well was test pumped at 100 gpm (gallons per minute) with 60 ft of drawdown. This 701-ft well is outside of the Estancia drainage area, in the SE¼NW¼SE¼ sec. 33, T. 6 N., R. 13 E. Water is inferred to enter the well from brecciated zones that are associated with faults (R. Smith, 1957, p. 82-83). The company drilled 4 holes in a well field before the successful well was completed. The well indicates that permeability can be anomalously high in Precambrian rocks, but the high permeability is thought to be a very localized phenomenon.

The volume of ground water that is transmitted annually toward the center of Estancia Valley through the Precambrian rocks on the east side is thought to be very small. Rainfall is not high in this area. The ground-water divide follows the topographic divide fairly closely (R. Smith, 1957, pl. 2), and the width of the Estancia drainage area underlain by Precambrian rocks, or by Precambrian rocks overlain by Yeso strata, in the southern part of the rim is only a few miles. These factors, coupled with low permeability of the rock, imply low recharge to the basin from Precambrian terrane.

The Precambrian rock throughout the rest of the basin is overlain by more than 1,000 ft of Pennsylvanian and younger sedimentary rock. At the crest of the Manzano Mountains the overlying Pennsylvanian rocks are about 1,000 ft thick (Read and others, 1944; Reiche, 1949; Myers, 1966). The Precambrian surface lies progressively lower with distance to the east, so that in the Witt Ice #1 Meadows test hole, sec. 23, T. 6 N., R. 7 E., the Precambrian-Pennsylvanian contact is at a depth of 1,900 ft (Foster and Stipp, 1961). In the Murphree and Bond #1 Berkshire test, sec. 19, T. 6 N., R. 9 E., the Precambrian is at 3,120 ft, and in the Gardner #1 Kidwell test, sec. 21, T. 6 N., R. 10 E., it is at 5,680 ft.

Thick shale beds in the overlying strata reduce the possibility of upward flow from Precambrian rocks toward the point of natural ground-water discharge in the center of the basin. Furthermore, the low permeability of the

Precambrian rocks that is measurable at and near the outcrops may be reduced even more where the overburden is a few ft to several thousand ft thick. Recharge to the basin by flow through more deeply buried Precambrian rock is therefore thought to be negligible.

Pennsylvanian

Rocks of Pennsylvanian age include the Sandia Formation and the Madera Limestone. The Sandia Formation consists of black shale, dark gray limestone, gray to brown sandstone, and occasional coal seams. The formation probably ranges from 10 ft to about 250 ft thick (Read and others, 1944; Kelley, 1963).

The Sandia Formation is not known to have been tested for ground water in this area owing to its great depth of burial and to the usual availability of at least small supplies of water from the overlying Madera Limestone. In discussions of hydrology, the Sandia Formation will be included with the Madera Limestone.

The Madera Limestone is conventionally divided into a lower Gray Mesa Member and upper Arkosic Limestone Member. The lower member consists of massive beds of cherty gray limestone with interbedded calcareous gray and black shale. The upper member, in contrast, has a much higher clastic content and consists of alternating light-gray cherty limestone, arkosic calcarenite, red or brown arkosic sandstone, and gray shale (Read and others, 1944; Anonymous, 1952, p. 107-108; Kottlowski, 1961, p. 101). In the Manzano and Sandia Mountains thicknesses of about 1,300 ft have been measured in outcrop (Read and others, 1944; Kelley, 1963). The upper member is 800 to 900 ft thick in the Manzano Mountains (Read and others, 1944), although near the crest several hundred feet have been removed by erosion.

The top of the Madera is mapped on the top of the highest marine limestone. The upper part of the Madera is transitional into the overlying Abo red bed sequence. In the transition zone, dark-red shale and sandstone predominate over the thin limestone beds. The transition zone is separated and named the Bursum Formation, of Permian (?) age, in the southern part of the Manzano Mountains. In Abo Pass (sec. 5, T. 2 N., R. 5 E.) the Bursum is about 120 ft thick (Wilpolt and others, 1946).

The Madera thickens eastward in the subsurface to a maximum of more than 3,000 ft in the structural trough under Estancia Valley. Kottlowski (1961, fig. 1) indicates a thickness of about 4,000 ft for Pennsylvanian rocks in the vicinity of the San Juan #2 Randall and the Gardner #1 Kidwell oil tests in secs. 20 and 21, T. 6 N., R. 10 E., and states (p. 101) that this may include 530 to 1,000 ft of Sandia Formation rocks. Eastward thickening of the sequence is the result of large contributions of clastic sediment from the positive area of the Pedernal uplift in the Pennsylvanian Period.

The Madera has the largest outcrop area of any pre-Tertiary formation in Estancia Valley, and its outcrops are mostly high on the west side of the valley where the greatest rainfall occurs. Its potential for collecting and transmitting recharge to the valley fill is great, hence its hydrologic characteristics will be considered in some detail.

Analysis of data collected by the author from 300 holes drilled for water in the Madera Limestone in the Manzano and Sandia Mountains indicates that within the upper 600 ft the permeability varies indirectly with depth. Dry holes versus producible wells in the formation were used to construct fig. 4, which shows the percentage of producible water wells (producible wells/total holes) plotted against the 100-ft depth intervals to which they were drilled. The depth of the piezometric surface was not considered, except that, to be included in the data, a dry hole had to extend at least 20 ft below the piezometric surface as measured in that hole or in nearby holes. The few holes that were excluded by this constraint did not reach the piezometric surface. Because the depth of the piezometric surface is less than 200 ft in all but a few local areas, and the drilling success ratio is highest in the 0 to 200-ft interval, this method of graph construction is valid. By definition, a dry hole is any well that was so described by its owner or driller, or, if production rates were available, any well that would not yield 150 gallons per day (about 0.1 gpm). Yields of as much as 0.25 to 0.5 gpm (360 to 720 gallons per day) were usually reported by owners or drillers, as these are significant, even if frequently inadequate, for domestic or stock supply. It is recognized that some

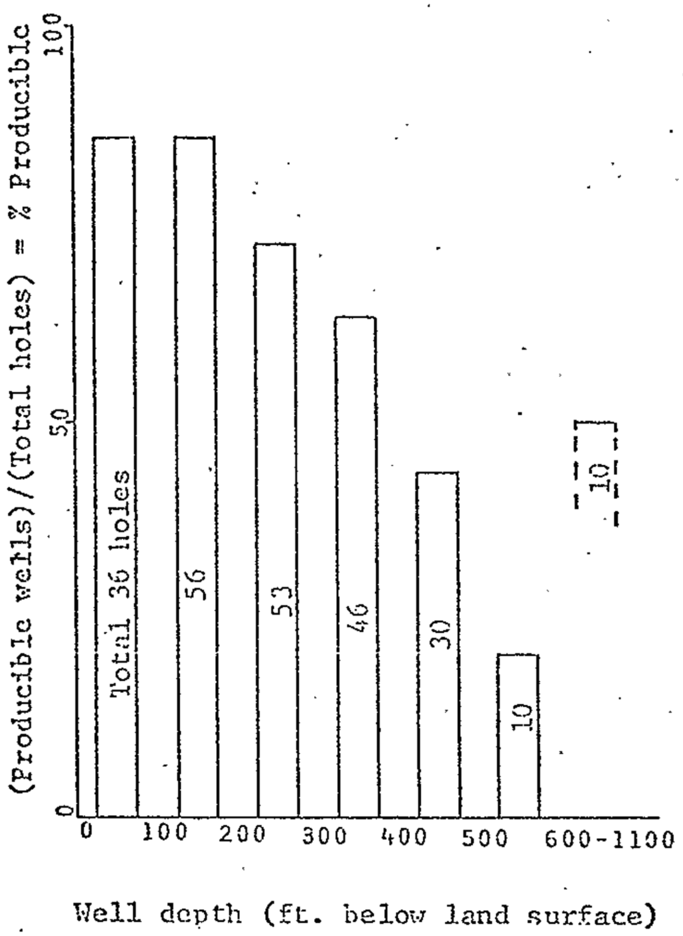


FIGURE 4 -- Graph showing percentage of producible water wells drilled in the Madera Formation, by depth. ("Producible well" yields > 0.1 gpm.)

reports of dry holes may not have been consistent with the bulk of the reported data, but the number of these is not thought to be large. A dry hole, by this definition, thus may have a water level that is representative of the piezometric surface at that point.

Fig. 4 shows an increase in the percentage of producible wells for those drilled deeper than 600 ft. The sample is small for the combined interval of 600 to 1,100 ft, but the results are thought to be significant. The 2 deepest wells were drilled to 1,100 ft in Tijeras Canyon, outside of the Estancia drainage area, by Ideal Cement Company. They are both in the E½ sec. 22, T. 10 N., R. 5 E. Water was encountered in both wells between 450 and 500 ft and between 800 and 1,000 ft. Drilling was continued below the shallower producing zone because the yield was not adequate for commercial use. They would have been considered producers, by definition here, in the 400-to-500-ft interval. Their location in a highly faulted area may make the permeability data atypical of the Madera generally. Even if these wells were not used, however, the success ratio for deeper wells would still be 38 percent. The other deep wells that were successful are all small producers. It may be concluded, therefore, that the deeper parts of the formation do have small but significant permeability.

The permeability and porosity exploited by shallow wells in the Madera is mostly the result of solution-enlarged fractures in limestone beds, and reports by drillers of water coming from "fractured rock," "brittle rock," and "caves" are common. Small solution channels in limestone beds of the Madera can be seen in road cuts; some of the best exposures are on NM-10 south of the village of Tijeras, and on I-40 several miles east of Tijeras. In these outcrops the solution features, which mostly parallel bedding planes, have maximum cross sectional dimensions of a few inches.

Few drillers report production of water from sandstone in the Madera, and the permeability of most sandstone and arkose beds seen in outcrop is low. Fracturing is as evident locally in sandstone beds as it is in limestones, but fracturing without subsequent enlargement of the openings by solution apparently does not produce significant permeability.

The position of the zone of greatest solution in limestone terrain has been the subject of many publications. Early investigators in the United States argued that principal solution took place in the vadose zone, that is, above the zone of ground-water saturation (Greene, 1909; and Beede, 1911). W. M. Davis (1930), in his classic paper on the origin of limestone caves, suggested that caves are excavated in the phreatic zone, that is, the zone of saturation. Many of the more recent publications (Piper, 1932; Swinnerton, 1932; and Davies, 1960) suggests that solution is most active in the shallow part of the phreatic zone.

Thrailkill, in a theoretical analysis of ground-water flow, temperature, and calcite-carbon dioxide concentrations, concludes that the effect of each of the three, "tends to produce more undersaturation [of calcite] in the upper part of the ground water body (shallow-phreatic zone) than in the deeper parts" (Thrailkill, 1968, p. 37). Hence, he reasons that greatest solution occurs near the top of the saturated zone. This is consistent with what is known of the hydrology of the Madera Limestone in the Sandia and Manzano Mountains, where it may be inferred that the small solution channels exposed in outcrops and indicated by wells have formed since uplift and tilting of the Manzano and Sandia fault blocks, and since overlying formations were stripped away. Permeability in the rock lying above the present water levels, therefore, probably developed at times of higher water levels which existed before canyons were cut to their present depth. The absence of large caves and of karst topography in most areas suggests that since exposure, water levels have not remained the same for long periods of time. The well-known Sandia Cave, a site of human occupancy in late Pleistocene time in the northern part of the Sandia Mountains (Hibben, 1941; Bryan, 1941), was probably formed much earlier, and under different structural and topographic conditions than the smaller, more typical solution features found in the limestone.

From the data presented in fig. 4 and from the presence of solution features in outcrops, it is concluded that the permeability of limestone beds in the Madera is greatest in the upper 200 ft of the formation, and that the permeability in this depth range is of reasonably even vertical distribution. Below 200 ft the permeability decreases with increasing depth. The average maximum depth of the present piezometric surface is about 200 ft. Obviously, during most of geologic time since the formation was uplifted and overlying formations removed, the level of the piezometric surface has fluctuated at and above its present position; therefore, as land surface has been reduced by erosion, net movement of the piezometric surface has been downward.

An anomalous highly permeable zone in the Madera Limestone has recently been recognized from pumping data by the author and, independently, by J. T. Everheart, geohydrologist in the State Engineer Office. Water wells that produce more than 100 gpm from the Madera are mostly restricted to TPs. 6 to 8 N., Rs. 7 and 8 E., and in this area yields greater than 1,000 gpm are not unusual (fig. 5). The proximity of the high-yield Madera wells to an area of carbon dioxide entrapment in the formation suggests a causative relationship between carbon dioxide and the permeability.

Whereas pure water can dissolve only small amounts of calcium carbonate, the solubility increases markedly when there is an abundant supply of H^+ ions. The dissociation of carbonic acid, H_2CO_3, is one of the most important sources of H^+. A series of schematic equations expressing the various reactions is:

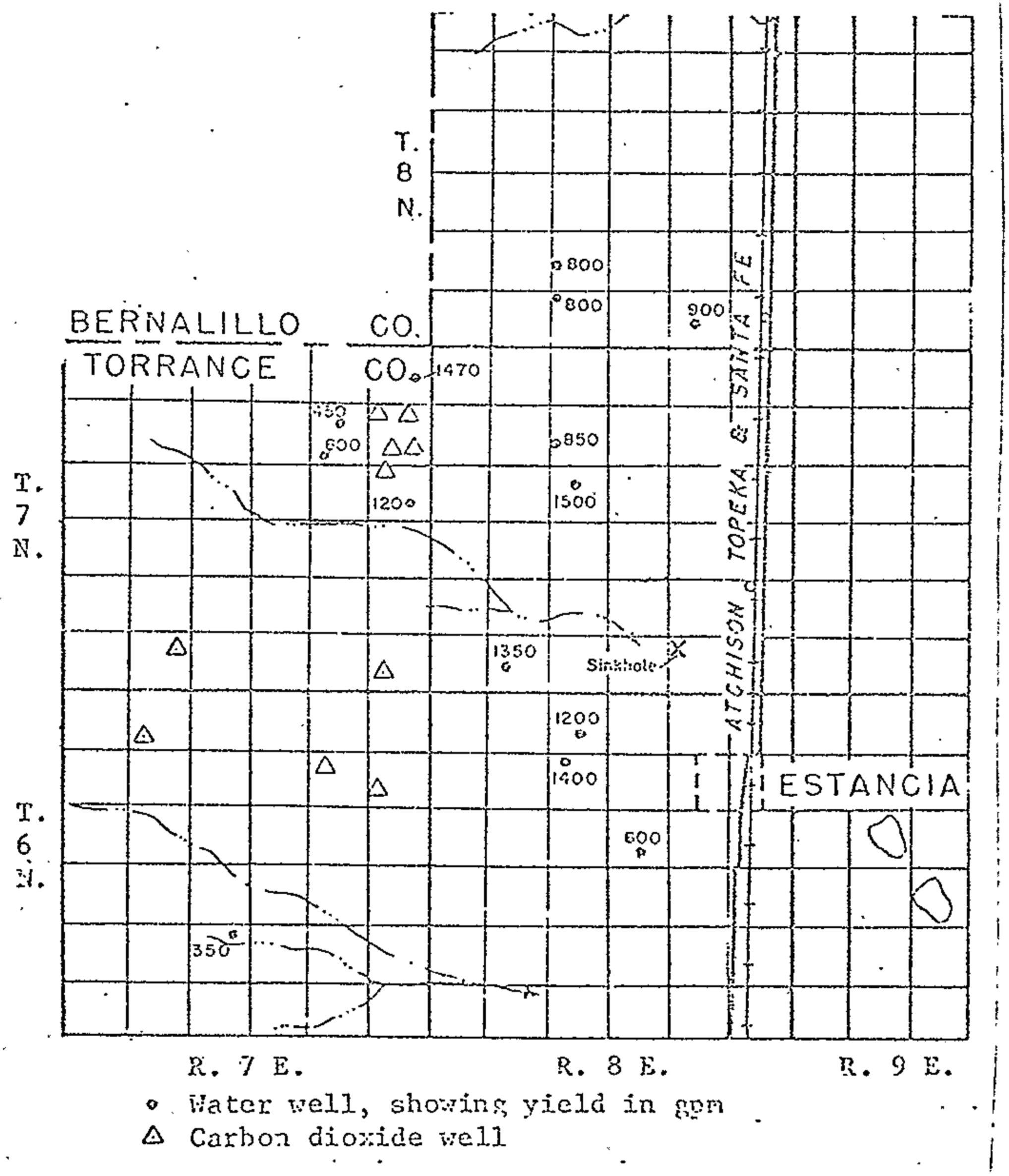


FIGURE 5 — Locations of high-yield water wells and carbon dioxide wells producing from the Madera Formation.

$$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^-$$

$$HCO_3^- = H^+ + CO_3^{--}$$

$$CaCO_3 + H^+ = Ca^{++} + HCO_3^-$$

If abundant carbon dioxide is present, the dissociation will proceed only as far as the bicarbonate stages. If the pH is increased, however, the ratio of carbonate (CO_3^{--}) to bicarbonate (HCO_3^-) ions increases and calcium carbonate will be precipitated. In most natural waters the amount of carbon dioxide in the system is the controlling factor, hence when carbon dioxide is added, solution continues; when it is removed, deposition will most likely occur (Davis and DeWiest, 1966, p. 102).

Talmadge and Andreas (1942, p. 7), reporting on carbon dioxide occurrence in New Mexico, tabulated data for 10 wells in the Estancia Valley field that bottomed between 1,000 and 2,000 ft. Most of the wells were drilled between 1928 and 1941, and there has been no known production since 1942. Two new wells, drilled in 1963 but unused since completion, are reported by the owner to be capable of large production.

Carbon dioxide leakage from the gas field is confirmed by high gas content in water pumped from many shallow wells, and it is not uncommon for gas to evolve from water that is caught in a container at the well head. The rate of leakage may have increased since the gas trap was exploited owing to improper well construction and inadequate sealing around casings. The direction of regional ground-water flow in the vicinity of the gas field is eastward, as is indicated by slope of the piezometric surface. Hence carbon dioxide dissolved in the ground water is swept in this direction, thus accounting for the location of the high-permeability zone east of the gas field.

J. T. Everheart (oral communication, 1968) has stated that in 1965 part of the surface of an irrigated field in the NW¼NW¼ sec. 35, T. 7 N., R. 8 E., 5 miles east of the gas field, collapsed leaving a depression 40 to 60 ft across and about 30 ft deep (fig. 5). The landowner filled the hole with trash and soil, and re-leveled the field for irrigation, but collapse occurred again at the same site when runoff from a heavy rainstorm flowed across the field. Pleistocene lake sediments mantle the surface at this location, but the collapse indicates that limestone in which solution has been active lies at shallow depth. The owner told Everheart that several irrigation wells in the immediate vicinity produce ground water from "caves" in limestone. In 1972 the sinkhole was being used for disposal of refuse which included lumber, automobiles and cattle carcasses.

Water wells producing from the high-permeability zone have tapped only the upper few hundred feet of the Madera. Whether similar permeability exists in the limestone at greater depth is not known, but it is reasonable to expect that it does. In most of the area of heavy pumping the Madera is overlain by saturated valley fill of variable thickness. Ground water is pumped from the limestone, but the limestone is probably immediately recharged by water from the alluvium. Thus, an unusually favorable well-hydraulics system is thought to exist, in which permeability is provided by large channels in the limestone, and porosity by the water-table conditions in the alluvium.

Permian

The Abo Formation, overlying the Madera, crops out in TPs. 4 and 5 N., Rs. 5 to 7 E., and in small areas in the northwestern part of the Estancia drainage basin. In the subsurface it is assumed to be coextensive with the Madera. Its subcrop beneath the valley fill adjoins on the east that of the Madera. Its outcrop and approximate subcrop pattern is shown on the geologic map (fig. 3).

The formation is a red-bed sequence, consisting mostly of dark-red shale with interbedded sandstone and arkose, that was deposited in a terrestrial environment. Needham and Bates (1943) measured a thickness of 810 ft in the type section in Abo Canyon, in the vicinity of T. 3 N., R. 6 E. Kelley (1963) reports a maximum of 950 ft cropping out in the Sandia Mountains outside the Estancia drainage. Electrical logs of the Murphree and Bond #1 Berkshire oil test in sec. 19, T. 6 N., R. 9 E. and the Superior #28-31 Blackwell test in sec. 31, T. 6 N., R. 11 E. indicate thicknesses of 950 to 1,000 ft in the subsurface in the central part of the valley.

Water wells drilled into the formation in Estancia Valley generally are dry holes or yield a few gallons per minute. An exception was a 82-ft municipal test hole for Mountainair drilled in 1938 in sec. 32, T. 5 N., R. 7 E. that yielded a reported 80 gpm, and had a specific capacity of 1.4 gpm/ft of drawdown after 24 hours of pumping (R. Smith, 1957, p. 117). In the vicinity of the village of Tijeras, T. 10 N., R. 5 E., outside of Estancia Valley, the Abo Formation yields sufficient water for domestic use from a highly faulted area. R. Smith (1957, p. 29) reports that the formation in Torrance County is "unsatisfactory as a source of enough water for irrigation and uncertain even for domestic or stock water."

The Abo Formation, because of its thick shales and low-productivity sandstones, is assumed to severely restrict flow of ground water across its bedding.

The Yeso Formation crops out over large areas on the east side of Estancia Valley, and the upper part crops out in the base of the scarp of Chupadera Mesa at the south end of the valley (fig. 3). Wilpolt and others (1946) describe the Yeso in the Chupadera Mesa area as follows:

> The Meseta Blanca sandstone member [at the base] of the Yeso Formation consists of uniformly bedded, red-brown and variegated sandstone and sandy shale. The thickness ranges from 104 to 222 feet. The Torres member comprises the bulk of the Yeso Formation. It consists of alternating beds of orange-red and buff sandstone and siltstone, gray limestone, and gypsum. The thickness ranges from 350 to 600 feet. The Canas gypsum member contains some thin gypsiferous siltstone and limestone but is

> chiefly white gypsum. It ranges in thickness up to 103 feet. The Joyita sandstone member consists entirely of orange-red, buff and yellow sandstone, silty sandstone, and siltstone, and ranges in thickness from 60 to 90 feet.

Near the base of the north-facing scarp of Chupadera Mesa in T. 3 N., R. 9 E. the upper part of the Canas Gypsum Member crops out as a single massive gypsum bed 20 to 30 ft thick. The lower part of the member is mostly covered, but scattered local exposures suggest an aggregate thickness of about 100 ft of gypsum.

The Yeso in the subsurface in the east-central part of Estancia Valley is more than 1,000 ft thick, as is shown by several oil test holes. The Gardner-Kidwell test in the SE¼SE¼SW¼ sec. 21, T. 6 N., R. 10 E., which is immediately east of the playa-depression field, penetrated the upper part of the Yeso beneath the valley fill, and drilled 1,020 ft of the formation before entering the Abo Formation at a depth of 1,280 ft. Drilling samples from this hole, on file at New Mexico Bureau of Mines & Mineral Resources, show that between depths of 500 and 830 ft the formation is predominantly gypsum. About 4 miles west of the playa-depression field, in sec. 19, T. 6 N., R. 9 E., the Murphree and Bond-Berkshire test penetrated only about 150 ft of sandstone in the lower part of the Yeso before entering the underlying Abo. The Yeso was beveled by erosion in the central part of Estancia Valley prior to deposition of the valley fill.

The formation decreases in gypsum content to the north, and limestone grades into sandstone (Bates and others, 1947, p. 32). In the Sandia Mountains, Kelley (1963) shows 70 to 150 ft of the Meseta Blanca Sandstone Member and 250 to 400 ft of the San Ysidro Member (equivalent to the Torres, Cañas, and Joyita Members at Chupadera Mesa). The San Ysidro Member in the Sandias consists of sandstone and cavernous limestone, and is only locally gypsiferous in the upper part (Kelley, 1963).

The Yeso Formation rests conformably on the Abo in the normal stratigraphic sequence, but it overlaps to lie directly on Precambrian rocks in the Pedernal uplift on the east side of Estancia Valley. Erosion has removed the upper part of the formation from outcrops south of the Pedernal Hills, and the maximum remaining thickness is a few hundred feet.

Permeability and porosity in the Yeso is mostly in sandstones, although some water wells produce from "fractured rock" or cavities in limestone beds. Of 145 wells tabulated by Smith (1957, table 14), all but a few produce less than 15 gpm (R. Smith, 1957, p. 32). Among the exceptions are two municipal wells for Mountainair in sec. 23, T. 4 N., R. 7 E., which were capable of yielding 500 and 460 gpm from cavities in limestone when drilled in 1944, but had declined to 240 and 133 gpm by 1956 (R. Smith, 1957, p. 31). Two irrigation wells in secs. 18 and 19, T. 7 N., R. 10 E., which R. Smith (1957, table 14) thought produced 2,000 to 3,000 gpm from the Yeso, are now believed to be bottomed in and to produce from the San Andres Formation.

The Glorieta sandstone, which overlies the Yeso Formation, is white to yellow, clean, and usually well sorted. It is generally thick bedded, cemented to moderately friable, and is in many places crossbedded. Small iron oxide concretions commonly are disseminated in the sandstone. The formation crops out in the central part of the east side of Estancia Valley and in the scarp of Chupadera Mesa at the south end of the valley (R.Smith, 1957, p. 33-35; Bates and others, 1947, p. 32-33). Smith reports 280 ft of Glorieta at the north end of Chupadera Mesa, and Read and others (1944) show 150 to 200 ft in the outcrop area east of Lobo Hill.

About 4 miles northeast of Moriarty the Glorieta crops out in 2 small hills that project through the valley fill (fig. 3). This pre-Tertiary bedrock high is probably due to faulting along the axis of the Lobo Hill uplift to the south. Well records in the State Engineer District Office in Albuquerque, and those tabulated by R. Smith (1957, table 14), show that the formation here is the most productive aquifer in the valley. One irrigation well in sec. 35, T. 10 N., R. 8 E. had a discharge measured by Smith at 3,040 gpm with only 6 ft of drawdown, and many wells in the area produce more than 1,000 gpm from the formation. Drillers' logs suggest that the high permeability is due to intense fracturing of the sandstone. In the area of the high-yield wells, the Glorieta is overlain by saturated valley fill which is thought to provide recharge to the aquifer during pumping.

The San Andres Formation consists of finely crystalline gray limestone with some gypsum and sandstone. The formation is 200 to 300 ft thick on Chupadera Mesa (Bates and others, 1947, p. 34) but thins northward to about 100 ft at the northeast rim of Estancia Valley (Read and others, 1944). R. Smith (1957, p. 35) reports 100 ft of the "limestone member" near Clines Corners, with the upper part of the unit having been removed by erosion. The San Andres is particularly susceptible to development of solution features, as is indicated by a complex karst topography that antedates the overlying Triassic rocks (R. Smith, 1957, p. 35) and by numerous sinkholes that have formed in present outcrops on the east side of Estancia Valley.

R. Smith (1957, p. 35, 36) concluded that the San Andres Formation in Torrance County was everywhere above the water table, and that no wells derived ground water from it. However, Northrup, in a detailed sample log on file at New Mexico Bureau of Mines & Mineral Resources, identified 224 ft of San Andres below a depth of 324 ft in the California-Minerman oil test in sec. 32, T. 7 N., R. 10 E. about 10 miles south of Lobo Hill. Drillers' logs from several water wells, such as 2 wells in sec. 19, T. 7 N., R. 10 E. (Appendix A), suggest that the San Andres here is separated from the base of the valley fill by up to 275 ft of Triassic rock. It is in secs. 18 and 19 of this township that 2 irrigation wells capable of yielding 2,000 to 3,000 gpm are thought to be completed in the San Andres rather than in the Yeso as concluded by Smith.

Triassic

Triassic rocks, undivided on the geologic map (fig. 3), include the Santa Rosa and the Chinle Formations. The Santa Rosa in the Sandia Mountains consists of up to 400 ft of sandstone and mudstone, and the Chinle consists of 1,500 to 2,000 ft of red to variegated mudstone and lenticular sandstone (Kelley, 1963). The rocks are above the water table in the outcrop area along the northeast rim of the valley. The lower part of the section crops out at the south end of the Lobo Hill upland, and extends southward as a narrow tongue beneath the valley fill for several miles. Triassic rocks are in contact with the base of the valley fill in the northern part of Estancia Valley, but the location of the subcrop is known in only a few places (fig. 3).

Jurassic and Cretaceous

Rocks of Jurassic and Cretaceous age do not crop out in the valley, but they are in contact with the base of the alluvium high on the slope at the north end of the basin. Insufficient data are available to map subcrop contacts between rocks of Triassic to Cretaceous age on fig. 3.

Structural Features of the Basin

The west side of Estancia Basin is bounded by the structurally uplifted and eastward-tilted block of the Manzano Mountains. On the northwest the structural boundary is marked by Precambrian rocks that crop out in a small area along the topographic rim in TPs. 11 and 12 N., R. 6 E. On the east, the bounding uplift is the Pedernal positive element which has been shown by Foster and Stipp (1961) to have Precambrian rocks at altitudes of more than 6,000 ft along nearly the entire length of the basin (fig. 6). The lowest point in the Precambrian ridge is nearly coincident with the topographic low point in the rim near Cedarvale at the southeast corner of the basin.

Configuration of the Precambrian surface at the north end of Estancia Valley suggests the possibility that ground water could leak from the basin and move northwestward through pre-Tertiary rocks toward the Rio Grande structural trough. The north end of the Estancia topographic basin overlies the Galisteo structural basin (fig. 6). Contours on the Precambrian surface at the northwest side of the Galisteo structural basin have been substantially modified on fig. 6 from those of Foster and Stipp (1961) to adjust the level of the surface to the inferred thickness of overlying Pennsylvanian-Tertiary strata. The effect of the modification is to show that the Galisteo structural basin opens westward toward the

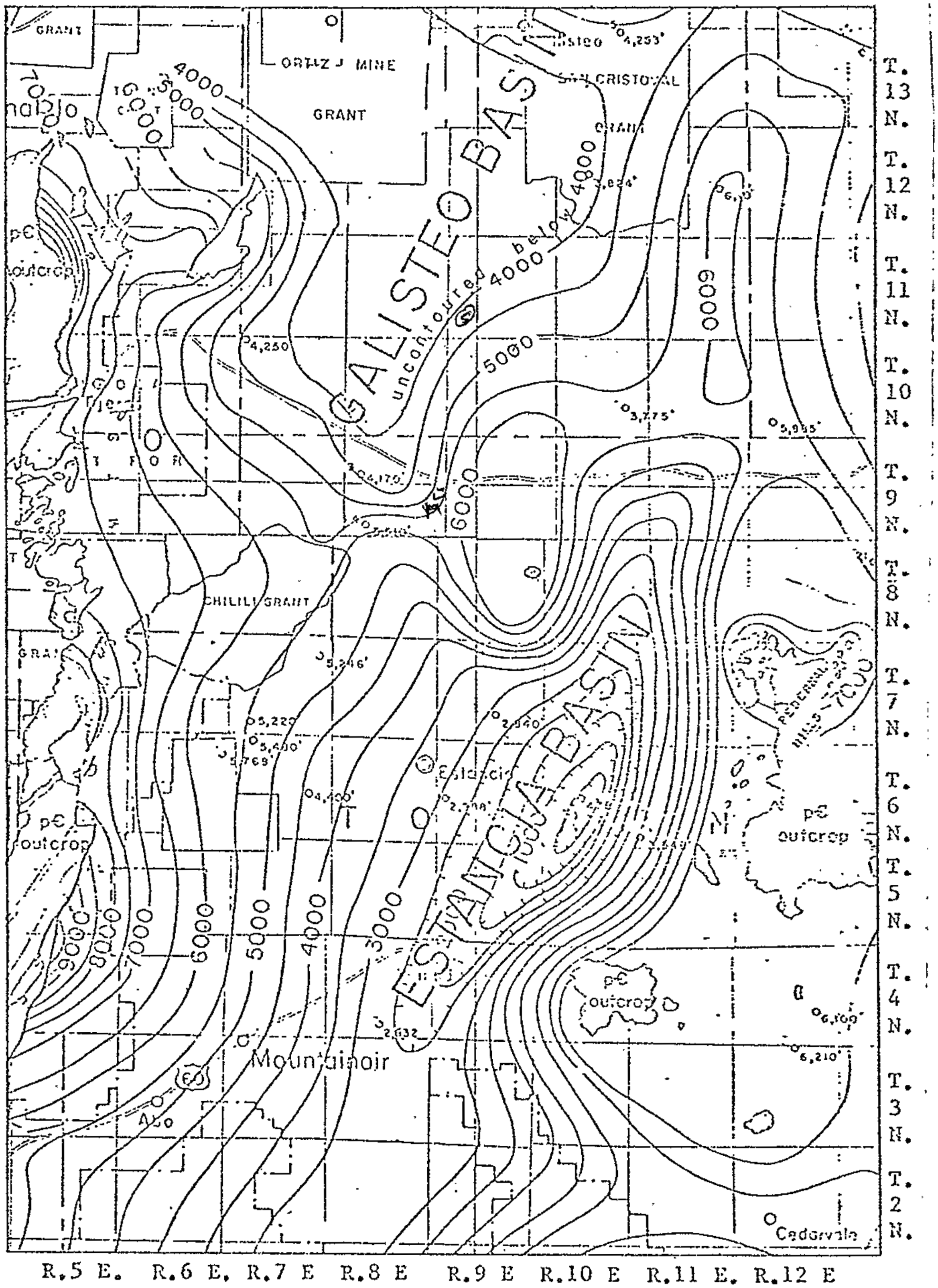


FIGURE 6 — Relief map of the Precambrian surface in the vicinity of Estancia Valley (modified from Foster and Stipp, 1961). (Contours and wells show elevation of surface).

Rio Grande structural trough. Consideration of land-surface elevation in Galisteo Creek north of Madrid (about 5,700 ft) and thickness of Paleozoic and Mesozoic strata underlying the land surface (estimated at more than 7,000 ft) indicates that the Precambrian surface here is below sea level. Similarly, the Precambrian floor of the Galisteo structural basin under the north end of Estancia Valley is concluded to be below sea level. From the south end of the Estancia Basin, the axis of the structural trough, as indicated by Foster and Stipp's contours, continues southward, with the Precambrian surface at an elevation of between 2,500 and 3,000 ft. The trough connects by way of the Claunch sag with the deep Sierra Blanca structural basin beyond the map area of fig. 6 (Kelley and Thompson, 1964).

The east side of the Estancia Basin has probably been faulted down against the west side of the Pedernal uplift. Darton suggested the presence of such a fault (1928, fig. 120), as did Read and others (1944). Kelley shows (1972, fig. 3) approximately 1,000 ft of downfaulting in the southeast part of the basin, and professes surprise (p. 37) that the displacement is this great. During collection of stratigraphic data on the Yeso where it underlies the valley fill, evidence was found that the Superior-Blackwell oil test in sec. 31, T. 6 N., R. 11 E. was drilled through a fault at a depth of 2,590 ft, where the hole passes from the Madera into Precambrian gneissic granite. Electrical logs and samples show that above the horizon at which the fault was encountered, the stratigraphic sequence in this hole is correlative with the sequence in the Murphree and Bond-Berkshire test 12 miles to the west, in sec. 19, T. 6 N., R. 9 E. At the fault the Superior hole passes through 10 to 15 ft of fault gouge (?) into the Precambrian, whereas the Murphree and Bond hole continues through about 650 ft of Madera before entering the Precambrian. No attempt was made to estimate true vertical displacement, but it is certainly more than the indicated minimum of 650 ft.

STRATIGRAPHY AND HYDROLOGIC PROPERTIES OF THE VALLEY FILL

The valley fill consists of 2 major units: an earlier alluvial unit, here named the Estancia Valley formation, that crops out on the sloping sides of the valley and is found in the subsurface in the central part of the valley; and a later lacustrine unit, here named the Dog Lake formation, consisting of upper and lower lacustrine members separated by a medial sand member, which crops out in the valley floor and in some places low on the valley sides (fig. 7). Alluvial facies of the lacustrine members can be recognized locally resting on the alluvium of the Estancia Valley formation in the bottoms of stream valleys. The largest outcrops are a few square miles in area. Because of difficulty in distinguishing between the younger and older alluvium, on the basis of either lithology or hydrology, all the alluvial sediment is included in the Estancia Valley formation. Recent dunes scattered over the surface of the Dog Lake formation in the south-central part of the valley floor, and thin modern sediment beneath playas in the same area are not considered part of either of the above-named formations, and they are discussed later, in the section on geology of the playa depressions and dunes.

In his description of the surficial unconsolidated sediment in Estancia Valley, R. Smith recognized 2 units. "Valley fill," Smith's older unit (1957, p. 38-39), is

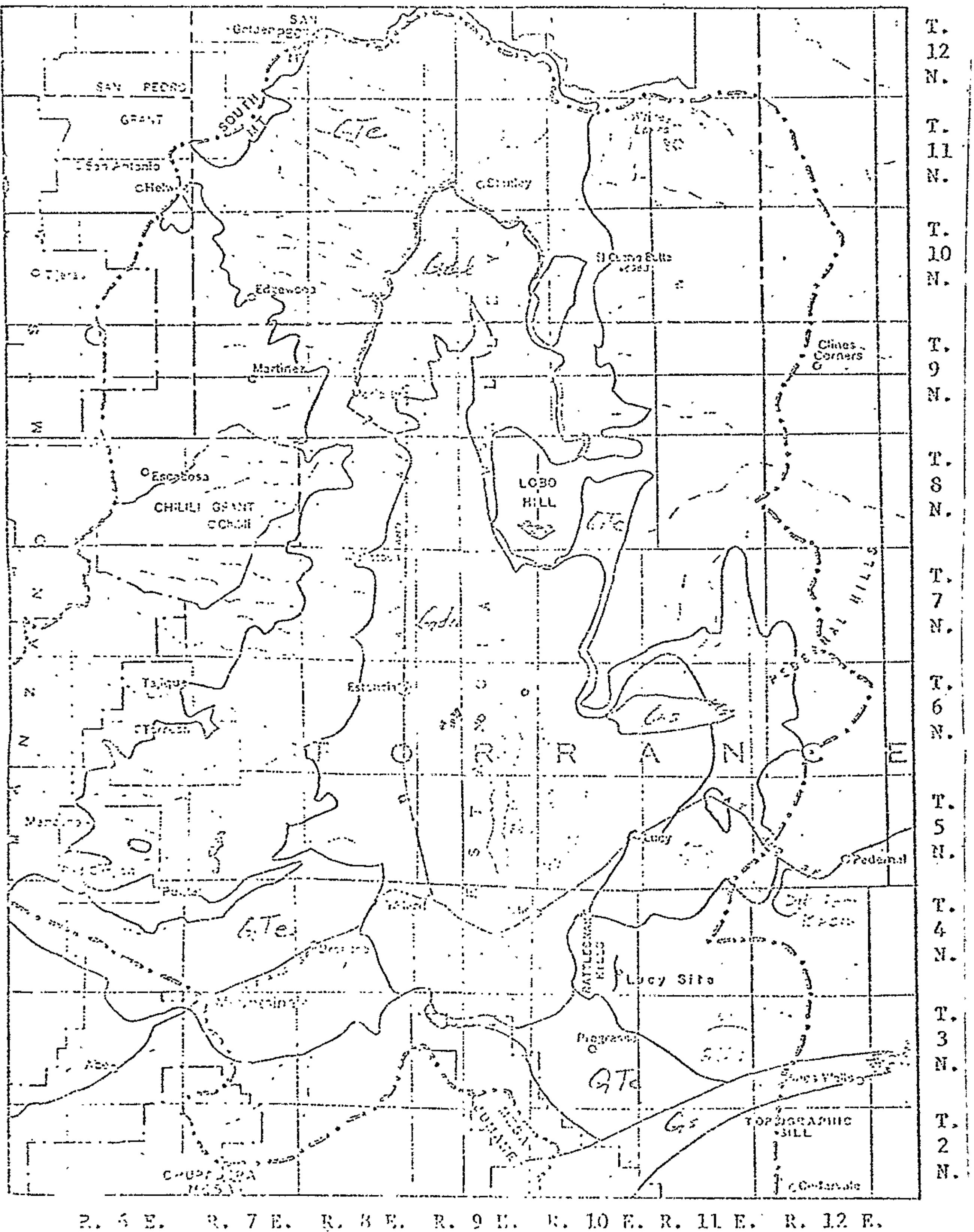


FIGURE 7 — Geologic map of the valley fill, showing outcrops and early Lake Estancia shoreline features.

identical with the Estancia Valley formation. It consists of "sand, gravel, silt, and clay" derived mainly from the uplands to the west and "deposited in a structural basin which formed as a result of mild downwarping related to late stages of the development of the adjacent Rio Grande trough." Smith correlated the valley fill with the upper beds of the Santa Fe Formation north of Galisteo Creek, and assigned them an age of late Pliocene(?) and Pleistocene. Smith's valley fill rests on the Paleozoic and Mesozoic bedrock and is overlain in part by his second unit, the "lake and dune depsits." Smith's lake and dune deposits include strata of the Dog Lake formation and also include the dune and playa sediments that are considered separately in this report. Smith described his units only very briefly; his emphasis was on availability of ground water and not on determination of the sequence of geologic and hydrologic events.

The Estancia Valley and Dog Lake formations of this report attain a combined thickness of more than 400 ft in a narrow zone along the axis of the valley (fig. 8). The sediment accumulated in the 2 broad subbasins forming the northern and southern parts of Estancia Valley and in the narrow section of the valley that connects the subbasins west of Lobo Hill.

Estancia Valley Formation

This alluvial formation has a thickness of from 300 ft to more than 400 ft along most of the axis of the valley.

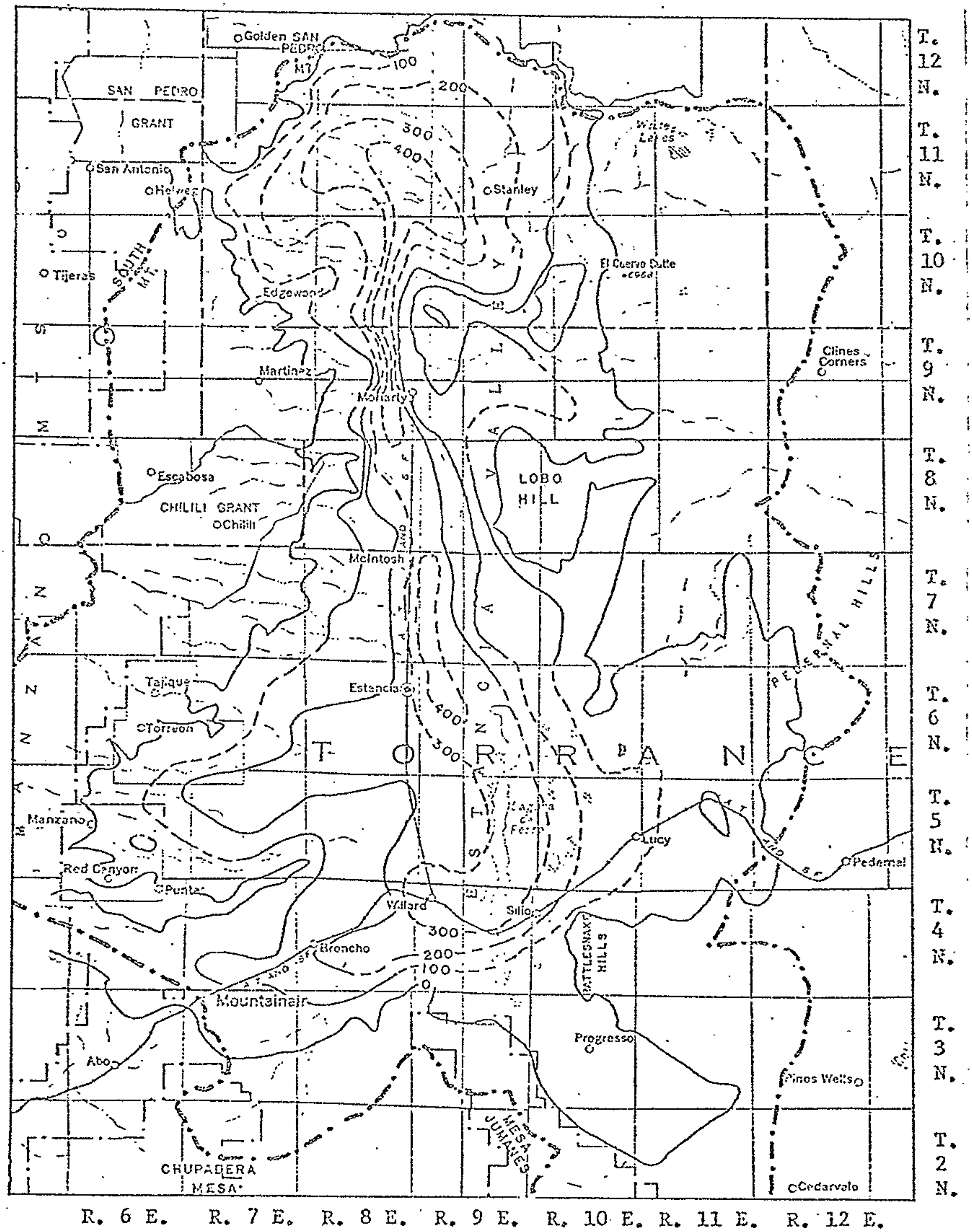


FIGURE 8 — Map showing thickness of the valley fill (modified from New Mexico State Engineer Office, 1965).

In a test hole drilled for this and other projects, 270 ft of alluvium was penetrated at a location in the SE¼SE¼NW¼ sec. 22, T. 6 N., R. 9 E. Here the formation is overlain by 104 ft of the Dog Lake formation (see sample logs in Appendix B). The formation is more than 400 ft thick in the central part of the north subbasin (fig. 8); it thins with increasing distance from the axis of the basin and terminates in an irregular feather edge, which lies mostly below an elevation of 6,800 ft. The upper surface of the alluvium is strongly dissected by stream erosion in most places on the sides of the valley.

On the west side and at the north end of the basin the Estancia Valley formation crops out in a band 3 to 10 miles wide that separates outcrops of pre-Tertiary rock from those of the Dog Lake formation. On the east side and at the south end, in contrast, the outcrop width is highly variable with Dog Lake lacustrine sediment in places overlapping pre-Tertiary rock (fig. 7). The slope into the basin is generally steeper and much less regular in these areas than elsewhere on the basin sides, [and the alluvium was deposited on a dissected surface by subsequent streams.]

A type section for the formation is not proposed among the outcrops owing to the variability of the stratigraphy. One drill hole in the central part of the valley that completely penetrates the section is described later; other drill holes supplement the stratigraphic data.

These will serve to describe a standard section for the formation.

Stratigraphy

Alluvium of the Estancia Valley formation consists in outcrops of reddish-brown to tan silt and sand, interbedded with gravel. Clay beds are rare, but clay is a common constituent of silt and sand beds. There is a marked tendency for gravel to be coarse at high levels on the slopes, and to be finer toward the center of the basin. However, gravel of cobble size is not uncommon well down the slopes. Silt and silty sand beds constitute more than 80 percent of the exposed sediment in most locations. Most sand and gravel strata are thin bedded, and in most localities are crossbedded. Cut-and-fill structure and lenticular bedding is found in nearly all outcrops. Without exception, observed bedding planes dip toward the center of the basin. In most places the dip is not parallel to the present slope of the land surface, although it is usually close.

Alluvium of the formation varies lithologically from place to place in the basin depending upon the source rocks for the sediment. Gravel in outcrops on the west side of the valley is composed predominantly of limestone eroded from the Madera, and sandstone fragments from the Madera and the Abo Formations are lesser constituents. Toward the south end of the basin, fragments of red sandstone, arkose, and some buff to pink limestone derived from the Abo or uppermost part of the Madera, are common. Farther to the south, between Mountainair and Willard, sandstone fragments from the Yeso and Glorieta Formations, and limestone fragments from the San Andres Formation are recognizable.

Gravels in the southeastern part of the basin consist of Precambrian rock and of sandstone and limestone from the Yeso, Glorieta, and San Andres Formations. In the vicinity of Lobo Hill the alluvium contains fragments of white quartzite from Precambrian rock forming that hill. North of I-40, limestone and sandstone derived from nearby outcrops of the Glorieta, San Andres, and the Triassic rocks make up the gravel.

The composition of gravel in the formation at the north end of Estancia Valley differs from that anywhere else in the basin; monzonite porphyry predominates over other types of rock. In sec. 23, T. 12 N., R. 9 E., where NM-41 crosses the north rim of the basin, cobble gravel of this type constitutes more than 50 percent of the alluvium. The Estancia Valley formation, which here rests on a gently southward-dipping surface cut on the Mancos Formation, is about 160 ft thick at the basin rim where erosion has truncated the northward-thinning alluvial wedge. The coarseness and composition of the gravel, and the high proportion of gravel to finer sediment suggest that the source terrane comprised nearby small outcrops of Tertiary intrusive rock, which are compositionally similar to larger outcrops in South Mountain and San Pedro Mountain that have been described by Atkinson (1961).

Tertiary intrusives of lithology similar to that of cobbles in the gravel crop out on Cerro Pelon, a large rounded hill about 5 miles northwest of the Estancia Valley rim, and in small areas between Cerro Pelon and San Pedro Mountain. Cerro Pelon is the most likely source area for the gravel on the rim in the south half of T. 12 N., R. 9 E. Drainage in the vicinity of Cerro Pelon is now northward toward Galisteo Creek, but if the intrusive rock in that hill was the source of the gravel, the topographic divide has been moved at least 5 miles southward by headward erosion of the Galisteo Creek tributaries.

The elevation at the rim is now about 6,700 ft, and the highest peak of Cerro Pelon is below 6,900 ft. Projection of the dip of bedding planes at the rim toward Cerro Pelon suggests that erosion has reduced the height of the hill by several hundred feet since the time that it is presumed to have contributed gravel to the Estancia Valley formation. The circumstances suggest that deposition of the gravel on the rim took place at an early geologic time relative to the age of other features in Estancia Valley. Stearns (1953, fig. 9) concluded that the area now drained by the upper reaches of Galisteo Creek probably was, in middle and late Santa Fe time, part of Estancia Valley drainage. Thus, the correlation of the base of the alluvium with late Pliocene(?) Santa Fe sediment to the north, as made by Smith, appears to be reasonable (R. Smith, 1957, p. 38-39).

Caliche, common in outcrops of the alluvium but not universally present, is usually found around the north end of the basin only above an elevation of about 6,300 ft. Here it is moderately to well developed. On most slopes of the west side of the basin caliche is thin to absent. West of Willard, however, where the formation crops out in bluffs 100 ft high overlooking the valley floor, caliche thicknesses of up to 20 ft are exposed in the bluffs and in railroad cuts. Two to five ft of well-developed caliche forms a resistant cap that in this area has partially protected a high-level surface on the alluvium from destruction by erosion.

Caliche is also well developed in the alluvium on the east side of the basin in TPs. 7 to 9 N., R. 10 E., where outcrops exposing more than 10 to 20 ft are common. In the NW¼ sec. 19, T. 9 N., R. 10 E., J. T. Everheart (oral communication, 1968) has observed more than 15 ft in a pit dug by a local resident. Southeast of Lucy, in the southwestern part of T. 5 N., R. 11 E., a resistant caliche zone of similar thickness crops out high on the sides of stream valleys cut into the alluvium.

The well-developed caliche in the upper zone of the alluvial formation at the locations described is thought to have formed under a relatively stable land surface, possibly during a single period of calichification. Estensive dissection of the surface will later be shown to have taken place before the lacustrine phase of basin history. The possibility exists that the preserved surface is in some places only slightly below the highest depositional surface of the Estancia Valley formation. The evidence, although suggestive, is not conclusive.

Younger alluvium, in actuality a facies of the lacustrine Dog Lake formation, covers the floors of arroyos that drain the sides of the valley. Tributaries to the south subbasin tend to be integrated with a few master streams, and here the lower reaches of the valleys and the outcrops of younger alluvium are in some places more than a mile wide. Lithologically, the younger alluvium is indistinguishable from the older material on which it rests, except that nowhere does it have caliche developed in it. Material forming the younger unit was derived from the older unit and from the same pre-Tertiary rocks that contributed sediment to the older unit. For this reason, the overlying alluvium is included in the Estancia Valley formation in spite of its younger age. The younger alluvium, although occasionally cut by minor channel erosion in the arroyos, generally is not incised. Its upper surface is nearly everywhere one of deposition, whereas the surface of the older material is erosional in most places.

In the central part of Estancia Valley, the Estancia Valley formation is covered by the lacustrine sediment of the Dog Lake formation (fig. 7). An attempt was made to extract stratigraphic information about the Estancia Valley formation from drillers' logs on file with the

State Engineer Office and the U.S. Geological Survey, but most logs proved too generalized to be of use. The most reliable data were obtained from test holes drilled by personnel of New Mexico Institute of Mining and Technology, for this and other related projects. All the test holes are in T. 6 N., R. 9 E., east of the town of Estancia, except for 1 shallow test 6 miles south of Estancia.

Four deep and six shallow test holes were drilled for the project. The locations and depths of which are as follows:

Location (sec., T., R.)	Depth (ft)	Name
NE¼NW¼SW¼ 12 - 6N - 9E	133	Means #1
SW¼SW¼SW¼ 16 - 6N - 9E	360	School Section #1
same	42	School Section #1-A (shallow offset to #1)
NE¼NE¼SE¼ 20 - 6N - 9E	38	Berkshire #3
SE¼SE¼NE¼ 20 - 6N - 9E	59	Berkshire #4
SE¼SE¼NW¼ 20 - 6N - 9E	355	Berkshire #2
same	42	Berkshire #2-A (shallow offset to #2)
SE¼SE¼NW¼ 22 - 6N - 9E	390	Berkshire #1
same	45	Berkshire #1-A (shallow offset to #1)
NW¼SE¼NW¼ 12 - 5N - 8E	55	Reinauer #1

Only the 4 deeper holes passed through the Dog Lake formation and reached the alluvium of the Estancia Valley formation, and only the Berkshire #1 test reached the base of that formation. Sample logs for the 4 deep tests are included in Appendix B, and locations of all holes are shown on figs. 7 and 9. When the Reinauer test at the southwesternmost location was started, the intention was to drill to the base of the valley fill, but equipment difficulties and poor weather conditions forced the abandonment of the hole. All holes were drilled as multipurpose tests, and were completed to allow aquifer tests in them as part of a related project. The stratigraphic relationships determined during drilling are reported here.

The deeper holes are open below depths of about 70 to 100 ft, but are cased above, with the casing cemented in place. Casing was necessary to prevent collapse in a shallow sand zone (the medial sand member of the Dog Lake formation), and more importantly, to keep salty water in the shallow sand from circulating into the underlying Estancia Valley formation, which contains better quality water. Electrical, radiation, and caliper logs were run in Berkshire holes #1 and #2 and the School Section #1 by J. D. Hudson of the U.S. Geological Survey, but the logs are incomplete owing to collapse in the lower parts of some holes and to the necessity of installing the casing before logging. Correlation of strata in the Estancia Valley formation from hole to hole is tenuous because the unit varies laterally within short distances in the subsurface just as it does in outcrop. Some general characteristics could be correlated, aided by use of the logs.

The alluvial formation in the area drilled is overlain by about 105 ft of mostly clayey sediment of the Dog Lake formation. Clay in the alluvium is easily distinguished from the overlying lake clay by color. The alluvial clay is brown to reddish brown, becoming red in the lower part of the section, and is usually sandy and silty in contract to the cleaner lake clays. Gypsum, common in parts of the lake clay, is not a component of the alluvial clay.

It is extremely difficult to distinguish between basal Estancia Valley alluvium and the uppermost strata of the Yeso from drill-hole information. The lower part of the alluvium consists of red silt and clay interbedded with sand and very fine gravel, and the strata are partially cemented, appearing during drilling to be much like sandstone in the Yeso. During drilling, it was concluded that each of the 3 holes drilled below 350 ft had penetrated the Yeso, but later evaluation of samples in the laboratory showed that only the deepest hole, Berkshire #1 drilled to 390 ft, had actually done so. The red clay and silt near the base of the Estancia Valley formtion were probably derived largely from the Yeso subcrop (fig. 3). Similar material may also have come from the Abo and upper part of the Madera, both at that time cropping out to the west.

Small, broken pieces of thin gastropod shells, one of which included the axis of coiling, were collected from cuttings of red silty clay from 352 to 374 ft in the Berkshire #1 test hole. A silt-filled seed pod, measuring about 2 mm by 3 mm, was found embedded in clay cuttings from the 360-ft to 362-ft interval. Dr. C. L. Balk inspected the fossils and confirmed the interpretation that their presence indicated valley fill. The Berkshire #2 hole also had gastropod fragments near the bottom. In Berkshire #1, the Yeso was penetrated at 374 ft; that formation consists here of red, silty, sandy clay, and gray sandstone, with minor amounts of pale green clay. White gypsum was encountered near 390 ft, the bottom of the hole.

In the Berkshire #1 and Berkshire #2 holes a 10-ft bed of tan limestone was found at 342 and 330 ft, respectively (Appendix B). The limestone is silty and clayey, and appeared during drilling to be interbedded with or to contain coarse sand and possibly red or gray clay. The limestone is either a well-developed caliche, or a fresh-water limestone. The limestone chips showed no sign of fossils; the snail fragments were present in the coarse sand fraction of the cuttings. This limestone bed did not show the typical limestone character on electrical logs, inasmuch as the resistivity indicated on the logs is not much greater than that of sand or gravel beds higher in the holes. The spontaneous-potential curve had a marked deflection to the left, similar in magnitude to that of the higher sands and gravels. High relative permeability of the limestone stratum, suggested by the spontaneous potential, is verified by the fact that in the Berkshire #1 hole, drilling fluid was continually lost from the hole after the limestone was penetrated.

Caliche is common in the buried alluvium of the Estancia Valley formation, occurring both as nodules disseminated in clay and sand strata and as beds several feet thick. The Means #1 hole bottomed 2 ft into a well developed caliche bed at 133 ft. In Berkshire #2 a 7-ft caliche section, from 128 to 135 ft, correlates with that in the Means hole. This caliche was not encountered in the Berkshire #1 or School Section #1 holes, although in both of these the horizon, lying at the top of 50 ft of sand and red clay, could be recognized from correlation with Berkshire #2. Caliche was also found at depths of 181 to 184, and 209 to 218 ft in Berkshire #2. This interval in Berkshire #1 consists of fine to very fine sandy gravel that is variably cemented by calcium carbonate.

Jupe Means, rancher and landowner in this part of the valley, has drilled several water wells, each of which has encountered a caliche zone between 100 and 120 ft in depth. His irrigation well in NW¼NW¼SW¼ sec. 1, T. 6 N., R. 9 E., about a mile north of the Means #1 test hole, bottomed at 117 ft after penetrating 11 ft of nodular caliche. According to Means (oral communication, 1966), the well will yield 3,000 gpm with 33 ft of drawdown, making it one of the more productive wells in the older alluvium. Means' well in the NE¼NW¼NW¼ sec. 7, T. 6 N., R. 9 E., also reportedly penetrated caliche at about 110 ft.

Gravel was found in cuttings from all the deep drilling tests. It was most common in the Berkshire #1 test hole, and least common in the School Section #1 hole. All gravel recovered during drilling was fine, the maximum size being granules. Whereas coarser materials was recovered from the drill holes and is frequently reported by water-well drillers in other holes, our experiences suggests that the coarser material is usually nodular caliche. The granule gravel is mostly quartzose but commonly contains minor amounts of pink feldspar. Gravel beds could not be correlated from hole to hole, but there is a marked tendency for gravel to occur between about 175 and 200 ft, and between about 300 and 350 ft.

Because of fineness of the gravel, specific source areas for sediment in the central part of the basin could not be identified. Where fresh feldspar grains are present, however, an Abo or uppermost Madera source is suggested. The alluvium contains no material that can be interpreted as autochthonous except for caliche and the limestone in the lower part of the section that has either a caliche or a fresh-water lacustrine origin.

Environment of Accumulation — A Through-flowing River

The alluvial unit is interpreted as having accumulated in a slowly subsiding basin under subaerial conditions while the valley was drained by a through-flowing river. Geomorphic evidence for a southward-flowing river that turned eastward at the south end of the valley is presented later. The red color of clay and silt indicates that, unlike the overlying lacustrine clayey strata of the Dog Lake formation, the sediment was not subjected to strongly reducing conditions that would have altered the color inherited from source rocks. Horizontal variations of strata in the subsurface, and the presence of coarse sand and fine gravel, support the conclusion that the sediment was deposited in an alluvial environment.

The lack of coarse gravel in the sediment of the central part of the valley, at least in the limited area of the test holes, implies that the rate of subsidence of the basin floor approximated the rate of sediment accumulation. If subsidence at any stage had been rapid and the amount great, coarse gravel probably would have been transported to the center of the basin. Furthermore, rapid subsidence would have closed the basin topographically, causing ponding and formation of a lake. Such may have been the situation for a short time early in the history of the basin, provided that the 10-ft limestone bed at a depth of about 340 ft, and the snail shells, can be interpreted as evidence of temporary lacustrine conditions. The existence of caliche at various depths indicates that contemporary surfaces were stable long enough to allow soil processes to from caliche.

Slow subsidence probably was accompanied by intermittent faulting along the east side of the valley. The west faces of Lobo Hill, the samll hills of outcropping Glorieta north of Moriarty, and the hill in which the

Glorieta crops out 10 miles east of the town of Estancia, may be remnants of fault scarps in the central part of the east side of the valley (fig. 3). The Rattlesnake Hills composed of Precambrian rock, in T. 4 N., R. 10 E., may also indicate the presence of a fault. The implication that displacement occurred along a single fault line is not intended. The nature of the faulting, and also the location, is inferred; direct evidence related to faulting was found only in the Superior-Blackwell oil test (Sec.31, T. 6 N., R. 11 E.) at a depth of 2,590 ft, as described earlier (p. 39). If the hills mentioned are indications of nearby faulting, the scarps have been severely eroded since faulting took place.

Age

R. Smith's (1957, p. 38-39) correlation of the alluvial unit with the upper part of the Santa Fe formation to the north, thus giving it a late Pliocene(?) to Pleistocene age, has already been noted. Myers (1967) mapped 3 small remnants of pebble to boulder gravel, which he called pediment deposits, on the tops of hills near the town of Manzano in T. 5 N., R. 6 E. The outcrops now stand 100 to 250 ft above the present stream valleys, and the gravel rests on both Abo and Madera formations. J. T. Everheart (oral communication, 1968) has found outcrops of similar gravel in Sec. 15, T. 6 N., R. 7 E.

Myers assigned the pediment material a Quaternary age; however, in this report it is considered to be correlative with the Pliocene Ogallala gravel and caliche mapped by Darton (1928) on the east side of the Pedernal Hills, and extended by Fallis (1958, p. 29) to include scattered, dissected remnants on the west side of the Pedernals. Bretz and Horberg (1949, p. 482), in a discussion of the Ogallala Formation west of the Llano Estacado, supported the correlation of the Pedernal gravels and caliche, and other similar outcrops along U.S.-60 west of Vaughn, with the Pliocene Ogallala.

Kelley (1972), after mapping the extensive deposits of Ogallala and the associated pediment deposits in the vicinity of the Pedernal Uplift bounding the east side of Estancia Valley, concluded that the Estancia Valley probably did not exist in Ogallala time. He envisions a great sloping plain extending from the Manzano and Sandia Mountains eastward to the present Llano Estacado, with only a few hills, including the Pedernals, standing above it. If such is the case, then the pediment gravels topping hills at the foot of the Manzano Mountains and the Ogallala remnants on the west side of the Pedernal Hills must have correlative pediment strata at the base of the Estancia Valley formation deep in the present basin.

The time of initiation of valley subsidence may have been either late in Ogallala time or possibly somewhat after that. Subsidence of the valley that allowed accumulation of the Estancia Valley formation probably was accompanied by renewed uplift of the Manzano Mountains on the west, as is suggested by the erosion that has left pediment gravels in the Manzanos high above present stream levels. As erosion of the valley sides proceeded, much of the sediment was deposited in the subsiding valley but some material was removed from the valley by the through-flowing river. Kelley (1972, p. 48) refers to gravel deposits west of Vaughn that are "tilted into the sag against the Vaughn Fault, "and to other gravel deposits south of Vaughn on the Vaughn Ridge. These deposits are along the proposed route of the river that discharged from the Estancia area during and after accumulation of the Estancia Valley formation. Kelley is reluctant to conclude that the gravels were deposited as late as the time that lakes filled the Estancia Basin in Wisconsinan time. I concur and suggest that a more reasonable time of origin for the gravels is during earlier Pleistocene time, while the Estancia Valley formation was being deposited in the subsiding Estancia Basin.

This chronology is consistent with the interpretation that the ancient Estancia River constituted the headwater drainage of the river that cut, then filled back, the Portales buried valley on the Llano Estacado 80 miles to the east. The Estancia drainage area is larger than any other that can be proposed for the Portales valley, and the locations of the 2 valley segments are such that connection is reasonable. Furthermore, no other channel across the Llano Estacado of sufficient size to fit the inferred size of Estancia River can be found south of the Portales valley.

Total volume of the Estancia Valley formation is estimated to be 5 x 10^{12} cubic ft (34 cubic miles). In a basin of 2,000 square miles, erosion of 90 ft over the whole area of the basin would produce the estimated sediment volume, assuming that the density of the second generation sediment is the same as that of the source rock.

If it is assumed that erosion occurred in only two-thirds of the area, then average erision of 135 ft is required to produce the valley fill. Greatest erosion would of course occur high on the slopes and lesser amounts on lower slopes. Because the amount of material that was removed from the basin by the river cannot be estimated, the depth of erosion calculated above is a minimum. It is significant that the calculated minimum depth of erosion is of the same order of magnitude, but somewhat less than, the amount of local erosion that has taken place since the deposition of the probable Pliocene pediment gravels in the vicinity of the town of Manzano.

Irrigation Wells Pumping from Alluvium

R. Smith (1957, table 14) lists more than 30 irrigation wells in Estancia Valley that yield more than 1,000 gpm from the alluvium. Since the time of Smith's field work, the number of wells has increased substantially. A few yields of more than 2,300 gpm have been measured, such as from a well in the NW¼NW¼SW¼ sec. 17, T. 5 N., R. 8 E. (R. Smith, 1957, p. 120). Specific capacities, where data are available for their calculation, generally range between

20 and 80 gallons per minute per foot of drawdown in wells that are known to be producing from the Estancia Valley formation. The highest specific capacity is from a well in the SE¼NE¼SE¼ sec. 8, T. 5 N., R. 8 E. which produced 1,360 gpm with a drawdown of 17 ft (R. Smith, 1957, p.118).

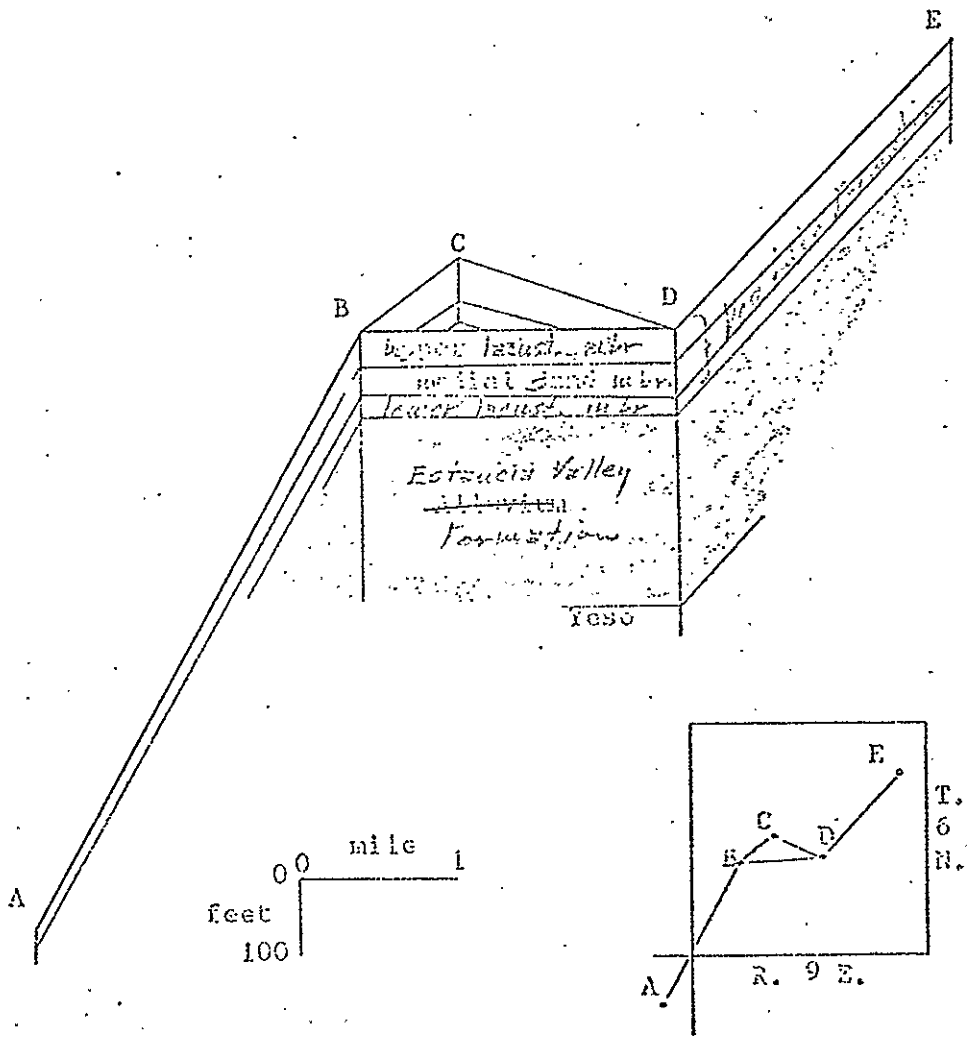
R. Smith (1957, p. 131) lists 6 irrigation wells in sec. 3, T. 7 N., R. 8 E., which have yields of up to 1,400 gpm, and which he interpreted as producing from the valley fill. Specific capacities, which can be calculated for 2 of the wells, are 312 and 375 gpm per ft of drawdown. Specific capacities in this range have been measured in wells drilled through the alluvium and into the Madera, and which are known to produce primarily from the Madera (fig. 5). Such wells tap an anomalously permeable part of the Madera, as has been previously mentioned. It is likely that the 6 wells in sec. 3 are pumping mainly from the Madera, but discharging both the Madera and the alluvial aquifers.

The distribution of water wells that produce from the valley fill are controlled by 3 factors: chemical quality of the ground water, saturated thickness, and availability in the saturated zone of significant thicknesses of gravel beds. These factors have resulted in concentration of irrigation wells on the west side and at the north and south ends of the valley. The chemical quality of water is probably the most important of the three factors (R. Smith, 1957, p. 60).

Dog Lake Formation

This lacustrine formation, here named the Dog Lake after the large playa depression in which its upper member crops out extensively, has a thickness of slightly more than 100 ft in the central part of Estancia Valley. The formation stratigraphically overlies the alluvial Estancia Valley formation and consists of a lower clayey lacustrine member, a medial sand member, and an upper clayey lacustrine member. Each of the lacustrine clayey members is surrounded by a lacustrine coarse-clastic facies. The 3 members of the formation have been distinguished only in the central part of the valley where the lacustrine strata consist predominantly of clay. The top 20 to 40 ft of the upper member is exposed in the walls of the numerous playa depressions in the central part of the southern subbasin. The lower and medial members and the basal part of the upper member are described from drill-hole information obtained from test drilling. The outcrop area of the unit is shown on fig. 7, and the general stratigraphic relationships are shown on fig. 9.

The Pleistocene succession of geologic and hydrologic events is described later, but it is important to mention here that lake flooding of the valley became possible only after subsidence of the basin floor closed the valley topographically. Subsidence of nearly 400 ft is indicated by the present difference in elevation between the base of the Dog Lake formation and the topographic sill on the



A Reinauer #1 test hole
B Berkshire #2 test hole
C School Section #1 test hole
D Berkshire #1 test hole
E Means #1 test hole

FIGURE 9 — Fence diagram of test holes drilled in T. 6 N., R. 9 E.

southeast, through which the prelacustrine river drained the valley. Presumably the subsidence resulted mainly from downwarping of the broad valley but probably was accompanied by renewed faulting, especially along the west sides of Lobo Hill and the Rattlesnake Hills.

Stratigraphy

The 4 deep test holes in T. 6 N., R. 9 E. were drilled through the Dog Lake formation, and the 6 shallow test holes, 3 of which are paired with deep holes, were drilled to the medial sand member of the formation to be used for aquifer tests. Only the deeper holes, therefore, could be used for stratigraphic information about the lower lacustrine member; the shallow holes provided additional information about the medial sand and the upper lacustrine member. Drillers' logs from privately owned water wells proved useful in determining the extent and depth of the formation. It was found from the study of nearly 90 logs in Tps. 4-8 N., Rs. 8-9 E. that, in the upper parts of the wells where the strata include clay beds of the Dog Lake formation, approximate correlation is frequently possible with the test holes. The thickness of the formation in the central part of the valley is about 100 ft; in the test holes it ranged from 98 to 105 ft.

The base of the lower lacustrine member rests in most places on a caliche zone that is up to 20 ft thick. The caliche is mentioned in the logs of most water wells drilled in the central part of the valley because it is usually a producing zone. In the test holes, the caliche was penetrated either at the base of the lake clay or within 15 ft below it. In the Means #1 test hole a few flakes of carbonized wood from 10 ft below the lake clay suggests the presence of a soil zone. The caliche clearly indicates subaerial conditions prior to inundation by the lake.

The lower lacustrine member, where penetrated by test holes, is 20 to 24 ft thick except in the Berkshire #1 test where it is only 10 ft thick (fig. 10; Appendix B). It consists of tan, very pale orange, and gray clay similar in appearance to cuttings from the clay of the upper member. Some important differences exist, however, for very few ostracods and very little gypsum are found in the sediment. Gypsum crystals were found in cuttings from the Means test hole, but these were only near the top of the member. The lower lacustrine member is generally more silty than the upper lacustrine member, and the lower member also appears to contain thin sand stringers or sandy zones, as well as a few thin zones of pale-red silt. From study of water-well drillers' logs, it appears that the lower lacustrine clay member is progressively more red with distance from the center of the valley, and that in the marginal zone of the valley floor the member has a reddish-brown, clayey facies. Geomorphic evidence and interpretation of the lacustrine history of the basin indicate that the lower lacustrine member estends well beyond the edge of the upper lake clay member, and rests much higher on the sides of the basin (fig. 7).

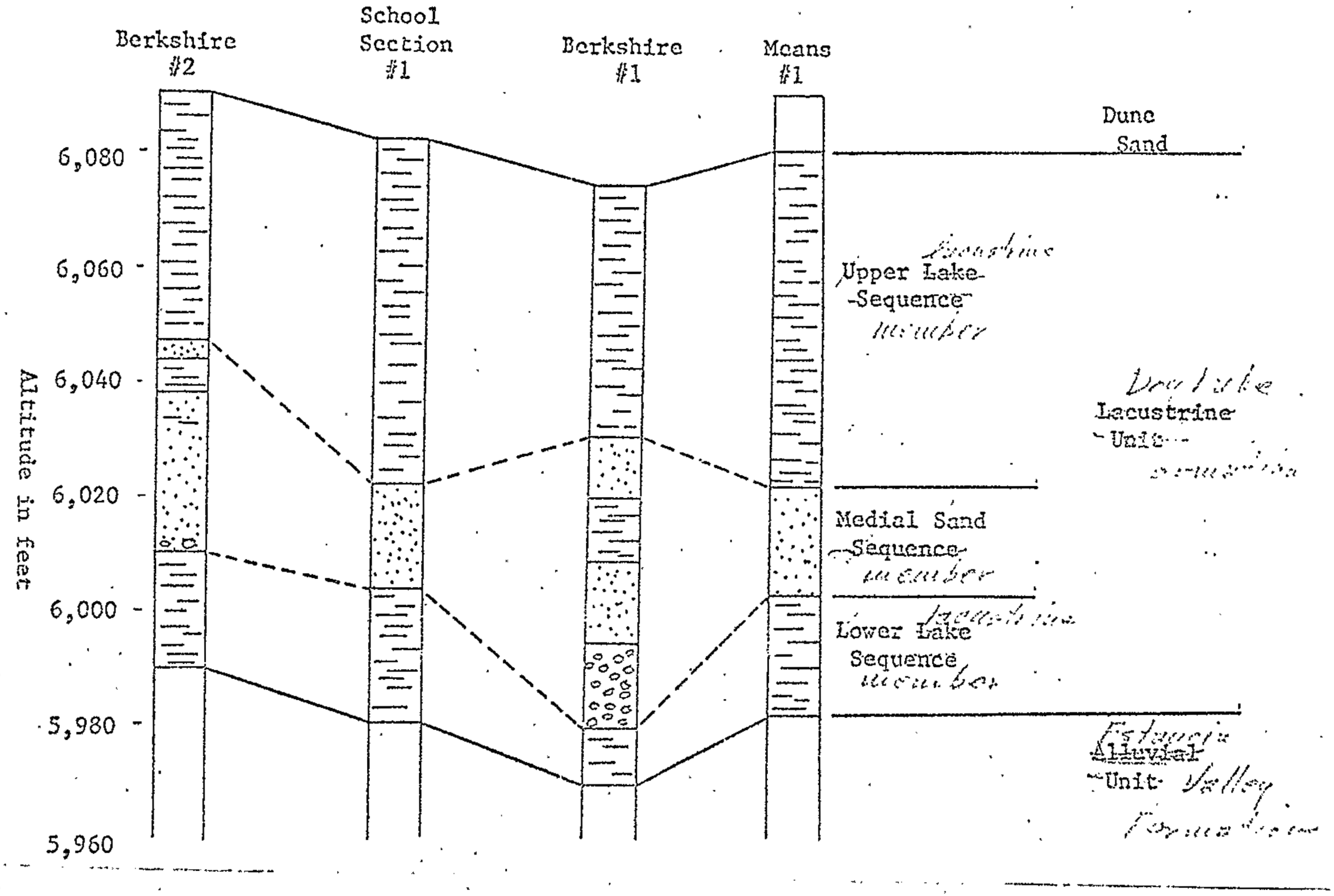


FIGURE 10 — Graphic sections of the Dog Lake formation from test holes in T. 6 N., R. 9 E. (location of holes shown on fig. 9).

The medial sand member is lithologically distinctive from the overlying and underlying lake clays, and, because it is commonly a problem to well drillers, it is usually reported in their logs. It occurs in the subsurface under most of the area of the valley floor. Drilling samples from the test holes show that the sand is quartzose, and is mostly fine to medium, well sorted, well rounded, frosted, and unindurated. It tends to run into drill holes freely during all phases of well construction, and even after casing is installed, caving frequently can be troublesome. An example is an irrigation well in the SE¼ sec. 18, T. 5 N., R. 9 E. which, according to the owner, finally collapsed after pumping large amounts of sand, even though the uncemented casing extended well below the base of the sand. Ground water in the medial sand contains more chloride and sulfate in the central part of the valley than water in the Estancia Valley formation; therefore, most wells are drilled to the deeper formation, and the medial sand is carefully cased off. The unit can be effectively sealed off only by driving oversize casing through it with a cable tool rig or by very careful cementing.

A tan lacustrine clay bed 12 ft thick was encountered in the Berkshire #1 test hole beneath 11 ft of fine to medium sand, and a thinner bed of gray to white clay was encountered in the Berkshire #2 test (fig. 10; Appendix B). Correlative strata were not found in the other 2 deep test holes. The middle and lower parts of the medial sand member in some places consist of sand that is coarser than that in the upper part. Well-rounded granule gravel and some clay can also be mixed with the sand or interbedded with it in this part of the section, and where gravel or coarse sand predominate, the member is often partly cemented by calcium carbonate. The member is 51 ft thick in the Berkshire #1 test but in the other test holes is 18 to 37 ft thick. Except at the location of Berkshire #1, the combined thickness of the medial sand and the overlying upper lacustrine member is nearly uniform as a consequence of the upper member being thinner over thick sections of the medial sand (fig. 10). In the Berkshire #1 test the medial sand sequence is thick at the expense of both the upper and lower lake clay sequences, and the lower 15 ft of the medial sand consists of sandy, well-rounded granule gravel.

The stratigraphic, lithologic, and textural character of the medial sand suggests that the member was deposited mainly under alluvial and possibly partly under eolian conditions. It is unlikely that the gravel and coarse sand could have been transported by lake currents to the central part of the valley floor. The thinness of the lower lacustrine member and the 15 ft of gravel found in the Berkshire #1 test is thought to indicate cut-and-fill structure and stream deposition. Cemented zones, and the calichelike fragments that are commonly found with them, suggest subaerial exposure and cementation by formation of caliche. The fine-grained, well-sorted, frosted sand that is found mainly in the upper part of the medial sand member is inferred to be at least partly the result of eolian transportation and deposition, hence may be partly dune deposits. This conclusion is consistent with the irregular upper surface of the member. The lacustrine clay stratum within the medial sand in the Berkshire #1 and #2 tests probably indicates a short-lived lake within the period of subaerial deposition. The conclusion that the medial sand was deposited after disappearance of the early lake is supported by the presence of gypsum crystals at the top of the lower lacustrine member, which suggests precipitation of gypsum as the early lake evaporated. The significantly higher concentration of dissolved solids in ground water in the medial sand than in water in the Estancia Valley formation beneath the lower lacustrine member may be partly due to redissolving by ground water of precipitates left by evaporation of the early lake (Appendix C).

The upper lacustrine clay member was deposited over the irregular surface at the top of the medial sand. The sequence, when seen in drill cuttings, is gray, tan, or pale yellow to pale orange. It is slightly silty, especially in the tan parts, and it commonly contains ostracod shells. Gypsum, as small selenite crystals, is very common throughout the section. Quartz sand grains are rare in the samples, but small aragonite crystals, easily mistaken for quartz grains, are common in the middle and upper parts of the sequence. Fibrous organic material, the vegetative part of charophytes, is found mostly in the lower part of the section.

Clay is the dominant constituent in outcrops of the top 20 to 40 ft of this upper member in walls of the playa depressions, constituting an estimated 70 to 80 percent of the sediment. The clay occurs in strata that are from a small fraction of an inch (laminae) to more than a foot thick. The sequence also contains aragonite, which occurs in laminae a fraction of an inch thick as fine to very-fine sand-sized crystals; ostracod shells, which may be either concentrated in laminae or disseminated in clay; and gypsum, which occurs as small selenite crystals disseminated in the clay or filling partings and fractures in the clay.

Distinctively laminated sediment sections several feet thick are found in the outcrops and have been traced for nearly 2 miles along the central part of the east wall of Laguna del Perro with little change in character. Probable correlative sections, of similar thickness and in similar stratigraphic position, have been seen several miles away on the same wall and in walls of depressions as much as 1 mile to the east. The lamination is threefold where best developed, consisting in ascending order of triplets of gray clay, aragonite crystals, and ostracod shells often with intermixed gypsum silt. In some zones there is mixing of lithologies between laminae. The triplets generally range in thickness from 0.5 inch to 1.5 inches. The presence of the triplets is suggestive of a particular limnologic environment that has been proposed by G. I. Smith from his work on the geology of Searles

Lake in the California section of the Great Basin. The Searles sediment contains aragonite laminae that alternate with clay laminae (G. Smith, 1966, p. 173-174). Ancient Searles Lake, according to Smith, is known from evidence other than the aragonite laminae to have been highly saline.

Lake Estancia can also be shown to have been saline during deposition of the upper lacustrine member from a) gypsum in the sediment, b) lack of surface discharge from the basin, c) hydrologic evidence, and d) faunal evidence (Bachhuber, 1971). The mechanism proposed by Smith for precipitation of aragonite in Searles Lake depends on the fact that solubility of calcium carbonate is substantially reduced by high salinity. Hence, water carrying dissolved calcium and bicarbonate that flows into a saline lake will precipitate calcium carbonate when it mixes with highly saline lake water. Precipitation would be expected to occur near the margins of the lake, but the wide distribution and even bedding of the Lake Estancia aragonite laminae, like those of Searles Lake sediment, suggest that the calcium- and carbonate-bearing water spread widely over the lake before precipitation took place.

The mechanism for distribution proposed by G. Smith is a chemically stratified lake with fresh, low-density water separated by a chemocline from saline water below. Transportation of dissolved calcium and carbonate ions over the lake area would occur in the fresh water where their solubilities are high. The mechanism, as envisioned by Smith, involves periodic mixing across the chemocline, with resulting rapid decrease in carbonate solubility and precipitation of the calcium carbonate. There is a well-known difficulty, however, with mixing water of different densities across an interface, and it appears that modification of the mechanism proposed by Smith is necessary.

In a chemically stratified lake, if the salinity of water below the chemocline is very high relative to that of water above, neither strong winds nor temperature differences between the layers can induce much mixing across the interface. The density difference between bottom water containing 35,000 ppm (parts per million) dissolved solids and top water containing about 1,000 ppm is more than 2.5 percent. (For comparison, the maximum temperature-induced density difference that can reasonable be assumed for 2 water layers of the same salinity is 0.18 percent where the bottom layer is at 4°C. and the top layer is at 20°C.) At present there is no way of calculating the salinity of the bottom water in Lake Estancia, but because gypsum precipitated from the water during accumulation of the lake sediment, the concentration of dissolved material in the water must have been very high. The upper layer of water, fed by runoff and ground-water inflow mostly from the west side of the basin, probably contained no more than 1,000 ppm immediately after the period of spring runoff.

A clay lamira forms the lower member of each sediment triplet. Transportation and deposition of the clay probably was accomplished by 1 of 2 mechanisms. Storms whipping the surface of the lake might have caused clay to be lifted from the bottom in shallow parts of the lake, allowing it to be transported in suspension over the entire lake area. This would require that source areas be above the chemocline because surface-induced turbulence is drastically reduced at a density interface, and flow does not take place across the interface. A more likely mechanism is that the clay was introduced into the lake during a spring season of heavy runoff from the basin sides. The lake existed under climatic conditions that produced heavy winter snow accumulation in the drainage area (Leopold, 1951), hence the period of greatest runoff would have been during the spring melt. Runoff, consisting of water low in dissolved solids, could spread suspended clay over the entire area of the lake if the water floated above the chemocline. As clay particles settled through the proposed chemocline some mixing of waters may have occurred, resulting in the often marly state of the clay layer. The possible seasonal contribution of clay implies that the triplets in the lake sediment may have been deposited during an annual cycle of events.

Aragonite, forming the second layer of the triplets, may have precipitated simply because of evaporative increase in chemical concentration in the upper layer during the summer months. An ample supply of calcium and carbonate ions was provided to the lake by ground water discharging the limestone terrain of the Madera to the west, and most of the discharge would have been at shallow depths in the lake therefore to the fresher water zone during the summer months. The fact that the level of Late Lake Estancia fluctuated within distinct limits indicates that annual evaporation approximately equalled annual inflow. As summer evaporation proceeded the chemical concentration of all constituents increased, and at some point during the summer the water would have become saturated with calcium carbonate.

Aragonite is more likely to form than is calcite when precipitation is rapid (G. Smith, 1966, p. 174), and it is also more likely at higher temperatures. The purity of the aragonite laminae suggests that precipitation may have taken place during a relatively short period of time; hence, it is possible that lake waters were supersaturated before precipitation occurred.

The ostracods that occur predominantly in the upper layer of the triplets, and are sometimes also found in the other layers, are mainly benthonic types; they include types that are generally fresh-water indicators as well as types that are salinity-tolerant (Bachhuber, 1971). If the proposed sedimentation mechanism of the triplets is valid, then one inference is that the fresh-water ostracods thrived seasonally in shallow parts of the lake where they were above the level of the chemocline. Death of the organisms may have been brought on annually by increased salinity, possibly by mixing across the chemocline. The ostracod layer commonly contains gypsum silt intermixed with the fossils. The gypsum probably precipitated from the lake water late in the summer as a result of the evaporative concentration of lake water.

Charophyte remains, consisting mostly of the vegetative part of the plant but also containing the calcium carbonate shell of the oogonium (gyrogonite), form mats up to 0.5 inch thick, in many places associated with laminated parts of the sediment section. The charophyte laminae appear to be most common in the lower part of the outcrops, that is, 20 to 40 ft below the top of the upper lake sequence.

Modern charophyta live in shallow, fresh, or brackish water (Peck, 1957, p. 4). Peck, citing Olsen (1944, p. 101), states that,

> .....the outer occurrence of Chara baltica, the species most often cited as living in marine waters, is drawn in the Baltic Sea at about the isohaline 18 parts chloride per 1,000. ....Olsen (1944, p. 200, 222) found that most species could tolerate considerable range in the amount of calcium carbonate in the water but that the pH conditions were of decisive importance. According to Olsen (1944, p. 197) charophytes are not found in highly acid waters, a few are found in fluctuating acid-alkaline waters, and most occur only in alkaline waters.

Modern charophytes are growing in a very small playa in the NE¼SE¼ sec. 20, T. 6 N., R. 9 E. Water depth in the playa is rarely more than a few inches; the plants are recumbent, but growth is luxuriant. Two water samples from the playa, analyzed by the U.S. Geological Survey, have dissolved-solids concentrations of 40,800 ppm and 20,900 ppm; chloride concentrations are 17,600 and 8,700 ppm, and pH values are 7.6 and 7.7 respectively. Sodium and sulfate are the other two important constituents of the water, and calcium and carbonate-bicarbonate are low. The chemical concentration of water on this playa seems to represent near that of the maximum tolerance of charophytes, as they are not found in waters of other playas that contain higher concentrations of salts. The presence of these living charophytes in water containing less than 50,000 ppm dissolved matter may suggest the concentration that existed in the lower saline layer in Late Lake Estancia.

From the central part of the lake area as one moves outward toward the shoreline, identification of clays of the upper lacustrine member becomes increasingly difficult. The clay beds thin and interfinger with sand and gravel of a marginal coarse-clastic facies. In this area of shallow-water deposition calcium carbonate is common, and drillers report substantial thickness of caliche, which in this case is an incorrect term. This area probably represents the chemical delta of G. Smith (1966, p. 173) in which calcium carbonate-bearing water, both runoff and ground-water inflow, entered the saline lake. Mixing of the water caused unusually heavy precipitation of calcium carbonate in the marginal zone.

Fish bones were found in the upper lacustrine member of the Dog Lake formation in 1967 by John Bradbury, and Bachhuber subsequently collected additional fossil material. In addition to many fragments, 2 complete specimens were found, only 1 of which could be removed intact. This specimen was 24 centimeters long. The fish have been tentatively identified as <u>Salmo clarki</u> (cutthroat trout), and a radiocarbon data on the bones indicate an age of 11,740$\pm$900 years before present (Bachhuber, 1971).

Bachhuber felt that the presence of trout in the lake, as well as the presence of some other biological species such as ostracods, required that Late Lake Estancia was at times fresh; however, he agreed that at other times during accumulation of the upper lacustrine member of the Dog Lake formation the lake was clearly saline. On the basis of his interpretation of varying salinity, he concluded further that during times of low salinity the lake was at a high stage at which it overtopped the topographic sill and spilled eastward through the ancestral river channel. The discharging river, he suggested, provided a route through which the trout and other freshwater organisms could enter the lake from downstream. The argument, while consistent with his extensive limnological data, I feel cannot be accepted for reasons summarized below.

If the lake overtopped the sill during Late Lake Estancia time, as it unquestionably did during Early Lake Estancia time, then the high-level strandline features (described later) should be nearly as well preserved as the well-known beaches at lower elevations because they would be of nearly the same age. In fact the higher beaches are quite dissected by erosion, and are recognizable as strandline features only in a few localities where for one reason or another they have been protected. Therefore, they are much older than Late Lake Estancia time.

Kelley (1972, p. 48) has concluded from structural and stratigraphic conditions in the spillway area that the amount of overflow from Lake Estancia was probably never very great and furthermore that the overflow never "fed a surface stream tributary to the Pecos River". Any surface water flowing down the ancestral river channel was diverted southward from the route of the channel west of Vaughn and into a karst terrane where the water went underground just as it does today. This being the case, the likelihood that trout could have been introduced is diminishingly small.

It is not necessary that a route for trout introduction be provided each time there is evidence of fresh water in the lake. It has been shown that a river flowed from the basin from late Pliocene(?) time through much of Pleistocene time prior to and during the time of basin subsidence and alluviation. During all this time a route was open for fish migration. Perennial streams surely drained from the Manzano Mountains during times that Lake Estancia occupied the basin, and these would be quite favorable habitats for trout and other fresh-water organisms whether or not the lake was saline. From the permanent streams, trout could have made excursions into the lake at any time the water chemistry was favorable.

It can be speculated that the lake would contain fresh water under 2 kinds of conditions: a) the seasonal chemocline with fresh water above saline water, or b) any sequence of years in which climatic conditions were such that inflow to the lake substantially exceeded evaporation. Little need be added to previous statements about the chemocline. Regarding the second kind of condition, each time that the lake evaporated to a low level as a result of a period of low precipitation and/or high evaporation, much of its dissolved-ion load would have been removed as mineral precipitate on the lake floor. When this inevitably was followed by a period of increased precipitation, the lake water obviously was freshened. If a chemocline prevailed during the lake-expansion interval, thus protecting the evaporite minerals on the lake floor from dissolution by exposure to fresh water, then the water could remain relatively low in dissolved solids until evaporation again increased concentration. During such times fresh-water organisms of many types could thrive in the lake. Bachhuber (1971, p. 216) recognized that conditions such as this were necessary to explain the existence of fresh-water fauna in the lake sediment at times when the lake clearly could not have been deep enough to discharge from the basin.

Hydrologic Properties

Both the lower and upper lacustrine members of the Dog Lake formation are confining beds for ground water under pressure in the Estancia Valley formation and in the medial sand member of the Dog Lake. The piezometric surfaces for the 2 aquifers both lie below the general surface of the valley floor but well above the level of floors of the playa depressions; thus they are within the upper lacustrine member. The piezometric surface for the Estancia Valley formation is in most places a few feet higher than that of the medial sand. Ground water in the medial sand is pumped by a few stock wells in the central part of the valley, but because water in this aquifer is more highly mineralized than water in the alluvial unit, it is not often used. Although the permeability of the upper lake clay member is low, a very small amount of water infiltrates from rainfall and moves very slowly toward the playa depressions.

GEOMORPHOLOGY OF BASIN, DESCRIPTION OF POST-LAKE SEDIMENT

The highest and oldest depositional remnants in Estancia Valley related to the valley fill are the pediment deposits on the west side that were mapped by Myers (1967), and the probable Ogallala gravel and caliche on the east side that were mapped by Fallis (1958). As has been mentioned, these probably represent deposition immediately preceding, or in the earliest stages of, accumulation of sediment in the valley. Thus they are probably lateral equivalents of the basal part of the Estancia Valley formation.

Erosion of Estancia Valley Formation

The surface of the Estancia Valley alluvium was cut to its present form during 2 distinct stages of stream erosion that were separated in time by the period of existence of Lake Estancia. The first stage of stream erosion was controlled by the through-flowing river that continued to discharge from the valley for some time after deposition of the formation ceased. Following this the valley was topographically closed by a final pulse of subsidence that lowered the floor several hundred feet below the level of the topographic sill. The topography left by the first stage of stream degradation was then locally modified by lacustrine standline processes. Subsequently the surface was further cut by streams of a centripetal system that drain toward the present floor of the valley.

On the west side and at the north end of the valley, where the outcrops of alluvium are broad and uninterrupted, the centripetal drainage is closely spaced and subparallel, a consequence of the depositional slope on which the streams initially formed. The upper surfaces of some outcrops high on the sides of the valley probably are remnants of this depositional surface, the largest area in which the surface may be preserved is in the northwest part of the basin near the foot of South Mountain and San Pedro Mountain. Stream dissection of the surface in this area is minimal, and bedding in the alluvium parallels the surface.

In the S½ T. 11 N., R. 7 E. (northwest corner of the basin), and from this area southward through T. 5 N., R. 7 E., streams have eroded more deeply into the alluvium. The closely spaced channels generally have narrow floors, and their sloping sides arise steeply to rounded divides. Interstream areas here have been degraded as the streams cut down, with the result that few if any remnants of the depositional surface remain. The slope of the arroyos is nearly everywhere greater than 40 ft per mile, and the angle is maintained until the channels descend to about the 6,200-ft elevation where, at the edge of the lake floor, the slope decreases abruptly. The arroyos now seldom carry runoff for any great distance before it infiltrates, and the floors as well as the sides of the valleys are mostly overgrown with grass. Except at higher elevations in the Manzanos, the arroyos do not appear to either be cutting or filling under present climatic conditions.

In the southwestern part of the valley a probable remnant of the depositional surface has been preserved in T. 4 N., Rs. 5 - 6E., between the town of Mountainair on the south and a spur of outcropping Abo Formation on the north (fig. 7). Erosion has hardly affected the surface in Rs. 5 - 6 E., and the surface can be followed upward to the west to elevations of more than 8,200 ft on the east side of Manzano Peak. Northeastward from Mountainair, stream erosion has cut progressively deeper into the surface, but long parallel ridges can be followed from the undissected area to their abrupt terminations in wave-cut bluffs a few miles west of Willard (fig. 11). The slope of the surface decreases steadily northeastward. Thick, well-developed caliche has resisted erosion, and bedding in the alluvium is parallel to the caliche layer. Geomorphic and stratigraphic relationships strongly suggest that the ridge crests are very near the original depositional surface of the alluvium.

The ends of the ridges are about 100 ft above the valley floor, and if the slope of the surface is projected 8 miles northeastward to the axis of the valley in sec. 15, T. 5 N., R. 9 E., which is immediately west of Laguna del Perro, it is found that the projected surface is more than 75 ft above the present level of the valley floor. At this location the eroded top of the alluvium is buried beneath about 110 ft of lacustrine sediment. Therefore, nearly 200 ft of the Estancia Valley Formation was removed from the center of the valley by erosion prior to establishment of Early Lake Estancia.

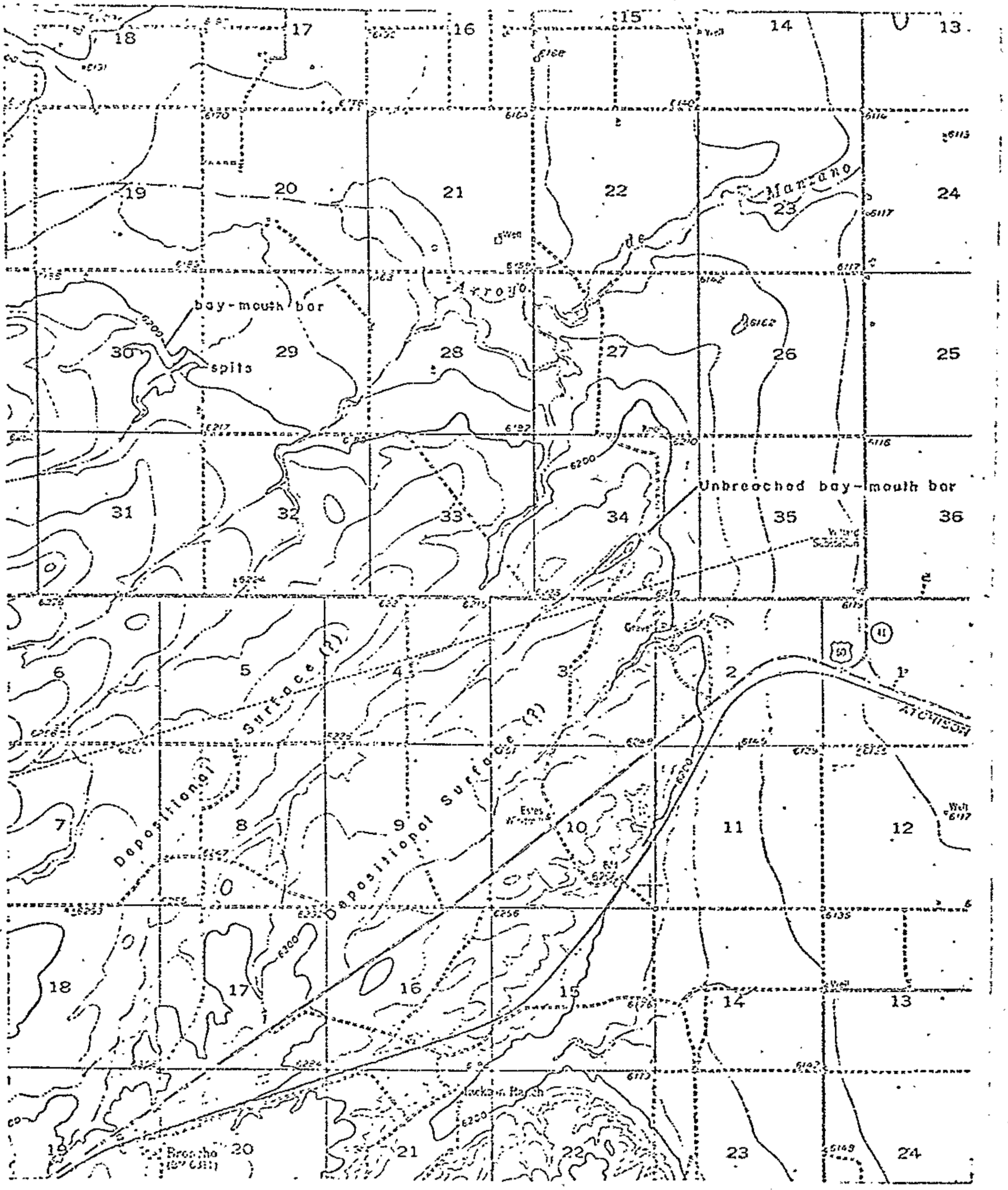


FIGURE 11.--Topographic map of parts of TPs. 4 and 5 N., R. 8 E. showing remnant of probable depositional surface of the Estancia Valley Formation, and bars built by Late Lake Estancia (base from U.S. Geological Survey, Mountainair quadrangle, 1:62,500).

Near the bluffs at the edge of the lake, the thickness of lacustrine beds cannot be determined accurately, but 1.5 miles east of the bluffs the lake sediment may be as thick as 50 ft, based on measurements of the lowest gray clay recorded in several drillers' logs. Inasmuch as the ridges are 100 ft high, approximately 150 ft of alluvium was removed from near the present bluffs before the lake was formed.

The degradation of 150 to 200 ft of Estancia Valley formation from the southwest and south-central parts of the valley prior to formation of Lake Estancia requires the conclusion that vigorous stream erosion preceded the lacustrine phase of valley history. Truncation of the ridges west of Willard was due mainly to stream erosion during this period rather than to wave-cutting, although waves in Late Lake Estancia undoubtedly smoothed the ends of the ridges and may have cut them back short distances.

Removal of such sediment volumes from the basin must have been by the river which still discharged from the southeast corner of the valley. Whereas no other likely depositional surfaces on the alluvial unit were recognized near the edge of the valley flat, stripped surfaces on the alluvium that project to elevations well above the contact between the alluvium and the base of the lacustrine unit in the central part of the valley are common. A minimum limit for prelacustrine stream erosion is established by the projections of the stripped surfaces.

On the east side of the valley, outcrops of the Estancia Valley alluvium are mostly found in already existing valleys cut into pre-Tertiary rock, and in much of the area pre-Tertiary rock crops out near the 6,200-ft shoreline of the lake (fig. 7). Stripped surfaces on the pre-Tertiary rock have erratic orientations, and their projection is meaningless because the drainage is subsequent, being controlled mainly by stratigraphy and structure.

Geomorphic Features Formed by Early Lake Estancia

Harbour (1958), in an unpublished master's thesis, described in detail the straigraphy of a pond deposit at an elevation of about 6,320 ft in the NE¼NE¼sec. 26, T. 4 N., R. 10 E. (fig. 7). At this location, known as the Lucy Site, members of the University of New Mexico Anthropology Department found early man artifacts of the Sandia culture. Harbour's work related the artifacts to local and regional geology. The site is in a wind-blowout area well up on the slope of the southeast side of the basin, and is east of Rattlesnake Hills, an isolated group of hills of Precambrian rock that reach an elevation of 6,500 ft. Present drainage, which has partly dissected and exposed the thin-bedded sand and clay, is northwestward around the north end of Rattlesnake Hills. The possibility that the "pond" sediment was actually marsh or lacustrine sediment associated with a previously unrecognized high stand of Lake Estancia stimulated a search for shoreline evidence.

A stand of the lake at this elevation, which is near the level of the topographic sill to the southeast, would indicate that the lake overflowed its basin and discharged to the east.

Evidence for such a high stand of the lake was found in restricted areas on the east and west sides and around the entire north end of the valley (fig. 7). As many as 7 levels of beaches and bay-mouth bars were found in remnants on the east side (Titus, 1969). Lyons (1969) found additional indications of the high lake stage, and Bachhuber (1971) subsequently added new observations.

In every case erosion has strongly modified the high-level strandline deposits and erosional features; in fact, strandline features that are clearly recognizable occur only in topographically protected areas. The condition of the outcrops alone is sufficient evidence that the features are much older than the very well preserved strandlines at lower elevations on the basin sides. Each student of the basin geomorphology has recognized the apparent great age difference between the high and low series of beaches (Lyons, 1969, p. 55; Titus, 1969; Bachhuber, 1971, p. 67). Correlation of the high-level shorelines with Early Lake Estancia was initially made for this reason.

Lobo Hill area

The shoreline features are best preserved between Lobo Hill and Interstate HIghway 40 near the Longhorn Ranch, in an area about 4 miles square that includes the southwest corner of T. 9 N., R. 10 E. (fig. 12). The highest feature is a wave-cut, gently sloping bluff in the E½ sec. 21, T. 9 N., R. 10 E.; the elevation of the base of the bluff is about 6,360 ft. Immediately below the bluff are patchy remnants of a depositional beach having a crest elevation of about 6,355 ft and an elevation at the toe, several hundred feet west, averaging about 6,340 ft. A correlative wave-cut bluff can also be seen about 2 miles south, along the east line of sec. 33, although at this location it is poorly preserved. A subsequent drop of lake level to about 6,335 ft is indicated by a small wave-cut bluff in the SW¼ sec. 33, and by beaches around a former island that includes most of the W½ sec. 20.

A relatively long stand at 6,320 ft is indicated by a beach that is about 0.5 mile wide and 2 miles long, in parts of secs. 29 and 32. The beach deposit has been highly modified by wind, but the preserved thickness seems to be 8 to 10 ft. Two small, breached bay-mouth bars in the SW¼ sec. 33 and in the NW¼ sec. 4, T. 8 N., R. 10 E., are at the same elevation. Successively lower beaches were formed at about 6,305 and 6,290 ft; only small patches of sand remain of the 6,305-ft beach, but the 6,290-ft beach, although thin and partly removed, is easily distinguishable near the west line of secs. 30 and 31, T. 9 N., R. 10 E. Each of these 2 lake levels also produced a small bay-mouth bar and wave-cut features in secs. 5 and 8, T. 8 N., R. 10 E. An unbreached bay-mouth bar, representing the 6,290-ft lake level, blocks a small

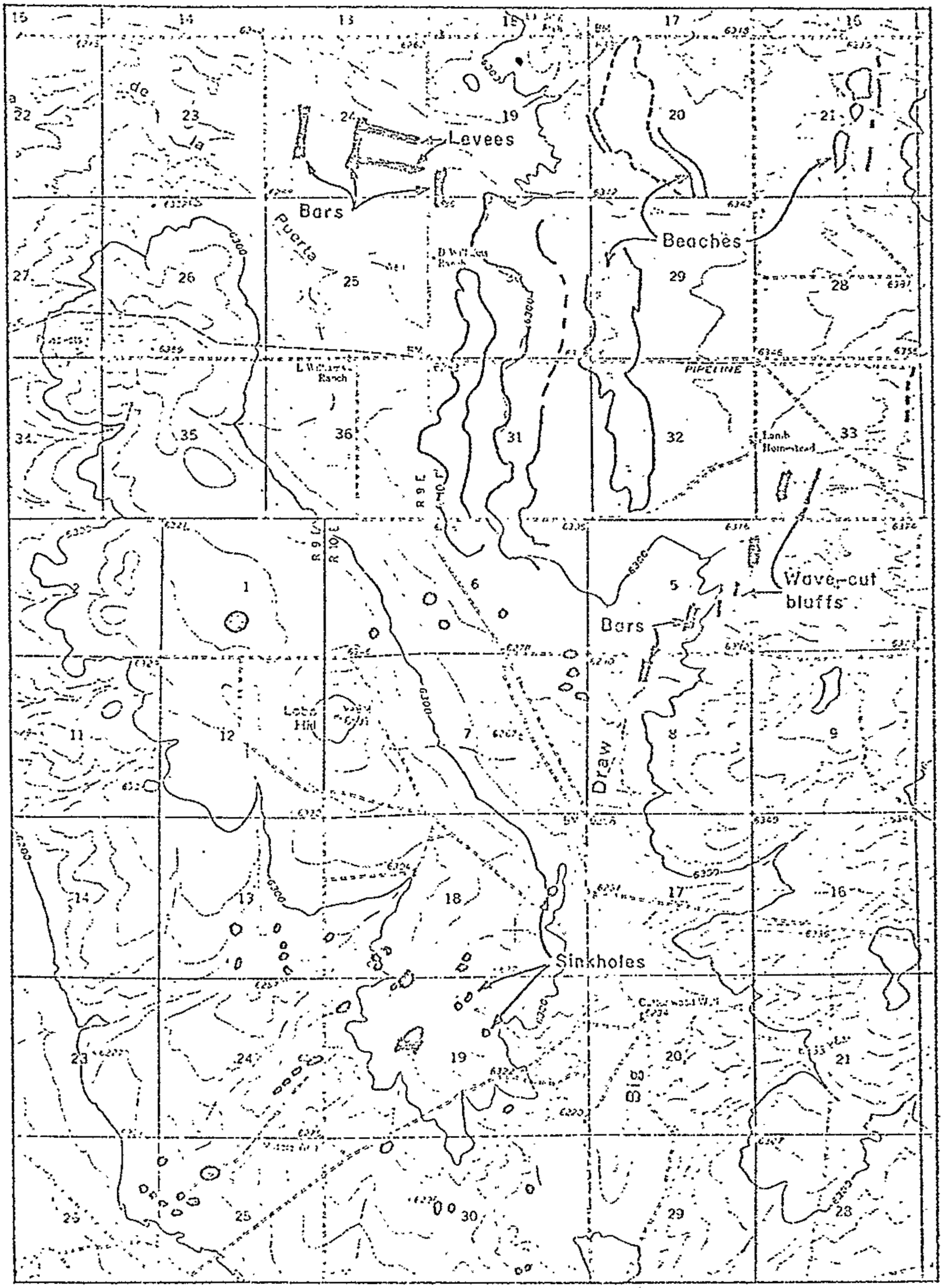


FIGURE 12.--Topographic map of parts of TPS. 8 and 9 N., Rs. 9 and 10 E. showing Early Lake Estancia shoreline features (base from U. S. Geological Survey, Lobo Hill quadrangle, 1:62,500).

channel near the SW corner, sec. 19, T. 9 N., R. 10 E.

At least 2 lower stands of the lake are indicated by breached bay-mouth bars across the same channel in sec. 24, T. 9 N., R. 9 E. Crest elevations of the bars are approximately 6,270 and 6,260 ft. Continued stream flow in this channel with lowering lake levels was assured by subaqueous construction in the lake of natural levees. The levees are preserved as low sand ridges standing a few feet above the general surface on either side of the channel. Additional bay-mouth bars may have been constructed as the lake continued to fall, but the topography and sand distribution do not clearly indicate this; hence, it is inferred that lowering of the lake may have proceeded rapidly below a level of 6,260 ft.

The high-level shorelines are probably preserved in this area because of the Lobo Hill upland to the west. The main stream channel that now drains the area turns southward to flow around the Lobo Hill upland before entering the floor of Estancia Valley. Its length is thereby substantially increased, and as a consequence, its gradient is less than half that of streams to the north and south. The Lobo Hill upland also disrupts the up-slope flow of strong west winds. The combined effect has been that the high-level shoreline is better preserved at this site than anywhere else in the valley.

In most of the area just described, alluvium directly underlies the beach and bar sediment, but it is only a thin veneer over the Glorieta Sandstone. Shallow, sediment-filled sinkholes with gently sloping, soil- and caliche-covered sides are common. A useful relationship is exhibited here, in which old sinkholes tend to be concentrated at elevations near the past lake levels. This is also the situation at the south end of the high surface around Lobo HIll (fig. 12). The elevation over most of this rolling upland surface is 6,300 to 6,360 ft, with hillocks at each end rising 10 to 20 ft higher. The symmetrical cone of Lobo Hill, composed of Precambrian quartzite, projects above the center of the surface to 6,501 ft. Most of the surface south of Lobo Hill is underlain by limestone of the San Andres Formation, and in this terrane there are more than 25 sinkholes between the elevations of 6,250 and 6,360 ft; these are clearly associated with the shorelines above and below 6,300 ft. Northeast and northwest of Lobo Hill 4 closed depressions in the same elevation range suggest that the San Andres underlies the soil-mantled surface. At the south end of the hill, between elevations of 6,200 and 6,220 ft, are 14 sinkholes (some not shown on fig. 12) associated with shoreline features prominently cut below 6,210 ft on the slope. Only 3 closely spaced sinks have been found that did not fall into one of the 2 groups; these are at about 6,240 ft at the south end of the hill.

One sinkhole near the head of a small valley in the SE¼NW¼ sec. 19, T. 8 N., R. 10 E. doubled the width of the valley by its formation. The soil-filled bottom of the sinkhole is on grade with the valley floor. This sink is unusual in that immediately downstream, a bay-mouth bar was constructed across the valley. The bar is 8 ft high, has a crest length of 300 ft, and is 400 ft wide. The height of the crest is depressed about a foot for a short distance in the center. The crest of the bar reaches an elevation of about 6,315 ft. A hole, dug 3 ft into the crest, exposed unstratified, medium to fine, uncemented, well-sorted quartzose sand containing a small amount of silt. The sand grains are rounded to subangular. A few layers of scattered, well-rounded caliche nodules were found, most of which were less than 0.5 inch in diameter. No fossils were found in these deposits. In one other sink, about 0.5 mile northwest, is a similar though smaller bar, and several other sinks in the area may also have had bars, but erosion has removed enough material so that identification cannot be positive.

The formation of sinkholes near the lake shoreline is probably the result of backflooding of the limestone by water containing CO_2 which was taken in at the lake surface. The mechanism is suggested by the work of Thrailkill (1968, p. 40-41), who ascribes some cave development near streams to the backflooding phenomenon.

North End of Basin

A change in general slope and in topographic form of the land surface is obvious around the north end of Estancia Valley at elevations between 6,300 and 6,360 ft. Arroyos and intervening divides slope at gradients of 30 to 60 ft per mile above 6,300 ft, but the gradients decrease by a factor of more than 2 at the old shoreline, and continue to decrease with distance downstream. Above the shoreline the channels are entrenched 40 to 60 ft, but the topography opens considerably and the arroyo valleys are more broad and shallow below 6,300 ft. Beaches and other shoreline features are not well preserved in the soft clayey sediment but bars were found preserved at several locations between elevations of 6,290 and 6,340 ft.

Tan to pale-red sandy clay and tan silty sand form the surface and can be seen a few feet beneath the surface in rare exposures on the open slopes below about 6,300 ft. The thickness of these deposits is not known. This sediment is thought to have been deposited in the shallow-water zone of Early Lake Estancia, and is correlated with the lower lacustrine member of the Dog Lake formations found in test holes in the central part of the valley. A few small pieces of broken gastropod shells, too fragmentary to be identified, were found in the sediment at several locations. These tend to support the interpretation of a moist, possibly lacustrine depositional environment. Identification of the environment depends as much on topographic relations and on depositional history determined elsewhere in the basin as it does on lithology.

The sediment does not contain noticeably large amounts of calcium carbonate cement, the presence of which would suggest the carbonate precipitation that occurs where runoff enters a saline water body. When the lake was higher than about 6,350 ft, it discharged over the sill at the south, and therefore probably contained fresh water.

West Side of Basin

On the west side of Estancia Valley, shoreline features related to the high stand of the lake have been mostly removed by erosion. Drainage density is high, and slopes of the channels decrease slightly below the 6,300-ft level but do not change appreciably until they approach the 6,200-ft level. Slopes along the crests of rounded stream divides are similar to those of the arroyos. If clastic sediment deposited in shallow water of the early lake remains in this area, it has not been distinguished from the alluvium on which it rests. Outcrops in arroyo walls commonly show cut-and-fill sedimentary structures and stream gravel, which strongly suggest alluvial deposition. As the 6,200-ft elevation is approached from upslope, soil cover obscures the surface and outcrops are more scarce. Shuman (1961), mapped the soils of a small area extending westward about 5 miles from Estancia. Shuman (p. 59) found chemical and soil-morphological evidence northwest of Estancia of an old soil buried at a depth of 65 inches below a modern soil profile. Conceivably, the 65-inch interval is what remains here of sediment deposited in Early Lake Estancia. The site is at an elevation of 6,200 ft, which is within the range of lake fluctuation during the lower stand of the lake, hence the upper sediment could represent a beach constructed during Lake Lake Estancia time, although high clay content does not seem to favor this explanation.

Extensive pebble to cobble gravel deposits up to 10 ft thick in a broad valley, 7 miles north of Mountainair (secs. 29 and 32, T. 5 N., R. 7 E.) may have been formed as gravel bars during stands of the lake at 6,320 to 6,330 ft elevation. The gravel is overlain by several feet of silt and clayey sand, but where exposed by excavation for road material, it is very similar in appearance to gravel in bars at lower elevations that formed in Late Lake Estancia. Two broad, closed, shallow depressions at 6,370 and 6,310 ft, on rounded stream divides north of the gravel deposits, are probably soil-filled sinkholes in the Madera Limestone similar to the sinkholes near Lobo Hill.

An exposure of probable beach rock was found 4 miles west of Moriarty (SW¼SE¼ sec. 17, T. 9 N., R. 8 E.) at an elevation of 6,310 ft. The outcrop consists of several thin ledges of hard, calcium carbonate-cemented sandstone that wraps down the sloping brow of a hill, apparently cutting across bedding of the alluvial sediment in which it is developed. Several deposits of probable beach rock were also seen in the N½ T. 4 N., R. 8 E.

The consistent elevation range of the high-level shoreline features that have been preserved indicate that there has been little or no tilting of the basin since it was closed by structural down-warping. Although remnants of the shorelines are discontinuous and highly eroded, their distribution is conclusive evidence of lakeshore origin.

Included as part of this evidence are the pond deposits described by Harbour (1958) at the Lucy site. The deposits must now be assigned a lake-margin or shallow-water origin in Early Lake Estancia. The thin bedding that to Harbour indicated a pond environment probably resulted from protection afforded by the offshore islands of Rattlesnake Hills west of the Lucy Site. The cycles of deposition and erosion that Harbour described probably resulted from subaqueous erosion, although the cause could have been fluctuations of lake level. Early Lake Estancia had surface drainage from its south end, hence, it probably was not subject to great fluctuations of level, unless occasional periods of relative dryness caused the level to drop below that of the sill.

The maximum depth for Early Lake Estancia was 380 ft. This figure is calculated from the difference in elevation between the highest shoreline remnants and the base of the lower lacustrine unit of the Dog Lake formation. During the early lake stage, lacustrine sediment accumulated to a present thickness of about 30 ft.

Topographic Sill, its Valley, and its Ancestral River

The geomorphology of the low point in the rim of Estancia Basin, and the valley in which it lies, is worthy of special note. The river that drained Estancia Valley during accumulation of the alluvial unit discharged through this valley. When the central part of Estancia Valley was lowered by the structural adjustment that established present topographic closure, the sill was left several hundred feet above the level of the basin floor. The basin was subsequently filled by Early Lake Estancia to the level of the sill, and surface water again discharged from the lake through the river valley although, according to Kelley

(1972), probably not in large amounts. At the end of Early Lake Estancia time, as the lake was lowered below sill elevation by evaporation, surface-water discharge through the river valley ceased and has not recurred.

From the south end of the Estancia Basin, a broad valley now slopes upward to the east toward the topographic sill north of Cedarvale (fig. 7). The gradient along the axis in the 13-mile reach is about 12 ft per mile. The valley floor is underlain by silt, sand, and some gravel over most of its length, but in the upper reaches of the valley and at the sill the Yeso Formation is at the surface, covered by a thin veneer of soil.

A large, bowl-shaped, solution-induced subsidence feature in the Yeso, the Big Sink described by Lyons (1969), opens into the north side of the valley in the E½, T. 3 N., R. 11 E. The flat floor of Big Sink, which is about 7 square miles in area, is at and slightly higher than the level of the axis of the valley. The amount of solution collapse appears to be 50 to 75 ft. Subsidence features of this size are common in the Yeso terrane south of the Pedernal Hills. Another example is the Dunmoor Basin (Bachhuber, 1971, p. 67-69), a closed depression more than 4 square miles in area in the Pedernals 5 miles south of US-60 (Tps. 4 and 5 N., R. 12 E.). Both of these satellite basin features contain lake shoreline features.

The contact between alluvium and Yeso in the floor of the valley west of the sill is obscured by a 2-mile wide linear deposit of eolian quartz sand blown from Chupadera Mesa more than 20 miles to the west (fig. 7). This sand deposit is well defined where it crosses the valley and drapes over the divide into Pinos Well Basin. West of a small peak of Precambrian rock that is immediately north of the sill, in sec. 29, T. 3 N., R. 12 E., the sand is about 10 ft thick. Its surface is irregularly hummocky, with a local relief of about 5 ft. A dense growth of mature juniper trees is restricted to the area of the sand deposit, probably because the sand absorbs more moisture from rain than do the surrounding soils. The sand, now fixed from further wind erosion by the junipers, blocks the flow of surface water down the valley, and a large area of temporary ponding lies on the upstream side of the sand dam in sec. 2, T. 2 N., R. 11 E. The pond probably quickly empties by seepage through the sand after a rainstorm. Channels on the valley floor west of the linear sand deposit are indistinct for a distance of about 2 miles, but below this and extending nearly to the point of discharge into the south end of Estancia Valley, gullies have been cut into the alluvium.

The present topographic sill, which during deposition of the alluvial unit in Estancia Valley was on grade with stream drainage out of that valley, is now a broad divide between the Estancia Basin to the west and steeply sloping tributaries of Pinos Wells Basin to the east (fig. 13). The surface at the sill is pock-marked by small sinkholes

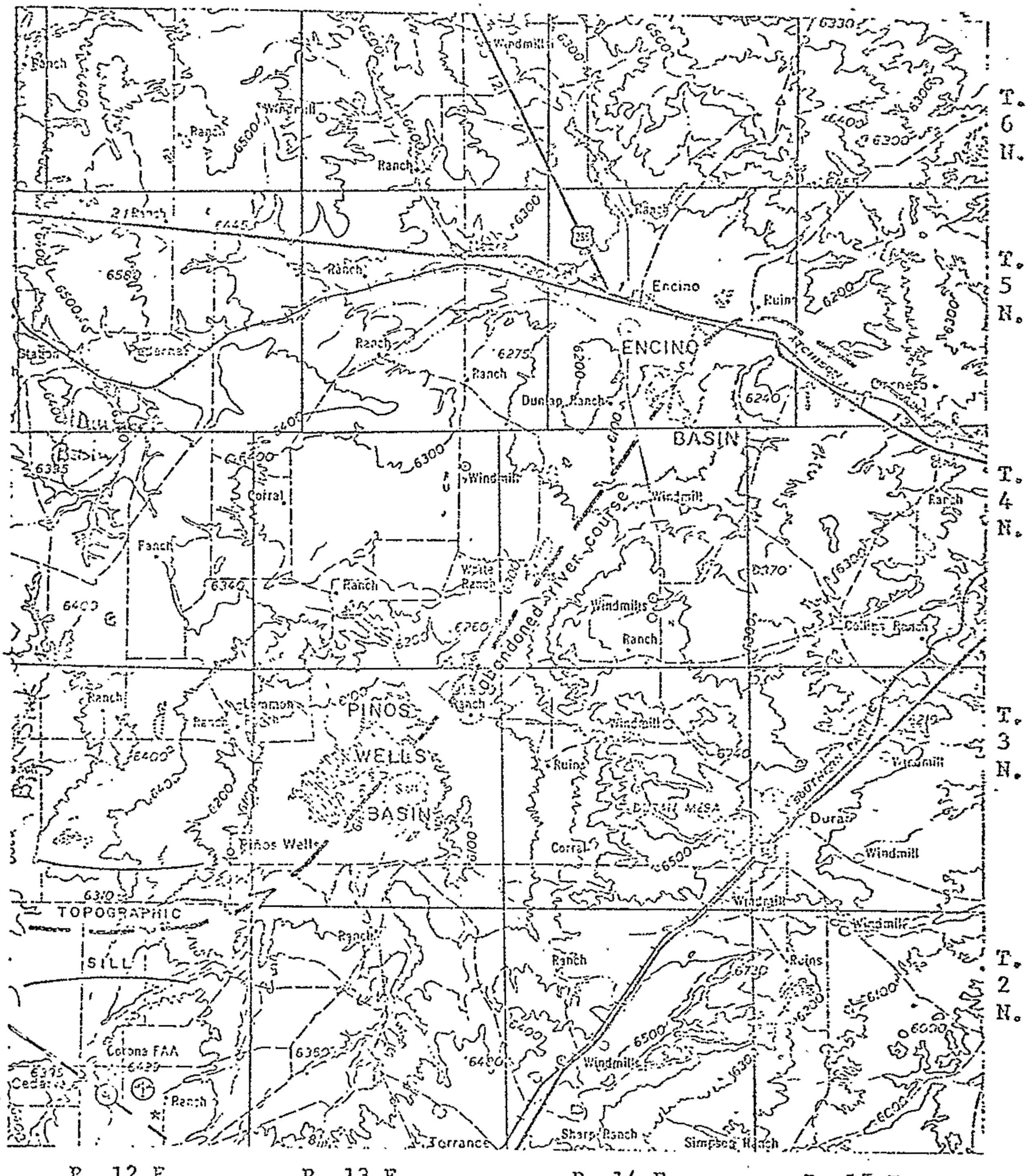


FIGURE 13 — Topographic map of Pinos Wells and Encino Basins showing axis of the abandoned river valley (base from U.S. Geological Survey Fort Sumner map, 1:250,000).

in the Yeso, and tributaries to Pinos Wells Basin are cutting headward into the east side of the divide. The highest elevation of the sill was surveyed at about 6,350 ft.

The width of the valley suggests the size of the ancestral river that cut it prior to the impoundment of Lake Estancia. The valley at the south end of the Estancia Basin floor is 6 miles wide, being constricted there between Rattlesnake Hills on the north and the high escarpment of Mesa Jumanes on the south. Eastward toward the present topographic sill, and at the sill, the gently sloping sides of the valley spread over a breadth of approximately 10 miles. After passing the present location of the sill, the river turned northeastward for a distance of about 20 miles before again swinging eastward to flow toward the Llano Estacado (fig. 13). The valley in its northeastward reach is 5 to 10 miles wide. A readily drawn inference is that the valley was created by a river of significant size.

The topographically closed depressions of Pinos Wells and Encino Basins lie on the axis of the river valley northeast of the sill. Although formation of these basins has substantially modified the floor of the river valley, an indication of its original gradient can be obtained from elevations of the valley floor at the local sills between the basins and east of Encino Basin. The elevation of the low divide between the Pinos Wells and Encino Basins is 6,240 ft (Kelley, 1972, p. 47). Solution in the underlying Yeso has probably lowered the level of this divide somewhat, as is suggested by the existence of a playa on the divide. Meinzer believed that the playa floor is well above the local water table (Meinzer, 1911, p. 84). At the downstream divide 6 miles east of the center of Encino Basin, the elevation is 6,260 ft. Hence the axis of the valley drops about 100 ft over a distance of 27 ± 2 miles (depending on unknowns in the course of the river) between the Estancia topographic sill and the divide east of Encino Basin. This implies an average river gradient of somewhat less than 4 ft per mile. For comparison, the gradient of the modern Rio Grande is 4.5 ft per mile.

Pinos Wells Basin has a drainage area of about 180 square miles, and in the center of the basin are 2 playas that occupy depressions similar to but shallower than those found in Estancia Valley. As in Estancia Valley, dunes composed of material derived from the playas have formed to the east. Unlike Estancia, however, the basin does not contain lacustrine sediment, and no shorelines are evident around the sides of the basin. (Smith, 1957, p. 84-86; Meinzer, 1911, p. 82-84; Bachhuber, 1971, p. 70). The sediment of the basin floor and the low divide to the northeast is mostly thin-bedded silt, sand, and clay, but layers of granule to pebble gravel are interbedded with the finer grained clastics. Wind erosion tends to leave a pebble pavement that locally protects the surface, a phenomenon also noted by Meinzer (1911, p. 83). The sediment, which is very similar in appearance to flood-plain deposits in the present Rio Grande and Pecos

Rivers, may be alluvium deposited by the ancient river.

Encino Basin, only slightly larger than Pinos Wells Basin, has a history similar to that of Estancia Valley in that after formation of the basin it contained a lake in which more than 20 ft of lacustrine sediment was deposited (Meinzer, 1911, p. 75-82; Smith, 1957, p. 80-84). A single playa depression occupies the center of the valley floor, and dunes of gypsum and clay lie immediately east of the depression. Shorelines similar to those of Late Lake Estancia were described by Meinzer; he also found 4 ft of laminated lacustrine sediment resting on yellow sand and gravel in a dug well less than a mile south of the town of Encino (1911, p. 76-78). A probable correlative of the sand and gravel, found in exposures about a mile to the southwest, is thinly bedded and silty; these are thought to be river alluvium.

Both Pinos Wells and Encino Basins are underlain by bedrock of the Yeso Formation. The Glorieta and San Andres Formations crop out high on the east side of the drainage areas of both basins in a ridge that separates these basins from the Pecos River drainage system. The ridge is breached by the valley of the ancient river east of the center of Encino Basin. Localized stream erosion has taken place in each of the low divide areas adjacent to basins since the river ceased to flow in the valley. However, except for obvious local gullying, the amount of degradation is small, and the general cross-sectional shape of the original valley seems well preserved at the divides.

Pinos Wells and Encino Basins, like the previously mentioned Big Sink (T. 3 N., R. 11 E.) and the somewhat smaller depressions in the Yeso terrane to the north, formed by subsidence following solution of gypsum in the underlying Yeso Formation. The floors of Pinos Wells and Encino Basins are nearly 200 ft below the levels of the intervening divides. Encino Basin formed early enough to have contained a lake that was probably contemporaneous with Late Lake Estancia; the absence of correlative lake strata in Pinos Wells Basin can be explained by one of two hypotheses.

One possibility is that Encino Basin developed more rapidly by gypsum solution in the Yeso, hence could contain a lake during Late Lake Estancia time, whereas Pinos Wells Basin has only completed subsidence since the end of that pluvial cycle. The difficulties with this explanation, which I proposed several years ago (Titus, 1969, p. 93), relate to the many similarities between the basins (size, stratigraphic and structural setting, topography, hydrologic and geomorphic history) and to the required conclusion that Pinos Wells Basin evolved not during a pluvial period, when maximum water was available for solution, but during post-pluvial time.

However, as a second possibility, it is assumed that the basins developed simultaneously, then the absence of lacustrine sediment in one suggests that it simply was not very efficient at holding water. In view of a) the solution and subsidence origin, b) the presence of a small subsidence(?) playa between the basins, and c) the karst topography that develops readily on this and overlying formations, a leaky basin is easily envisioned. Both Bachhuber and Kelley remarked on the absence of obvious strandlines at the overflow level for Encino Basin, and it may be that this basin leaked too, but at a rate slow enough for a lake to be maintained in which lacustrine sediment could accumulate.

In the absence of other information, the most reasonable direction of underflow from the basins is along the axis of the valley. Such being the case, water that leaked out of Pinos Wells Basin could directly enter the lake of Encino Basin. An eastward component of leakage cannot be ruled out, however.

Regarding time of origin of the basins, hydrologic arguments support formation during pluvial times but not while the valley was occupied by a flowing river. A river would likely deposit allivium in any subsiding part of its floor as rapidly as subsidence occurred. Thus, while solution of underlying rocks could take place, formation of a topographic basin would be precluded. Applying this argument, Pinos Wells and Encino topographic basins would not have formed until after the headwaters of the river were cut off by downwarping of Estancia Valley. Furthermore, topographic subsidence could begin in Early Lake Estancia time only if overflow from Early Lake Estancia was not large. It seems probable that most of the topographic basin formation took place in Late Lake

Estancia time when that lake was well below the level of its sill.

Kelley (1972, p. 48) has implied that the rate of surface-water discharge into the river valley from Early Lake Estancia was small, and such may have been the case. It is interesting to note, however, that in the axis of the Vaughn Sag, which probably existed in Early Lake Estancia time, he describes 200 to 300 ft of gravel. The Vaughn Sag, after it had formed, would have diverted southward into a karst terrane any flow down the ancestral river channel. The thick gravel deposits suggest a rather vigorous flow of reasonably long duration after development of the sag.

Geomorphic Features Formed by Late Lake Estancia

Meinzer (1911, p. 19-22) described the general character of the beaches, bars and other shoreline features formed between elevations of about 6,100 and 6,200 ft by waves and currents in Late Lake Estancia. Harbour (1958) mapped the beaches and described them in some detail, particularly in the southeastern part of the valley. The intention is to present here only information that will expand on work of previous authors and that is pertinent to understanding the role of water in the gologic development of the valley.

Harbour's careful mapping and measurement of beach heights (1958) was fully confirmed by field work in this study. The 12 main beaches in Harbour's Group A are found at remarkably persistent levels around the edge of the basin floor between 6,160 and 6,225 ft. The 2 highest shorelines, although well developed and easily identifiable in many places, are in other places more strongly eroded than those below. It is probable that these were formed early in the Late Lake Estancia stage, and were eroded slightly before the lower beaches were built.

The maximum depth of Late Lake Estancia, as indicated by the difference in elevation of the highest shoreline features and the base of the upper lacustrine member of the Dog Lake formation, was about 200 ft. During this lake stage 50 to 60 of sediment accumulated on the floor of the basin.

The 6,209-ft beach and bar system, the third highest level, is one of the most persistent in the group, and in many places the lake at this level formed an offshore bar hundreds of yards in front of the higher beaches. This is particularly demonstrable on the east side of the lake where streams draining the east slopes flowed into arcuate bays impounded by the bar. Upon subsequent lowering of the lake level, drainage from the bays developed at the lowest or weakest point in the bar, with the result that modern stream channels turn behind the bar and flow as much as 1.5 miles along the axis of a bay before reaching the breach as is the case near the north line of T. 6 N., R. 11 E. (See Meinzer, 1911, p. 20, for his description of this feature).

The 6,209-ft beach was formed during a stillstand during recession of Late Lake Estancia. Clear evidence that beaches below 6,209 ft were formed in sequence with lowering lake level is found to the south of this location, near US-60. Streams that broke through the bar here eroded channels downslope, and, as successively lower beaches were built, the ends of the beaches wrapped upstream into the channels a short distance on either side. The streams have not transported large amounts of sediment since the time of breaching, and the volume of sediment spread on slopes below the breaches is little more than can be accounted for by erosion of the breach and the slope below.

Broad flat-floored arroyos on the northeast and northwest shores of Late Lake Estancia are obvious indicators that the lake drowned the lower parts of a preexisting drainage system. These are best developed in the vicinity of Moriarty where, traveling up the channel, one sees the flat floors become narrow, the sloping walls close in and become higher, and the valleys become V-shaped above an elevation of about 6,220 ft. Streams entering the lake at the heads of bays dumped alluvium to partially fill the submerged valleys.

Bay-mouth bars were built as high as 20 to 25 ft while the lake stood at 6,209 ft. A bar of this height completely closes a small valley in sec. 34, T. 5 N., R. 8 E. (fig. 11). The depth of the closed depression behind the bar is about 20 ft. Projection of the channel profile through the depression and under the bar indicates that very little sediment has accumulated behind the bar. Bay-mouth bars on the order of 10 ft in height are more common on both sides of the valley than are the higher bars. An 11-ft bay-mouth bar is shown by topographic contours in sec. 30, T. 5 N., R. 8 E. (fig. 11). An opening near the center of the bar remained during bar construction, as is indicated by low spits that grew into the lake from each side of the opening. At their point of initial growth, the spits are at right angles to the main bar, but each curves away from the channel through the opening.

Very few of the numerous bays that are partly closed by bars show signs either of later stream erosion through the opening or of deposition behind the bar, and none of the depressions behind closed bay-mouth bars have received a significant amount of sediment since closure by the bar. It must be concluded that there has been little erosion of the sides of Estancia Valley since disappearance of Late Lake Estancia.

Numerous spits formed simultaneously with the beaches, and these are excellent indicators of water circulation patterns in the lake. One long spit, projecting northward from US-60 in sec. 24, T. 5 N., R. 10 E., began growing during the 6,209-ft stand of the lake, and grew northward more than a mile during this and the next 2 lower stands at 6,205 and 6,200 ft. The main transporting current was northward, thus suggesting counter-clockwise circulation in the main part of the lake. A clockwise current in the great bay to the east deposited sediment simultaneously on the east or back side of the spit. The vigor of the main current during early stages of growth is shown by the cobble gravel of which the spit is constructed. Current velocity decreased during the 6,200-ft lake stand, and sand was the dominant material deposited.

The direction of current flow reversed during the next lower lake stand, at 6,193 ft, and circulation apparently continued in the reverse direction until the lake had withdrawn from this part of the valley floor. The current reversal is indicated by erosion on the north end of the spit by an impinging current that cut away the point. The current split at the point, with the east branch turning into the great bay and depositing sand eroded from the spit to form a long, narrow secondary bar that extends eastward nearly 2 miles. The direction of current flow along the secondary bar is evident from horsetail-like streaks of sand carried over the bar and deposited on the back (south) side. Spits on the west side of the lake associated with lake levels at and above 6,200 ft confirm clockwise circulation, but evidence that suggests a general current reversal at lower levels of the lake is less conclusive.

Most beaches and bars are constructed of coarse sand to fine gravel. Gravel of cobble size is not common except in a few local areas. Beaches and bars above the level of 6,150 ft derived most of their material from the alluvial

Estancia Valley formation, although some beaches on the eastern shores derived sediment from pre-Tertiary outcrops. Where the lithology is distinctive, such as that of Precambrian rock, the source area usually can be found nearby.

Lacustrine Features Formed in Shallow Rejuvenated Lake

Harbour (1958) assigned 3 beaches lying between elevations of 6,130 and 6,145 ft to his Group B. These beaches were built on a much more gently sloping surface and their crests are more widely separated than the beaches at higher levels. The elevation of the highest of the Group B shorelines is very nearly the same as the elevation of a peculiar 20-mile-long sediment bar that formed 1 to 2 miles offshore on the east side of the lake, and now bounds the east side of the playa-depression and dune area in T. 4-7 N., R. 10 E. (fig. 14). The bars at higher levels were rarely built more than a few hundred yards offshore. This large offshore bar is distinguished from older bars at higher levels by its relatively great distance from shore, by its length and even crest altitude, and also by its shape and composition. The crest of the bar, which is 15 to 20 ft above the lake floor, is scalloped by transverse channels 4 to 8 ft deep that are regularly spaced a few hundred feet apart. The channels probably were formed by water surging across the crest, with the surge being induced by periodic strong southwest

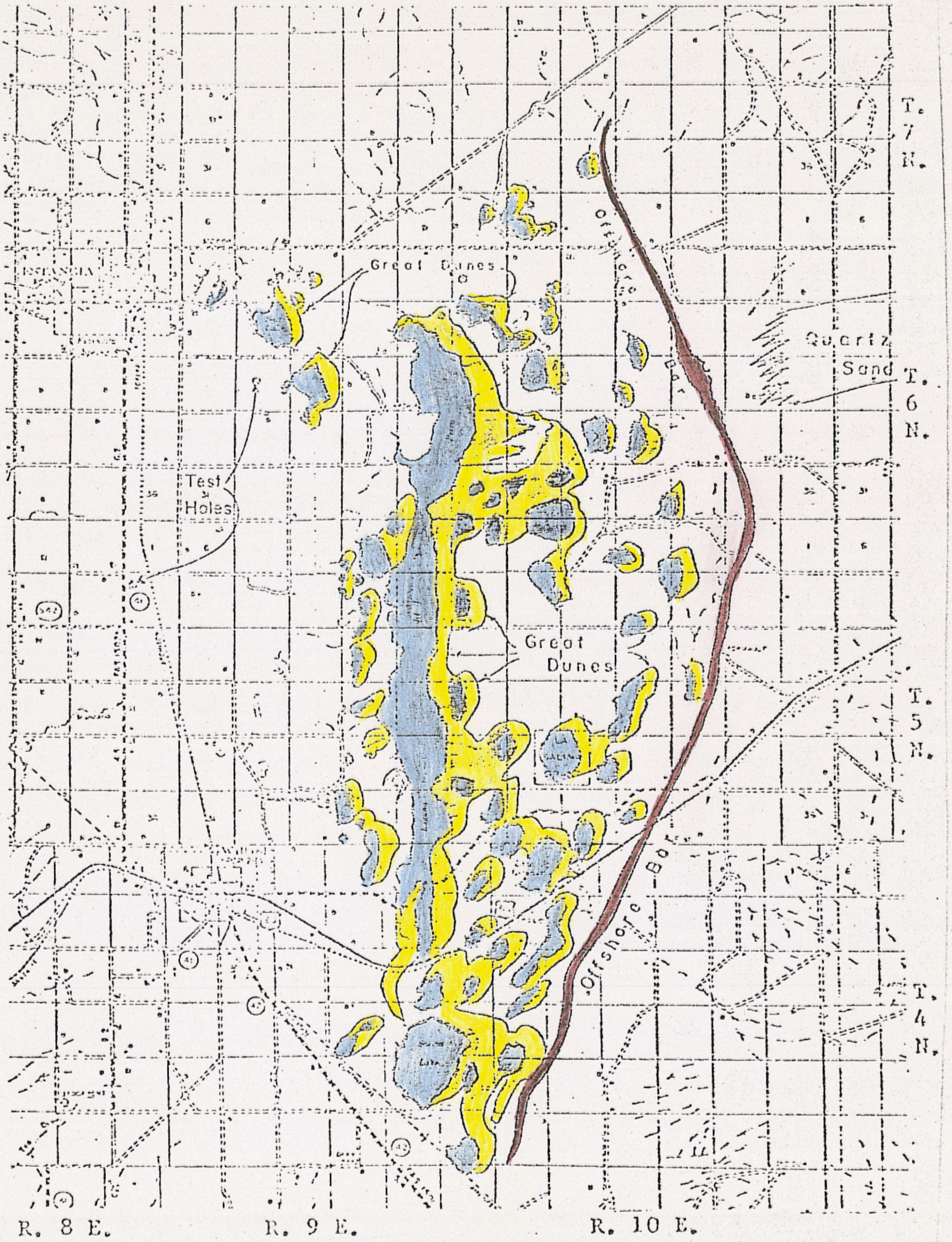


FIGURE 14 — Map showing locations of playas, great dunes, and the gypsiferous offshore bar.

or west winds that piled water up in the eastern part of the lake and released it when they diminished. Tide- and wind-surge channels across bars are common on marine coasts.

The sediment from which the bar is constructed is more than 50 percent gypsum and about 10 percent calcium carbonate, as indicated by microscopic examination and chemical analyses. The rest of the sediment is clay and silt, with minor amounts of fine quartz sand. Sediment in the correlative beach, and in lower beaches, also contains large amounts of gypsum, in contrast to the quartzose sand of higher beaches. The source of the gypsum appears to have been a system of small dunes that now lie to the west of the bar. Hence the bar and the Group B beaches of Harbour (1958) were formed in a shallow, temporary rejuvenation of Lake Estancia that followed a period of dessication in the basin. Maximum depth of the lake during this stage was about 70 ft.

The floor of the valley after evaporation of Late Lake Estancia, but before formation of the playa depressions, sloped gently toward an axis that was approximately coincident with the present location of Laguna del Perro (fig. 14). Slopes on both sides are about equal, and range from 6 to 9 ft per mile toward the axial elevation of about 6,075 ft. The surface, especially west of the axis where not now dune covered or destroyed by the playa depressions, is very slightly rolling, with no integrated drainage. Near the outer edges, the courses of the largest arroyos can be recognized on the former lake floor by indistinct braided deposits that have a maximum length of a few miles. Only rarely today do extremely heavy rains produce runoff that reaches beyond the ancient lake margin, hence transportation of allivium onto the lake floor is minimal under present climatic conditions.

GEOLOGY OF THE PLAYA DEPRESSIONS AND DUNES

The topography of the central part of the valley floor is dominated by numerous playa depressions and their associated great dunes (fig. 14). Laguna del Perro, the narrow, 12-mile-long playa extending north from US-60, is many times larger than any of the other playas. It averages less than a mile wide and is 7.5 square miles in area. Salina Lake, south of Laguna del Perro, is the second largest playa, measuring about 1.5 miles long and 1 mile wide. None of the other playa depressions are as large as a square mile in area. In all there are roughly 85 perennially moist playas that have a combined area of about 19 square miles.

Laguna del Perro and Salina Lake are on the low topographic axis of the valley floor. Approximately two-thirds of the smaller depressions lie within a gentle arc to the east of the axis; the remainder are near the west side of Laguna del Perro. Several playas, most of them very small, lie in a group somewhat separate from the main playa field about halfway between the north end of Laguna del Perro and the town of Estancia.

The depth of the depressions ranges from 20 to 40 ft, and depressions distant from the axis tend to be shallower than those near the axis. The playa of Laguna del Perro, at an elevation of 6,034 ft, is about 40 ft below the general level of the valley floor nearby. Its floor elevation is matched by those of a few playas immediately to the east, but apparently none are at a lower elevation. The few playas to the east having the same floor elevation may be in slightly deeper depressions because of the gently rising valley floor.

Dunes cover an estimated 80 percent of the valley floor between the playa depressions (fig. 15). Two distinct families of dunes are recognized on the basis of size, shape, and proximity to the depressions. The largest are those related to depressions, each dune lying on the east side of a depression and wrapping around the north and south ends. Dunes of this family are as much as a half mile wide, and reach heights of 130 ft above the flat valley floor adjacent to the central part of Laguna del Perro. Inasmuch as the Laguna del Perro depression is about 40 ft deep, the crests of the highest ones are 170 ft above the playa; heights of 110 ft were measured east of the north end of Laguna del Perro. The great dunes cover an estimated 10 percent of the valley floor.

Scattered among the great dunes are innumerable smaller dunes, which rarely exceed 15 ft in height and are generally less than 10 ft high. In contrast to the great dunes, locations and shapes of which were determined in part by the depressions, the small dunes have shapes determined solely by the wind. Transverse dunes, with north-south to northwest-southeast axes up to 3,000 ft long and widths on the order of 500 ft, are common among the

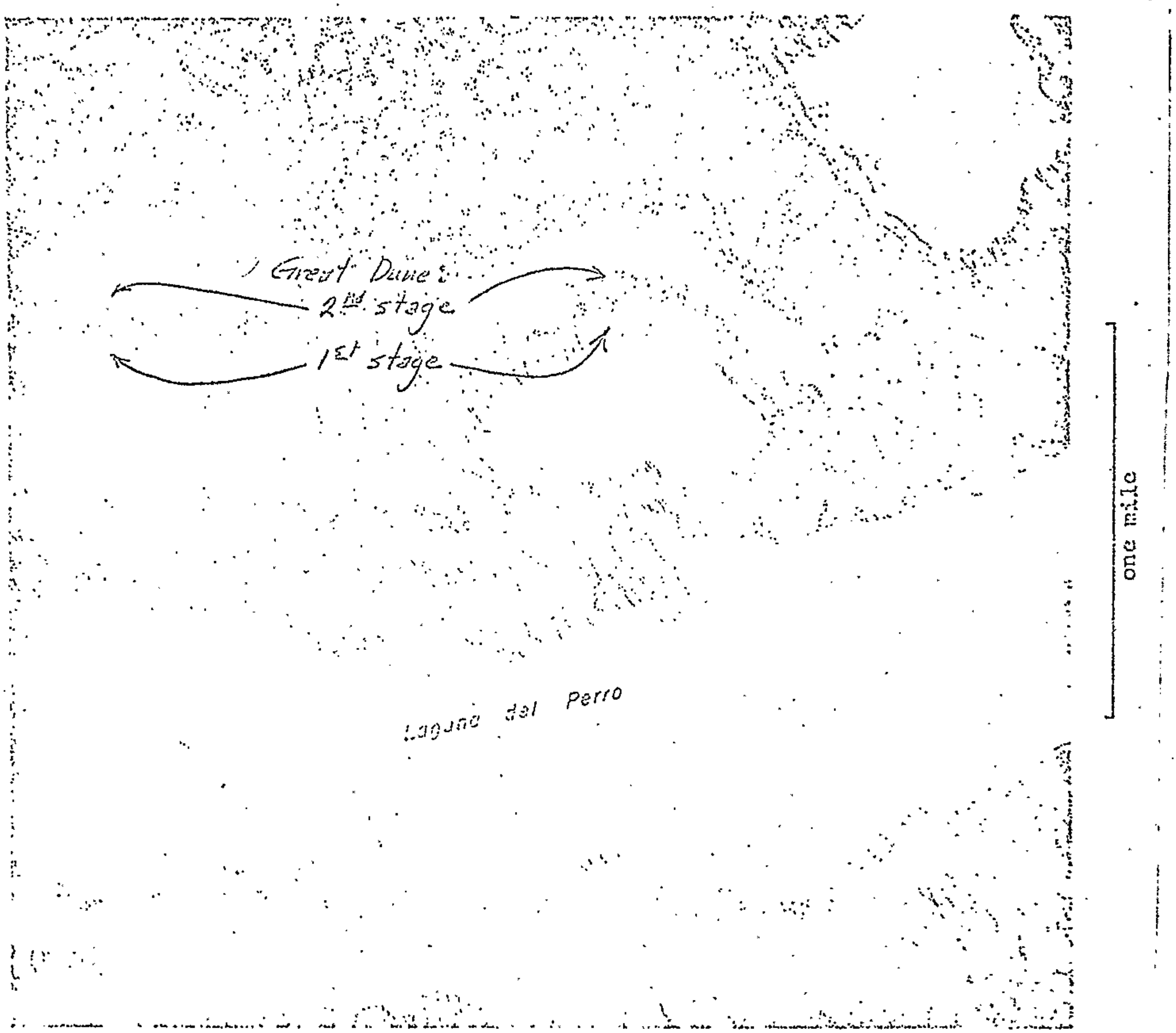


FIGURE 15 — Aerial photograph of the central part of Laguna del Perro and nearby playa depressions showing small dunes and two stages of great dunes.

small dunes. Equally common are elliptical to circular dunes with maximum lengths of 300 to 600 ft. Barchans are not common, but a few occur in the northeast part of the dune field; they are open on the east, and average about 800 ft from tip to tip. Dunes of this family are not found west of Laguna del Perro nor east of the long offshore bar (fig. 14).

Small Dunes

The small dunes are composed mainly of gypsum, and microscopic study of samples shows that the sediment is mostly medium-sand size cleavage flakes and rosettes of tan gypsum with slight amounts of clay and sand-size, chalky calcite grains. The sediment is commonly weakly cemented by recrystallized gypsum. Chemical analyses of 2 typical samples, collected from depths of a foot below dune crests, show that gypsum makes up 60 to 75 percent, clay 10 to 30 percent, calcite 5 to 8 percent, and salt (NaCl), less than 1 percent of the sediment. Much of the clay in the analyses is from inclusions within gypsum crystals rather than a clay fraction of the eolian sediment.

The dune forms invariably are rounded and smoothed (fig. 15), and the upper surfaces are protected by a tough gypsite crust that ranges in thickness from a few inches to more than a foot. The bunch grasses that grow on the valley floor and on the great dunes are sparse to absent on the crests of the small ones. No evidence of present-day wind sculpturing was found.

The small dunes are in many places partly buried by sediment at the toes of great dunes. The dark color and the toughness of the gypsite crust aid in distinguishing materials of the two where they are in contact. Small dunes also cap the west walls of playa depressions east of Laguna del Perro. In some places the small dune is intact on a projecting nose, and appears to have protected the edge of the depression from wind erosion, whereas in other places, part of the dune has been cut away during formation or enlargement of the depression.

The small dunes were built and their gypsite crust formed before development of the playa depressions and construction of the great dunes. They date from the time of disappearance of Late Lake Estancia, when west winds sweeping across the newly exposed lake floor picked up evaporite sediment from a broad initial playa and deposited it to the east. The playa-dune relationships, at the time of their development, may have been similar to present conditions in the White Sands area of Tularosa basin, although the gypsum sand deposit in Estancia is much less extensive and the gypsum is less pure.

Development of thin deposit of eolian quartzose sand, derived from beaches in the center of the E¼ T. 6 N., R. 10 E., and spread eastward in a broad streak across the great eastern bay of the former lake, may have begun at this time (figs. 7, 14). The lower beaches, bars, and even some of the dunes in the source area for the lineal sand deposit are composed of quartz sand derived from Glorieta Sandstone that cropped out as an island just to the north.

Winds that formed the gypsum dunes were from the west-southwest and tended to converge eastward. Dune orientation at the north end of the dune field indicates wind from S. 81° W.,whereas at the south end of the field the wind was from S. 68° W. The convergence angle is 13° and average wind direction was S. 75° W. The quartzose sand was blown eastward from its source. The convergence and the 10° to 15° change of wind direction on the east was caused by funneling of the wind by the topography of the eastern embayment.

After their formation the samll dunes were submerged by a short-lived, shallow lake. During submergence they were the source of gypsiferous sediment from which the great offshore bar and the beaches that lie below 6,148 ft were constructed (fig. 14). Microscopic examination and chemical analysis of sediment from the bar indicates lithologic similarity between it and dune sediment. A single chemical analysis shows: gypsum 51 percent, clay (insoluble) 34 percent, calcite 9 percent, and salt (NaCl) less than 1 percent. The remaining 5 percent is mostly organic material.

The suggestion that temporary rejuvenation of the lake followed initial disappearance of Lake Estancia was first made by Harbour (1958). Harbour reached this conclusion from observation of indistinct beach remnants well below the level of the Lake Estancia beaches. The offshore bar, and submergence of the small dunes, substantiates Harbour's conclusion, although the depth of the temporary lake was greater than he supposed. The height of the bar and beaches indicates that the rejuvenated lake reached a maximum depth of about 75 ft along the axis of the valley.

Erosion and shifting of dune sediment by currents in the shallow lake resulted in the present low, rounded form of the samll dunes. The gypsite crust on their surfaces probably formed initially as the dunes were exposed by evaporation of the lake. Low permeability of the initial crust has facilitated additional crust growth from rainfall followed by evaporation.

Great Dunes

Like the small dunes, the great dunes are composed of sand-sized gypsum, clay, and calcium carbonate. There are significant differences in the proportions, however. The results of 2 chemical analyses of typical samples show: gypsum 30 to 36 percent, clay (insoluble) 37 to 38 percent, calcium carbonate 15 to 20 percent, and salt 1.5 to 2 percent; 8 to 11 percent of the weight of the samples was material not determinable by the analyses. Most, but possibly not all, of the undetermined material was organic. The anions analyzed were sulfate, carbonate, and chloride; however, the undetermined material may have contained other anions. The calcium carbonate in the sample is partly aragonite, as small aragonite grains similar to those in the underlying lacustrine sediment were seen in microscopic examination of all samples. The samples that were chemically analyzed were collected at depths of about a foot below the surface of the dunes. Microscopic examination of samples from greater depths shows that the sediment contains somewhat more gypsum than that near the surface, but there is no other evidence of soil formation (except as noted below for certain early great dunes). It is estimated that gypsum constitutes 50 percent of sediment below the surficial zone of solution.

The source of sediment for the great dunes is easily established, as the material came from the playa depressions with which each of the dunes is associated. None of the great dunes has migrated away from its source area. Where playa depressions are closely spaced, dunes completely surround the depressions, as the area is not broad enough for separation of the depression-dune pairs.

The walls on both sides of the playa depressions have been strongly sculptured by west-southwesterly winds (fig. 15). On the east side of the depressions, where the sculpturing is best developed, parallel and closely spaced ridges and valleys sweep steeply up the walls of outcropping lake sediment, and continue uninterrupted up the more gentle slopes of the less competent great dunes. In spite of local curvature of the depression walls, parallelism of drainage tends to be maintained. In places, the alignment of ridge and valley axes differs by as much as 20° from a direction normal to the average slope. The tops of the great dunes are mostly sharp ridges. Slopes on the eastern, or lee, side of the dunes are more gentle and the topography is more rounded, yet the topography remains aligned with the direction of the wind. The depositional toe on the lee side is surprisingly distinct.

The dunes wrap around the sharply curving ends of the playa depressions in wings that terminate in alignment with wind direction. Erosion of sediment from the depressions and deposition of it as dunes were accomplished mainly by west-southwesterly winds, but the dunes have been modified by easterly winds to form the westward-projecting wings. Easterly winds are also responsible for the sharp demarcation of the east toes of the dunes and the lack of slip slopes on the lee sides. The dunes, with their westward-projecting wings, are most similar to parabolic dunes; however, their shape is not determined by the wind but by the shape and position of their parent depressions.

The direction of the critical winds is easily determined by the strong topographic grain on the sides of depressions and dunes. At the north end of the depressions-dune field, winds blew from S. 67° W.; at the south end from S. 62° W. Thus, as in the case of winds that deposited the older and smaller dunes, the winds converged slightly as they crossed the valley. The convergence is about 5°, as compared to a convergence of 13° for the earlier winds. The average direction of the wind was S. 65° W., as compared to S. 75° W. for the earlier winds.

On the surface where the dunes immediately east of Laguna del Perro were deposited, drainage channels toward the laguna had developed prior to dune growth. In depressions farther east channels were not seen. Gradients of the channels seem to be adjusted to several levels of the depression's floor, including a few adjusted to near the present level. Local dune growth may have begun when the depression floor was not far below the level of the surrounding valley flat. If so, the larger channels between the accumulating dunes remained open as the depression floor was lowered. With continued lowering, more and more of the channels were choked by eolian deposition, with only a few remaining open long enough to establish gradients near present playa level. One of the widest of the deep channels, located in the W½ sec. 23, T. 5 N., R. 9 E., connected a smaller playa depression to the east with that of Laguna del Perro; this channel is now filled with dune material that forms a high, narrow ridge between the two depressions.

Two periods of growth are recognizable in the great dunes associated with the few playa depressions adjoining the central part of Laguna del Perro where a sub-dune channeled surface was found. The earlier period is represented by smooth-crested dunes that wrap around the east sides of the depressions; their west sides, sloping into the depressions, are slightly dissected by short, steep gullies that are regularly and closely spaced along the slopes (fig. 15). In the later period of dune growth, additional sediment was blown over the rounded crests and deposited on the east slopes, building the dunes much higher and forming the sharp-crested ridges that are typical of the other great dunes throughout the dune field.

A similar shape is exhibited by the great dune associated with Salina Lake at the south end of Laguna del Perro. East of this playa the lower, smooth-crested dune lies a half mile from the depression. Here 2 small playa depressions east of Salina Lake both are cut into the rounded dune; hence these depressions were formed later than the Salina Lake dune. (Bachhuber, 1971, p. 81-82).

A thin, gypsiferous, clayey soil is found on the surfaces of the first-generation great dunes, and this brown soil is more than a foot deep in gentle swales between dune crests. The upper surface is slightly cemented, but the crust is not nearly as well developed as that on the small dunes that were submerged by the shallow rejuvenated lake. Cementation is adequate, however, to prevent blowouts in most places, even where grass cover is sparse.

During growth of the first-generation great dunes, and while some of the channels remained open, the topography may have been similar to present topography immediately west of Laguna del Perro. Dunes here, deriving their sediment from small playa depressions to the west, have grown relatively slowly, and many valleys remain open between the small depressions and Laguna del Perro, although nearly all of the valleys are a few feet higher than the floors of the depressions.

It is evident that the first-generation dunes, and therefore their associated playa depressions, were restricted to the central, or axial, part of the valley floor. There is no indication, however, of a first-generation dune associated with Laguna del Perro. These conditions prove useful in the deduction of depression-dune origin and history (discussed later).

Calculations of the relative volumes of depression and associated, second-generation dune were made for 2 depression-dune pairs where topographic control could be obtained. The depressions are in sec. 17, T. 6 N., R. 9 E., 2 miles east of Estancia, and in the NE¼ sec. 36, T. 5 N., R. 9 E. Elevations, taken using a frequently calibrated altimeter, were used to contour the dunes on stereoscopic pairs of air photos. Topographic maps, at 20-ft contour intervals, were available for the depression near Estancia. The calculations show that at the location near Estancia the total volume of sediment in the dune is equivalent to more than 50 percent of the volume of material that was removed to form the depression. In the other depression-dune pair to the south, the dune volume is equivalent to nearly 70 percent of the sediment removed from the depression.

Playa Depressions

The north-south elongation of Laguna del Perro establishes a dominant lineation to the depression field, and close examination shows that smaller depressions also tend to be aligned (fig. 16). Shapes and distribution of the smaller playas both contribute to the visual impression of alignment. The lineation of small depressions near Laguna del Perro parallels that of the laguna, but depressions in the eastern part of the playa field show a marked curvature that is concave to the west. The northwestward curvature of the north end of Laguna del Perro and the southwesterly alignment of depressions grouped around the large Salina Lake at the south end of the depression field emphasize the gently curved arc of the eastern depressions.

A significant conclusion from this study is that gypsum solution beneath the valley fill has been very important in controlling the locations and early development of the depressions (Titus, 1969, from which present ideas have evolved). That depression origin was controlled solely by wind action was never questioned until Smith (1957, p. 46) briefly speculated that the playas may have resulted from "combined action of solution, subsidence, and deflation." The obvious spacial relationship between great dunes and depressions led Meinzer to conclude that the depressions were formed by deflation; Johnson (1902), Keyes (1908), and others had concluded this before him. Meinzer (1911, p. 26-27) added that, "the work of excavation proceeded to the ground water level but could be carried no deeper, and hence the flat, miry, alkaline floors of the basins." More recently Bachhuber (1971) has subscribed to the same theory

FIGURE 16 — Playa-depression-scatter and playa shapes that suggest lineation.

of origin. The conclusions reached by these investigators, however, were based on the obviously eolian origin of the dunes, which is not questioned here, and not on critical examination of depression origin in the context of the geologic-hydrologic system.

One objection to a simple eolian mechanism is related to the difficulty of recognizing a means of initiating growth of depressions at their particular sites on the sloping floor of the valley east of the axial low. Winds can remove dry sediment that has been loosened and made fluffy by crystal growth in evaporating water. One proposal has been that there were shallow basins on the original lake floor in which ponds could collect (Bachhuber, 1971, p. 89). There may well have been such features, but signs of them have not been found in the area of the depressions. Furthermore, no acceptable reason for distribution of the hypothetical shallow basins in the arcuate pattern of the depressions has been advanced. Equally important, a number of shallow basins and swales on the valley floor west of the depression field meet all criteria for original basins, and yet deflation depressions did not develop at these sites.

The inference that subsurface solution and subsidence may have played a role in controlling location of the depressions may be drawn by comparing subcrop distribution of the Yeso beneath the valley fill with the positions of the playa depressions. Small, geologically recent sinkholes a short distance west of Lucy (in secs. 14 and 23, T. 5 N.,

R. 10 E.), into which lacustrine sediment of the Dog Lake Formation has collapsed, unquestionably indicate subsurface cavity formation immediately beyond the present eastern limits of the depression field. Whether these sinkholes will eventually result in other playa depressions is problematical, but their existence allows the inference that solution and subsidence in the Yeso, a mechanism that has resulted in closed depressions a few miles in diameter in the area of Yeso outcrops beyond the valley to the southeast, may also have occurred where the formation underlies the valley fill in Estancia Basin.

The Canas Gypsum Member of the Yeso is more than 100 ft thick in Chupadera Mesa southwest of the center of the valley (Wilpolt and others, 1946), and the Gardner-Kidwell oil test in sec. 21, T. 6 N., R. 10 E. immediately east of the depression field has been shown to have penetrated about 350 ft of predominantly gypsum strata at shallow depth below the alluvial unit. Hence, thickness of this soluble rock is an order of magnitude greater than the depth of the playa depressions. Evaporites in the Yeso diminish to the north, as indicated by their scarcity in outcrops in the Sandia Mountains (Kelley, 1963). If the depressions are related in any way to solution of gypsum, then the northern termination of the depression field in Estancia Valley might indicate subsurface wedgeout of thick gypsum strata, although this is not necessary for the hypothesis.

The available evidence points to a complex origin for the depressions involving subsidence initiated at depth, followed by substantial enlargement of the collapse depression by wind deflation. It is concluded, because of distribution of the depressions, that the westernmost subcrop limit of the Canas Member of the Yeso Formation beneath the base of the Estancia Valley Formation is (or was) approximately under the west edge of the depression field. Ground water in the alluvial Estancia Valley formation above the gypsum is thought to have dissolved sufficient gypsum at the subcrop to initiate subsidence at the surface following disappearance of the final lake, thereby determining locations of the original playas. The playas, being sites of preferential deflation, controlled the locations and dimensions of individual depressions. The depressions are thought tc have resulted mostly from deflation, however, with subsidence being responsible for a small proportion of the total volume. An important hydrologic aspect of subsidence is the disruption of lacustrine clay bedding, thus increasing vertical permeability beneath the playas. Slow upward leakage from underlying confined aquifers would have provided ground water to the protoplayas for evaporation, thus facilitating seasonal deflation. These and other hydrologic aspects are discussed in detail in the next section.

If these conditions are accepted as a working hypothesis, then other conditions that are difficult to explain by deflation alone are more easily understood. These include the existence of 2 generations of great dunes and depressions, and questions regarding relative rates of ground water discharge from the 2 aquifer units.

The 2 generations of great dunes, and particularly the small depressions east of Salina Lake that cut through the first-generation great dune, imply that some playa depressions formed later than others. The earliest depressions seem to have been Salina Lake, the few depressions immediately east of the center of Laguan del Perro, and probably all of the depressions west of Laguna del Perro. (The latter group is included because of the broad swales that lie between depressions, which are like the buried valleys east of Laguna del Perro). The remainder of the depressions lying to the east are all later.

The following model is postulated. A thick gypsum sequence occurs within the Yeso, which is in subcrop contact with the base of the valley fill beneath the older-generation depressions, but which to the east lies stratigraphically somewhat below the base of the valley fill (fig. 17). If the gypsum is being dissolved by ground water flowing in the highly permeable alluvium above the Yeso, then solution would be most rapid where the gypsum strata are in direct contact with the alluvium. Where the gypsum is separated from the alluvium by intervening Yeso strata, solution would proceed more slowly because water and/or dissolved ions from the gypsum would have to pass through these layers. Stratigraphic factors that would affect the volume of ground-water flow which could contact the gypsum remain to be determined. For example, it is unlikely that all solution is occurring in the same gypsum stratum, yet the local

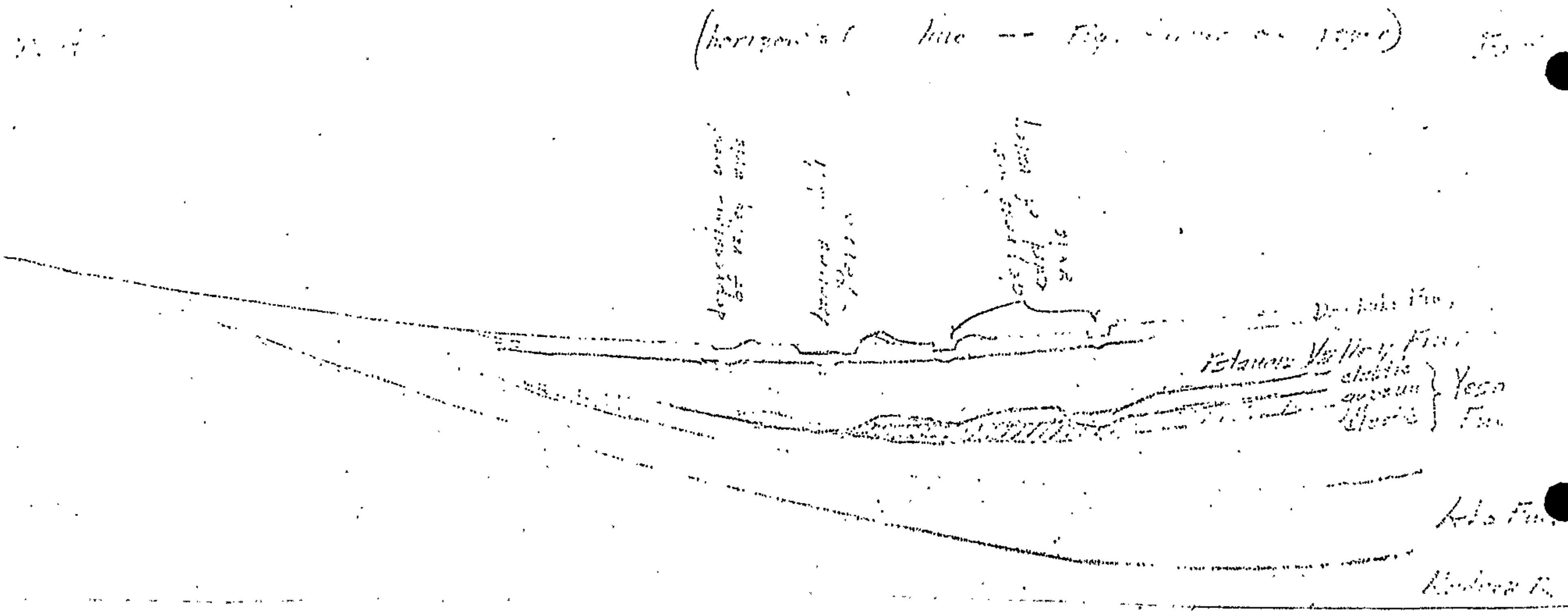


FIGURE 17 — Hypothetical cross section (W to E) through playa-depression field illustrating a model for solution-controlled depressions.

stratigraphic details are not known. Fracturing of Yeso strata may play a role in localizing solution or permitting cross-formational flow to the gypsum. The effects of ionic diffusion may or may not be significant.

Laguna del Perro itself, as a single integrated depression, may postdate slightly the initial depressions in the central part of the valley. This is suggested because no first-generation dunes are found associated with this great depression. The Laguna del Perro depression lies along the topographic axis of the valley floor, and can be expected to have a history that is partly modified by this condition which is peculiar to it.

The lack of continuity between depressions east of Laguna del Perro suggests uneven solution of gypsum which may be due either to differences in the thickness of gypsum that is available for solution, or, more likely, to variations in the permeability of overlying strata through which the dissolving water circulated. A few very shallow depressions are found in this part of the area that in the past contained playas but are now above the zone of saturation. These may indicate lesser collapse, possibly due to thinner gypsum beds in subcrop contact, but they more likely indicate local cessation of deflation as the water table was lowered by evaporation from surrounding playas.

In a discussion of the mechanism of solution and collapse, the question arises as to whether the phenomenon is peculiar to postlake time, or whether it was active at earlier times in basin history. The assumption must be that solution has taken place during all times in which ground water was not stagnant. During times when Lake Estancia occupied the basin, and particularly after lacustrine sediment having only slight permeability was deposited on the lake floor, movement of ground water probably ceased owing to the absence under the lake of a hydraulic gradient toward the center of the valley. When flow ceased, water at the subcrop would in time have become saturated with respect to sulfate, thus stopping solution of additional gypsum. Earlier in the basin history, however, during the period of deposition of the alluvium, flowing ground water should have dissolved gypsum, and it is presumed that collapse of overlying sediment accompanied the solution. Contemporary alluvial deposition would have buried the surface features. Such structures have not been recognized in drill holes, but the number of holes is not adequate, nor is their location proper to test the hypothesis. Furthermore, because the alluvium consists of lenticular and discontinuous strata, there is serious question as to whether collapse zones could be recognized from drill holes in the alluvial section.

No indisputable evidence of faulting of the lacustrine beds was found in the walls of depressions. Fractures with moderate slippage would be consistant with subsidence. A few large, slightly downdropped blocks at the ends of spurs projecting from the walls of depressions may have moved on faults formed during collapse of the depressions, but the blocks may also be interpreted as having slumped after formation of the depression. Elsewhere joints were found that dip toward the depressions at angles of about 45°, and in one exposure on the east side of Laguna del Perro, there appears to have been some movement on such a joint. In most places surface exposures of any fault zones have apparently been removed during the substantial enlargement of the depressions by winds.

A significant part of the gypsum now found in the great dunes could have come from chemical precipitation out of water evaporating on the playas, and not from gypsum in the deflated Dog Lake formation. There is some indication that the percentage of gypsum in the dunes may exceed that which can be accounted for easily out of the part of the Dog Lake formation exposed in the depressions.

The ground water now flowing to the playas will later be shown to come mostly from the Estancia Valley formation, with far smaller amounts from the medial sand member of the Dog Lake formation, and yet these aquifers are apparently separated from the playas by clayey strata of the Dog Lake formation. The clayey lacustrine strata are confining beds for water under artesian pressure. The much higher ground-water discharge rate from the deeper aquifer, the Estancia Valley formation, than from the medial sand of the Dog Lake formation can only be explained by assuming that the very low permeability of its confining bed does not exist beneath the playas. This supports, or even requires, the argument that subsidence has disrupted the clayey strata of the Dog Lake formation.

The water from the Estancia Valley formation that discharged to the early playas would have contained large amounts of dissolved gypsum from solution of Canas gypsum beds that resulted in the subsidence. Playa evaporation would precipitate the gypsum which, along with wind-eroded sediment of the lacustrine unit, would then have been blown up the sides of the depressions and dropped at the brow to form the great dunes. Thus, as the depressions were deepened by deflation, the great dunes accumulated sediment that was eroded both from the Dog Lake lacustrine member and from gypsum precipitated on the playa.

The mechanism would obviously not work under present climatic and hydrologic conditions. The playas are now never sufficiently dry for wind to remove any sediment. It is necessary to propose a period of aridity greater than that of the present to account for the deflation and dune growth.

Growth of the depressions by deflation implies an interesting and unusual hydrologic situation. First, regarding the position of the top of the zone of saturation, it is obvious that the water table is coincident with the surface of the playas. Meinzer observed this but failed to recognize, probably for lack of data, that each playa is at the center of a cone of depression in the water table that is analogous to cones around pumping wells. The cones of depression exist because each playa is a point of ground water discharge by evaporation, just as a pumping well is a point of discharge. Water levels rise outward from the playas at a rate of about 5 ft in 100 ft (Smith, 1957, p. 52), until within a short distance the water table may be 30 ft above the level of a playa. Hence the depressions have not been deflated to levels coincident with a planar water table. This anomaly cannot be resolved by suggesting that at the time of deflation the water table was lower, because in this part of the valley evaporation is the only mechanism for lowering the water table. Hence the water table must always have been near enough to the surface for evaporation to occur. Deflation of the depressions must have proceeded in spite of the high water table, and evaporation must have lowered the local water table as the basin floors declined.

Operation of such a system depends on two conditions: annual equilibrium between ground-water inflow and evaporative outflow at the playa, and evaporation potential that seasonally greatly exceeds inflow. The rate of inflow can be considered constant throughout the year; if water depth on the playa never became great, then the head difference, hence the pressure gradient, did not vary seasonally. If summer temperature were high enough, or summer humidity low enough, the evaporation potential could exceed the flow capacity.

Climatic conditions that would produce the required balance are similar to those in the interior parts of Southern California lying at the same latitude, and it is interesting to speculate that a similar climate may have prevailed in central New Mexico. Annual evaporation potential at elevations similar to Estancia Valley are 15 to 20 percent greater in the California area (Meyers, 1962, pl. 3). Furthermore, as the summer temperatures in the California desert are higher, and as the rainy season comes in the winter, a much greater part of annual evaporation occurs in the summer in the California area. Higher summer temperatures alone might have been adequate to increase the evaporation in Estancia Valley as required, but conditions favoring high summer evaporation would have been even more enhanced by a climate in which rainfall occurred mainly during the winter months, such as that in California and the Great Basin.

Playa Sediment and Hydrology

The playas are flat, perennially wet surfaces, but surfaces on which water depth exceeds a fraction of an inch only after a local rain. A recording water-level gauge on Laguna del Perro seldom indicated more than 6 to 10 inches of water. The expanses of surface are underlain by thin deposits of soft, non-coherent sediment that differ markedly from the tough, clayey Pleistocene lake strata on which they rest. Probing of the sediment across the north end of Laguna del Perro showed a resistant layer that varies little from a depth of 2 ft. In coring the sediment manually, no more than 2 ft could be recovered, although in a few instances the core barrel could be pushed slightly below this depth. Small fragments of material in the end of the core barrel consisted of tough, sticky clay thought to be from the Dog Lake formation. At the south end of Laguna del Perro, within a hundred yards north and south of the old Highway 60 alignment (SE¼ sec. 2, T. 4 N., R. 9 E.) cores of 2.4 ft were recovered from above the resistant layer.

A small playa in the SE¼ sec. 12, T. 4 N., R. 9 E. was probed to a depth of 3.4 ft near its south edge. Bachhuber (1971, p. 92) reported coring 3.7 ft of playa sediment farther out from shore on the same playa. It is interesting to note that the floor elevation of this playa is about 6 ft higher than that of a playa across US-60 to the southeast, and a quarter mile away. In the deeper playa, the sediment was probed to a depth of 2.6 ft near the north edge in the SE corner of sec. 12. North of Laguna del Perro, in the SW¼ sec. 6, T. N., R. 10 E., a playa that produces large amounts of salt was probed to a depth of 1.9 ft at the extreme south edge.

The greatest thickness of playa sediment recorded in Estancia Valley was noted by Hafsten (1961, p. 61, 62), who collected a core 8.5 ft long from a playa in the center of sec. 32, T. 7 N., R. 10 E. (Harold Rud lake). Pollen analysis was run on the core, and the climatic interpretation, from comparison with Llano Estacado cores, indicates extremely dry conditions (Hafsten, 1961, p. 77, 79, 82). Hafsten also cored 3.8 ft in Salina Lake in sec. 26, T. 4 N., R. 9 E., reporting that at a depth of 2 ft, "the gypsiferous mud...changed to a sticky clay, difficult to get out by means of the posthole auger." The sticky clay is interpreted here to be the base of the playa sediment.

The playa sediment consists predominantly of gypsum, with lesser amounts of silt and clay, and small amounts of organic matter. In the upper few inches scattered crystals of sodium chloride are found. Clayey layers a few inches thick in the middle and lower parts commonly contain small amounts of calcium carbonate, although the highest concentrations of calcium carbonate are generally near the base. Alternating with the clayey layers are thin (up to 2 inches) layers or pods of transparent, euhedral gypsum crystals, which are mostly of medium- to coarse-sand size and have a distinctive diamond shape. Gypsum crystals that are disseminated in the clayey layers, in contrast, are not euhedral and contain included clay which gives them a yellowish-tan color. Fibrous organic material, possibly vegetative parts of charophytes, form quarter-inch layers in some places. The sediment is soft, unindurated, slumps readily, and is highly porous, containing a large proportion of water, but the permeability is low except in the zones of euhedral gypsum crystals.

The upper small fraction of an inch is commonly tan gypsiferous silt and clay, but beneath the tan film the sediment is black, ranging to dark brown toward the base. The black color is caused by high organic content, and the sediment yields a strong sulfide odor when cores are extracted, or at any time the surface of the playa is disturbed. Most of the organic matter is extremely fine, and may be bacterial remains. Playa surface-water samples and sediment samples were submitted to C. Brierley and J. Brierley, bacteriologists at New Mexico Institute of Mining and Technology, for analysis. They reported the presence of *Halobacterium* in the water and *Desulfovibrio* and *Halobacterium* in the sediment. *Desulfovibrio* species are sulfate-reducing bacteria that require an anaerobic environment to function, and reduce organic matter as a source of energy. *Halobacterium* species in the sediment are probably not metabolically active, as they require oxygen-bearing water to function (Brierley and Brierley, written communication, 1968).

Greenish-yellow to pale-yellow zones up to 2 inches thick are found in playa-sediment cores, usually near or in the euhedral gypsum layers or pods. The color may be due to submicroscopic sulfur resulting from bacterial reduction of gypsum. Free sulfur occurs in places on playa surfaces in the presence of organic material such as cattle droppings, and nodules up to an inch in diameter have been found in the lake sediment at playa water level (R. H. Weber, oral communication, 1969; Bachhuber, 1971, p. 92). The process by which this sulfur forms probably requires a gas phase that transports sulfur as H_2S from the anaerobic playa sediment, in which bacteria are active, to the point of deposition in an oxidizing environment. The concentration of possible free sulfur in the sediment near the zones of euhedral gypsum crystals may be related to the unusually high permeability in these parts of the sediment.

Crystallization of the sand-sized euhedral gypsum probably occurs in voids in the sediment, as is suggested by the crystal form, the high permeability, and the lack of clay in the zones. Voids are thought to form by entrapment of large bubbles of H_2S gas. A few spherical voids up to a quarter inch in diameter were found in one core that was allowed to dry in the coring tube before being cut open. Gas can frequently be observed escaping very slowly along with water that flows continuously onto the playa surface from numerous vent holes a small fraction of an inch in diameter. It may be that gas bubbles can grow to some critical size in the sediment before leaking toward the surface through one of the vents. Vents are found in some places alongside such extraneous materials as tumbleweed twigs embedded in the sediment. The gas cavity, if it does not collapse, fills with water, and the euhedral gypsum crystals may then precipitate in it.

The cavities may tend to form at preferred depths because of the presence of a weak layer or a layer having slightly higher initial permeability. In one core, a quarter-inch layer of what is thought to be vegetative charophyte remains was found in the center of a 2-inch section of euhedral gypsum crystals. Small fragments of organic material were found with the gypsum crystals both above and below the organic layer, as if they had been displaced from the layer. However, most of the organic fibers, being intermeshed, were confined to a single layer.

In Laguna del Perro, vents appear to have random distribution, with spacing on the order of 25 to 50 ft. They can be located most easily during the spring when the playas are salt covered, at which time they are surrounded by salt-free areas, most of which are 1 to 10 inches in diameter. The size of the salt-free area is related to rate of water flow from the vent. New vents in some places can be started artificially by inserting a finger or stick a few inches into the sediment near an existing vent, but elsewhere flow does not necessarily take place when a hole is made. The artificial vents tend to flow for a period of hours or days, and then to disappear.

Much of our knowledge of the vent phenomenon results from observation of 2 large vents near the east shore of the north end of Laguna del Perro. These vents, the largest that have been found on the playas, have salt-free areas that vary in size with time, but that have been observed to reach 16 ~~to~~ by 20 ft across. Salt-free flow channels may extend another 20 ft from the central salt-free area. The flow channels are ephemeral, and their existence and direction, as well as the shape and size of the central area, depend in large part on the strength and direction of the wind.

Although large vents are apparently rare, the 2 that were observed are probably not unique. At some locations on the playas, shieldlike areas 10 to 20 ft in diameter rise an inch to several inches above the general playa surface. Sediment forming the shields is soft and usually more moist than surrounding sediment. The shields may have been built from wind-blown sediment collecting in the wet area of a large vent. The high moisture content of the shield sediment indicates that the vents are still discharging water.

The vents in the center of the 2 large salt-free areas are conical and are about an inch in diameter at the top, tapering to a fraction of an inch at depths of about a quarter of an inch. Upward-flowing water suspends sediment in the throat of the vent and makes size estimation difficult without destroying the surface features. Every effort was made not to change the natural condition of either of the large vents in order to allow precise measurements to be made later on the undisturbed system. By feeling gently in the throat of the vents, it was determined that the pipe narrows to less than a quarter inch at a depth of about an inch. A thin layer of black sediment, brought up through and discharged from the vent, covers the surficial sediment over a radius of 6 to 8 inches around the vent.

Discharging water flows in a density layer radially outward under the normal playa water. Water depth on the playas during the dry season, when the salt crust is present, is a quarter to a half inch, and the high-density layer that carries the vent discharge may be half that deep. The rate of discharge from the large vents was not measured precisely, but observing rate of flow in a confined channel that leaves the central salt-free area of one of the large vents, it was estimated to be a small fraction of a gallon per minute. The rate of discharge from all vents is increased by the weight of the observer on the playa surface at distances of several feet from the vents.

Specific conductance measurements were made on samples of water from the playa surface some distance from the vent. A typical pair of water samples have specific conductances of 158,000 micromhos for the vent discharge and 149,000 micromohos for playa water. Because of sampling difficulties, the vent sample was almost surely contaminated by overlying nonvent water.

There appear to be no vents of intermediate size between those with salt-free areas measured in inches and the large vents. Whether the water driving mechanism for vents differing so greatly in size is the same or different has not been determined. An obvious conclusion is that the vents are discharging ground water that is passing through the playa sediment from deeper formations. Superimposed on this general flow pattern, however, are other forces that are not yet clearly understood. For example, the vent discharge of highly concentrated water as a density underflow beneath playa water suggests the possibility that a membrane effect is operating in which the less concentrated surface water is being imbibed, thus raising the pressure and forcing discharge through the vents, which are in effect membrane leaks.

Water levels in the test holes in T. 6 N., R. 9 E. are mostly 10 to 15 ft below land surface, and the pressure head in the Estancia Valley formation is about 3 ft higher than that of the stratigraphically higher medial sand member of the Dog Lake formation. Pressure heads in both aquifers are higher than the levels of nearby playas, and Berkshire #3 test hole, completed in the medial sand at the edge of a playa, discharged about 8 gpm continuously onto the playa. Some water, known to be a small amount in most places, reaches the playas from slow seepage through the upper lacustrine member, but most of the water comes from vertical leakage from the alluvial aquifer and the medial sand (fig. 18). Under the west side of the valley floor, ground water flowing eastward from the recharge area has pushed the relatively more highly mineralized water in the alluvium and the medial sand eastward since the disappearance of Lake Estancia, and the interface

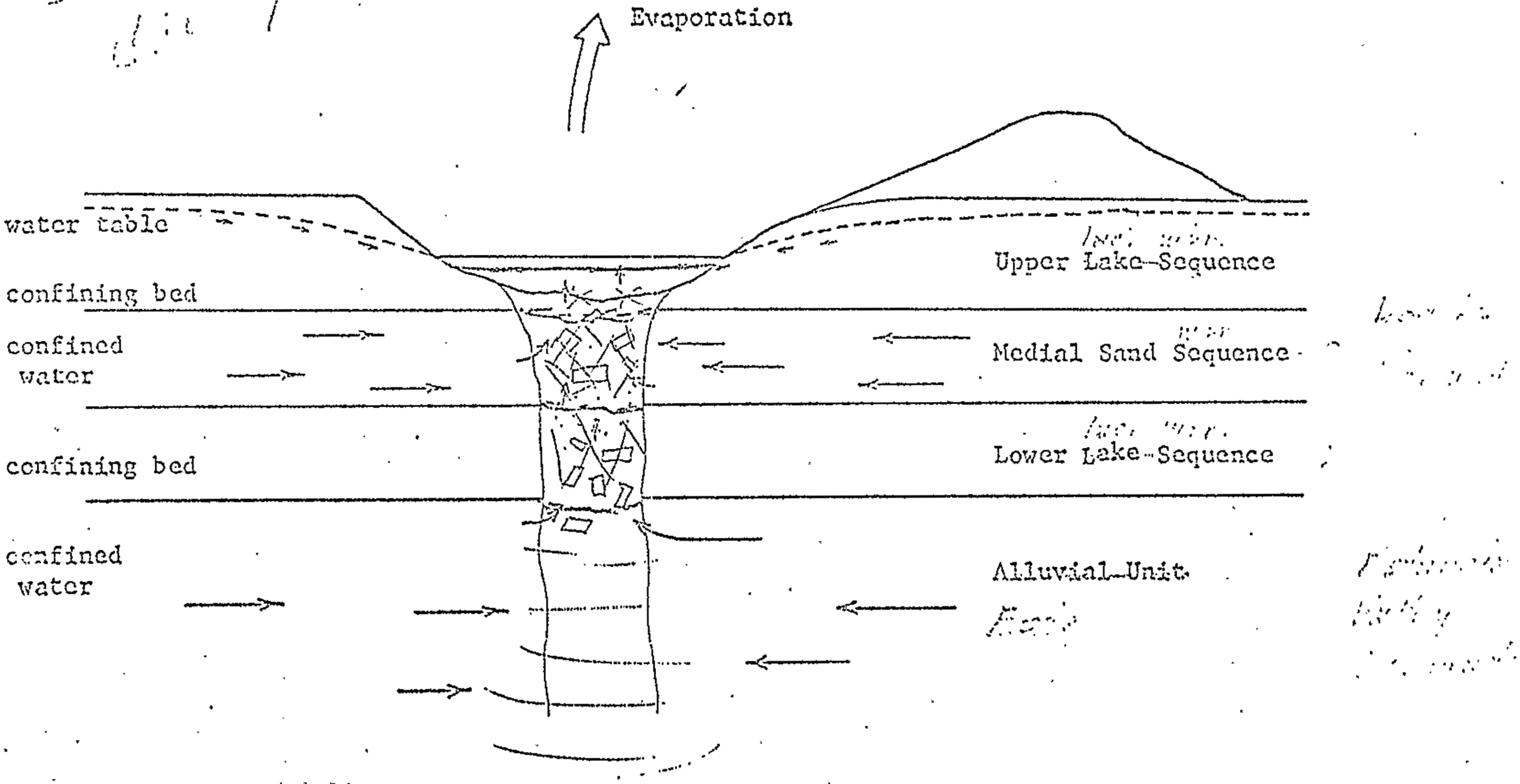


FIGURE 18 — Schematic cross section through a playa depression showing collapse zone and flow of ground water.

between the waters of different quality in the Estancia Valley alluvium is farther east than that in the medial sand. The eastward-moving ground water discharges to the playas. If porosities of the 2 aquifers are assumed to be equal, and hydraulic gradients are equal, then the greater thickness of the alluvium 10 times greater than that of the medial sand, indicates a proportionately greater discharge of the alluvium to the playas. Considering the different positions of the salinity interfaces, even this figure may be minimal. The Estancia Valley formation, therefore, contributes a major share of the dissolved solids that reach the playas.

Starting about the first of each year, salt precipitates from the playa water to form a crust. The salt crust forms and is dissolved by rainfall several times before it is established for the season, but by February or March it is usually reasonably permanent. The crust then lasts until the summer rains begin, usually in July. The first heavy rains dissolve the crust, and although a thin crust may appear temporarily during late summer, the thick crust is not reestablished until the following year.

The salt crusts, through most of the season, consist of high-purity sodium chloride (halite). Early in the season, when maximum water temperatures are below about 10°C., lathlike crystals of the mineral mirabilite ($Na_2O.SO_3.10H_2O$) grow to lengths of several inches. The mirabilite crystals were identified from X-ray powder patterns by R. W. Foster, New Mexico Bureau of Mines & Mineral Resources, and compositions were checked by chemical analysis by L. Brandvold, New Mexico Bureau of Mines & Mineral Resources. Chemical analyses showed that the mirabilite crystals commonly contain about 10 percent chloride, and thus are partly common salt. As water temperatures rise, mirabilite is dissolved and replaced by halite. Chemical analyses of salt crystals show that impurities do not exceed 0.1 percent by weight.

Phalen (1919) referred to the presence of bloedite, the double sulfate of sodium and magnesium ($MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$), in the playa salt of Laguna Salina in secs. 5 and 6, T. 5 N., Talmadge and Wootton (1937, p. 141-142) also mentioned the presence of bloedite, and commented on the presence of epsomite ($MgSO_4 \cdot 7H_2O$), and the common occurrence of mirabilite and its dehydration product thenardite (Na_2SO_4). Only the salt from Laguna del Perro was analyzed in this study, and no attempt was made to identify the exotic minerals. As has been shown, the presence of mirabilite at the surface is seasonal, and the mineral was not found at depth in the sediment.

The salt crust consists of a loose mesh of crystals that have very little structural strength. Walking on the surface at any distance from shore was accomplished only by wearing "skis" made of 1- by 6-inch lumber. The crystal mesh is always highly porous, with minimum porosity estimated at about 40 percent. Playa surfaces, at distances of more than a few tens of feet out from the edge of the flat, were found in more than 2 years of weekly observations never to be dry. Although the upper part of the salt dries out, free water is always found in the crystal mesh.

During the period of strong spring winds that blow from the southwest, small amounts of dust are deposited on the salt surface. Dust usually tends to collect on and behind surface irregularities, such as pressure ridges 1 to 2 inches high, although pressure ridges as high as about 6 inches have been seen on high salt producing playas. On relatively smooth crust the dust never totally obscures the surface, but it may accumulate to depths of about a half inch on the windward side of pressure ridges. Periodic rains wash the dust down through the crystal mesh depositing it beneath the crust. A silt-clay layer as thick as one-sixteenth inch has been found between the crust formed during the current year and a salt layer thought to be that of the preceding year.

The salt crust on Laguna del Perro and most other playas reaches a maximum thickness of about an inch. This thickness can be attained within a period of a few weeks, after which it does not increase significantly. This suggests that most of the salt that forms the crust comes from solution of crust from the preceding year, and it implies that the Na^+ and Cl^- ions that are added to the playa water system during a single year by ground-water inflow constitute a minute part of the total salt load at a playa.

Halite crystals in the playa sediment are common only to depths of a few inches below the ephemeral salt crust. Salt buried with the clay and silt is redissolved by the upward-moving ground water and returned to the surface. Any salt removal from the system must be by wind. White clouds of wind-blown material have on rare occasions been observed leaving the playas; however, salt is a very minor constituent of the dunes. Soil analyses of surficial material at the top of the Dog Lake Formation have not been made, but growth of grasses east of the playas does not appear to be less vigorous than elsewhere in the valley. Hence, it is concluded that little salt is being removed from the playa-water system by wind action.

It is suggested here that the playa-water salt system has only recently evolved to its present state, and is still evolving. The condition in which salt must be removed by permanent incorporation in playa sediment as fast as it is brought in by ground water has not yet been reached.

The depressions are in the process of being filled a) by crystal precipitation, mainly of gypsum, from evaporating water, b) by wind-blown dust trapped on the surface, and c) by material eroded from depression walls and washed onto the surface by runoff. The relative importance of each process has not been estimated. Low marginal deltas at the edges of playas, the heights of which are measured in inches, cover relatively small percentages of the playa surfaces except on the smallest playas, indicating that runoff carries some sediment onto the surfaces. Each of the other 2 mechanisms can raise the playa level only when the surface is moist. The relative rates of sediment accumulation from playa to playa may be controlled in large part by the rates at which ground water reaches the playa surface, and it is expected that flow rates vary somewhat from playa to playa, mainly as a result of difference in permeability in the collapse zone through which vertical flow occurs.

A difference in playa elevation of 11 ft was measured between the 2 larger playas nearest the town of Estancia (sec. 17 and 21, T. 6 N., R. 9 E.) (fig. 14). The southeastern playa of the pair, lying nearest the axis of the valley, has an elevation of 6,071 ft, whereas the other has an elevation of 6,060 ft. The valley floor elevation at the section corner between the pair is 6,083 ft. At another playa pair on opposite sides of US-60 near the SE corner of sec. 12, T. 4 N., R. 9 E., there is an elevation difference of 6 ft between them; the northwest playa is at 6,040 ft and the southeast at 6,034 ft, the same as Laguna del Perro. Two playas lying east of the north tip of Laguna del Perro are both more than 20 ft higher than Laguna del Perro. How much of the differences in elevation is due to maximum depth of the floors and how much to subsequent infilling has not determined.

The reversal of the playa process, from a condition in which deflation was occurring, to the present one in which infilling is occurring, obviously requires some explanation. It is tempting to explain the reversal by simple climatic change in the past few thousand years (Titus, 1969, p. 131). But when careful consideration is given to the hydrogeologic changes that must have accompanied deflation and reversal, and the changes that are now accompanying infilling, they lead to the conclusion that the depression-forming process in this system was probably self-limiting. This is not to say that the process has been independent of climate; its operation has depended for the most part on the degree to which evaporation has exceeded the sum of precipitation and ground-water inflow to the playas.

The rate of ground-water flow to the playa system at any time has been controlled by the difference in hydraulic potential (head) between recharge and discharge areas, and the transmissivity of different parts of the system, but particularly by the changes in vertical transmitting capacity of the upper lacustrine member of the Dog Lake formation as that member was thinned by deflation. Both of these factors were subject to change during the depression-formative, or deflation, stage. During this discussion it will be assumed that gypsum solution in the Yeso at depth, and the subsidence and structural disruption of the Dog Lake formation that created both the vertically permeable zones and the initial playas were completed before deflation began.

As deflation of a typical depression proceeded, the thickness of the upper member of the Dog Lake formation beneath the playa floor diminished; with diminishing thickness a high-resistance part of the flow path (hydraulically speaking) became progressively more transmissive, allowing water to flow upward more readily to the playa surface. Simultaneously, with decrease in level of the playa floor, the potential difference over the flow path increased. That is, the hydraulic gradient increased, and it increased most notably across the vertical interval through the flow-restricting Dog Lake formation. This too caused water to flow more readily to the playa surface. Even in the absence of any other change, deflation would ultimately reduce the level of the playa to a point where evaporation could never dry out the floor. As this condition was approached the rate of deflation progressively diminished, until at some stage the hydrologic system was in balance with the physical position of the playa, and deflation stopped.

Consider now another aspect of the system: the rate of evaporation of water that reached the playa at any stage would be controlled by climatic conditions and by the chemical concentration of the water. Climate will be assumed to be constant. Langbein (1961) has shown that as the amount of dissolved material in water increases, the evaporation rate decreases approximately proportionally to the percent by weight of the dissolved material (for example, water containing 200,000 ppm evaporates about 20 percent slower than pure water).

Superimposing this factor on the ground-water-inflow conditions suggests that even while the depressions were in the deflation stage, the rate of evaporation began to diminish slowly as dissolved solids left behind by evaporation increased the concentration of the playa water. An aspect of the chemical control phenomenon is that when the solution becomes saturated with respect to a particular mineral and that mineral begins to precipitate, the rates of increase are diminished for the ions forming that mineral. Thus, when gypsum began to precipitate in the playa sediment, calcium, the ion in shorter supply, no longer increased in concentration, and sulfate continued to increase with continued evaporation but much more slowly.

During the playa deflation stage the effects of this chemical factor were added to the hydraulic effects in controlling deflation rates. From the time that deflation reduced the playa to its minimum level and the hydraulic effects no longer changed the ground-water-inflow rate, the evaporation-induced change in chemical concentration became the dominant controlling factor. It was this factor alone, therefore, that could have triggered the infilling process.

Present evaporation rates are low enough that the playas are always covered by at least a thin film of water. The concentrations of Na^{+} and Cl^{-} ions in the water have increased to such levels that halite precipitates seasonally on the playas, but they have not yet reached concentrations that require permanent removal by incorporation of halite into the sediment. Until that concentration is reached, the Na^{+} and Cl^{-} ions will continue to increase. After salt begins to be incorporated into the sediment, the rates of Na^+ and Cl^- increase will decline. Other ions, of course, will continue to increase until their saturation points also are reached.

Chemical analyses show the difference between water in the aquifers and water now at the playas (Appendix C). The ratios between chloride and sulfate show that in the aquifers sulfate is the dominant anion: Estancia Valley formation, $Cl/SO_4 = 0.4$; medial sand of the Dog Lake formation, $Cl/SO_4 = 0.6$. Among playa waters, in contrast, $Cl/SO_4 = 1.9$. The concentration of all dissolved solids is 2 orders of magnitude higher at the playas than in the aquifers, reaching an upper limit over 440,000 ppm. It is interesting to note that calcium in water on the playas does not reach high concentrations, presumably because it is being removed by gypsum precipitation within the playa sediment.

The amount of salt crust that seasonally accumulates seems generally to be comparable among playas except that a few generate anomalously thick crusts. Playas included in this group are Salt Lake, east of Estancia (sec. 17, T. 6 N., R. 9 E.); Salina Lake and surrounding small playas at the south end of the basin (parts of secs. 23-26, T. 4 N., R. 9 E.); Laguna Salina, in La Salina Grant (secs. 29-30, T. 5 N., R. 10 E.); and an unnamed playa in the SW¼ sec. 6, T. 6 N., R. 10 E. (fig. 14). The first 3 of these have long been known by residents to be heavy salt producers, and have received names appropriate to their condition.

The unnamed playa, in contrast, reportedly began to produce large amounts of salt only in recent years. The anomalously large amounts of salt that appear on these playas are thought to come mostly from salt in the upper lacustrine member of the Dog Lake formation that has been dissolved and carried to the playas by shallow ground water. The implication is that these playas receive more water than most from the uppermost part of the zone of saturation in the Dog Lake formation, although the amount is still much less than the volume of water rising from the underlying Estancia Valley formation.

All these playas, for different reasons, are in locations where unusual amounts of surface recharge are available to the lake sediment. Salt Lake, near Estancia, is one of the westernmost of all playas, and lies in an area where any exceptionally heavy runoff from rainfall in the drainage area to the west collects in shallow swales near the playa. An insignificant amount of runoff was seen to flow into the depression during severe storm in August 1967 but ponds several feet deep and lasting many months formed outside of the depression on the west and south sides. Salina Lake, and small playas to the east, west, and south, are at the south end of Estancia Valley, where runoff from 3 sides of the basin converges and collects near, but rarely in, the playas. Laguna Salina does not have an obvious source of anomalous recharge, but it lies to the south of a large area in the center of the depression field that has no playas. It may receive a disproportionate amount of the recharge that comes from rainfall on this area.

The unnamed playa in the SW¼ sec. 6, T. 6 N., R. 10 E. has provided direct evidence that salt can be dissolved out of the upper lacustrine member and transported to a playa. Prior to about 1959 the playa did not produce thick salt crusts, according to several ranchers and farmers who live nearby. At about this time, irrigation of fields 1 mile to the west and 1 mile to the southeast began. Irrigation to the southeast has since ceased, but irrigation continues in the field to the west. The thicker annual salt crust was noticed by the residents after irrigation had continued for an unknown length of time. Very small seeps around the playa now discharge at levels a few inches above the floor. Rates of discharge have not been measured, but a single seep yields only an extremely small fraction of a gallon per minute. Similar seeps have been found at the edges of many playas, including Laguna del Perro, but nowhere else are they as numerous or as closely spaced as at the unnamed playa described above.

The permeability of the upper lake clay is very low. R. Smith (1957, p. 52, 113) reports construction of a 10-ft-deep hole, 200 ft west of the south end of Laguna del Perro. The water level in the hole rose to a height 10 ft above playa level. The high slope of the water table indicates low but not significant horizontal permeability. To Smith, the water level indicated upward leakage through the lake clays from a lower aquifer, and this was used to support the argument for such leakage supplying water to the playas. As has been discussed in this paper, however, vertical leakage to the playas more likely occurs through the collapse zone. The height of the water table measured by Smith is no doubt due to the lake sediment being a leaky confining bed. However, the water in the upper part of the saturated zone can only come from recharge at the surface.

The top of the Dog Lake formation, which formed the lake floor at the time of disappearance of Late Lake Estancia, was the site of gypsum precipitation as the lake evaporated, as is indicated by the mineralogy of the group of small, early dunes. During late stages of this evaporation, and more importantly, during late stages of evaporation of the rejuvenated shallow lake, the residual brine must have contained concentrated sodium cholride. Thus salt is presumed also to have precipitated on the lake floor, but it is not now present on the floor nor in the shallow soils. The amount of salt apparently was small enough that it was subsequently carried downward into the lake beds by infiltrating rainfall.

Although salt crystals are not seen in outcrops of the upper member of the Dog Lake, they were found occasionally during drilling at shallow depths in the sequence. More often, the salt dissolved in the drilling mud. In one test hole (Berkshire #3), which was drilled through the upper lake sequence and finished in the medial sand at 37.5 ft in 70 minutes of drilling, sequential chemical analyses of water substantiate the salty character of the lake sequence. The hole is located on the west side of the playa in sec. 21, T. 6 N., R. 9 E., and the well head is about 2 ft above playa level. The well has artesian flow, and the flow stabilized at about 8 gpm. Water that discharged from the hole initially contained an anomalously large concentration of chloride for ground water in the medial sand. As the well continued to flow, the chloride concentration diminished and stabilized at a normal concentration for the aquifer. The following Cl/SO_4 ratios were calculated from chemical analyses tabulated in Appendix C (well drilled 12/8/67):

Date	Cl/SO_4 Ratio
12/12/67	1.21
1/4/68	.64
4/23/68	.61

The average Cl/SO_4 ratio for water in the medial sand is 0.6. The high chloride concentration in the early flow probably came from salty drilling mud slowly washed from the open hole, slower flushing of salt water and salty mud that had infiltrated the medial sand during drilling, and salt that subsequently dissolved from the walls of the hole. Although fresh water was used for drilling, the mud became salty from halite and salt water in the formation.

This evidence confirms the thesis that part of the chloride in playa water is salt dissolved from the upper member of the Dog Lake formation and transported by shallow ground-water flow to the playas. Because the amount of salt on the playas and in playa water is not really large, and because ground water in the 2 aquifers contains from 300 to 500 ppm chloride, it must be concluded that the hydrologic process that concentrates salt at the playas has been active for only a very short period of geologic time. A reasonable estimate is a very few thousand years.

HYDROLOGY OF THE BASIN

The idealized natural circulation pattern for water in the basin is relatively simple (fig. 19). Recharge takes place mostly on the sloping sides of the basin, and ground water flows to the central part of the basin where it returns to the surface to be removed by evaporation. Surface runoff from the sides of the basin to the central part is rare. Water that does not percolate to the water table to become recharge, for the most part evaporates near the place at which it falls. Most precipitation that falls on the central part of the basin evaporates where it falls, but a very small part moves slowly through the upper lacustrine clayey strata near the surface to the playas where it evaporates along with water that has risen from below. Part of the ground water at the north end of the basin does not leave the basin by evaporation but rather by subsurface leakeage.

Subsurface Leakage

Meinzer (1911, p. 37-38), having no data on which to base a firm conclusion, emphasized that the pre-Tertiary rock formations in the sides of and underlying the basin are relatively impervious but, recognizing that the level of the basin floor is well above the level of the surrounding territory, he suggested that leakage might occur, and that it might be substantial. R. Smith (1957, p. 52), in contrast, concluded that natural discharge takes

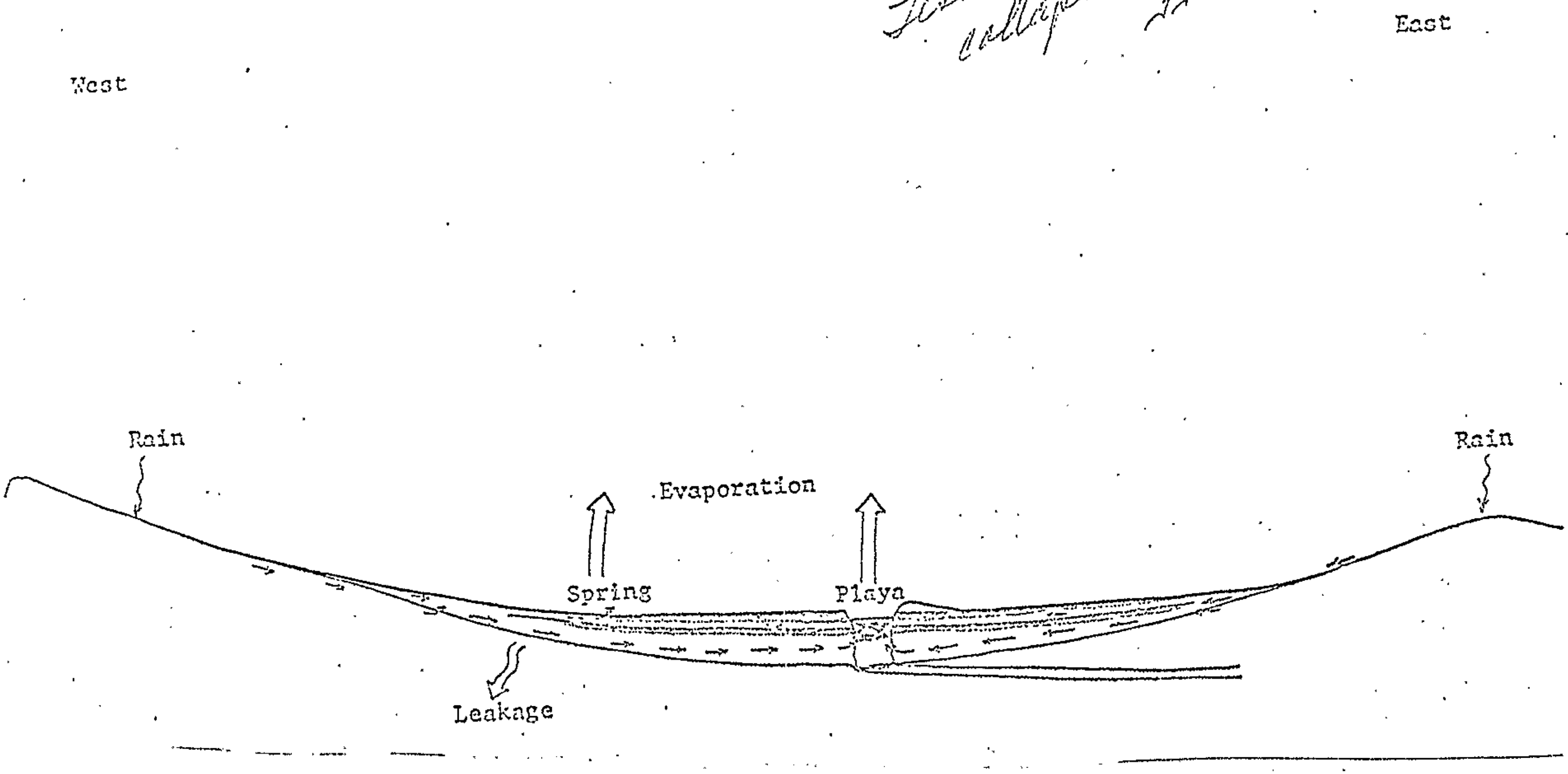


FIGURE 19 — Schematic cross section of the valley showing flow of ground water.

place only in the vicinity of the playas. He considered the possibility that ground water might flow southeastward toward the topographic sill area, but rejected the hypothesis because his water-quality data did not support it.

R. Smith (1957, pl. 2) presented water-level data that show a ground-water ridge surrounding the basin, the axis of which is approximately coincident with the topographic rim. His project area did not include the north end of the basin, but measurements made later by personnel of the State Engineer Office and in my investigations, show that the ground-water ridge is continuous here too. Smith's contours and the later measurements indicate that the crest of the ridge on the north, east, and south is nearly everywhere between 6,200 and 6,300 ft.

The theory of regional ground-water flow allows ground water to pass, at relatively great depth, beneath a ground-water ridge under certain conditions. The conditions relate mostly to thickness of the ground-water reservoir, height of the ridge, anisotropy due to interlayering of high- and low-permeability strata, and the regional gradient (Toth, 1963; Freeze and Witherspoon, 1966, 1967). Regional flow beneath a ground-water mound is favored by great reservoir thickness in comparison to height of the mound, by much greater horizontal than vertical permeability, and by high gradients.

The upland terrane along the west and east sides of

Estancia Valley is underlain by Precambrian rock, the upper surface of which in most places is above the elevation of the valley floor. Subsurface ground-water leakage in either of these directions can be rejected intuitively upon consideration of the very low permeability of the Precambrian rock, the thin reservoir zone, and the height of ground-water ridge.

Referring to the Precambrian-surface map (fig. 6) it will be seen that most promising routes for leakage are south-southwestward from the Estancia structural basin, or northward into the Galisteo structural basin. The possibility of southward leakage will be considered first. The upper part of the Yeso Formation, and overlying strata, crop out in bluffs of Mesa Jumanes at the northwest corner of T. 3 N., R. 8 E. (fig. 3), and strata of the lower part of the Yeso, the Abo Formation, and the Madera Limestone are below the surface at the foot of the bluffs.

The saturated thickness of these formations is more than 10 times greater than the height of the ground-water ridge, and the anisotropy is probably high owing to thick shale beds in the sequence. These factors would tend to allow deep regional flow beneath the ridge. However, the permeability of the formations is low. The Madera Limestone, the principal aquifer here probably does not have the solution-improved permeability that it has in areas where it crops out. The hydraulic gradient between the floor of Estancia Valley and the north end of the Tularosa basin (toward which flow would move) is also low.

Both of these factors are unfavorable to deep, regional outflow. The hydrology of the north end of the Tularosa basin does not indicate in any way that the area is receiving significant amounts of ground water from an external source (Weir, 1965, p. 30, 31). In the absence of any indication of southward leakage, it is concluded that loss in this direction from the Estancia Basin is insignificant, if it occurs at all.

In the north subbasin of Estancia Valley the entire pre-Tertiary stratigraphic sequence of rocks, from the Madera Limestone of Pennsylvanian age to the Mesaverde Formation of Cretaceous age, is in subsurface contact with the base of saturated alluvium (fig. 3). The pre-Tertiary section includes numerous sandstone and limestone beds that, in hydrologic investigations of nearby areas, have been shown to have adequate permeability for exploitation of ground water by low- to moderate-yield wells. The total thickness of pre-Tertiary strata in contact with the alluvium is on the order of 8,000 ft; the aggregate thickness of moderately permeable strata has not been determined, but it is probably 1,000 ft or more. The pre-Tertiary section also includes several thick shale sections which would cause the section as a whole to be non-isotropic. Shale and sandstone strata of Triassic and Cretaceous age underlie the Estancia Valley formation at the north end of the valley.

The Galisteo structural basin, in which the entire pre-Tertiary section is present, is shown on fig. 6 to be open toward the Rio Grande structural trough on the west.

The contour map of the Precambrian surface published by Foster and Stipp (1961), from which fig. 6 was taken, has been modified by deepening the surface here because of the thickness of pre-Tertiary strata that underlie outcrops of Cretaceous rocks. Alluvium of the Santa Fe Formation in the Rio Grande trough is in fault contact with at least the lower 5,000 ft of the pre-Tertiary section (Stearns, 1953, pl. 1).

The details of the hydraulic gradient between the north end of Estancia Valley and the east side of the Rio Grande trough are not known, but regional geologic, hydrologic, and topographic factors strongly suggest that the piezometric surface slopes generally toward the Rio Grande (Titus, 1961, fig. 1). The water table on the east side of the Rio Grande trough in the vicinity of Galisteo Arroyo is more than 800 ft below the level of the water table in the north end of Estancia Valley, indicating that if ground water were to flow along a 25-mile path around the north end of the Ortiz Mountains, the average hydraulic gradient would be more than 30 ft per mile. Water in the Santa Fe Formation at Algodones, about 15 miles down the Rio Grande valley from the point at which Galisteo Arroyo joins the Rio Grande, contains approximately twice as much dissolved solids as is normal for the formation farther to the south (Bjorklund and Maxwell, 1961, pl. 3b), and it is proposed here that this may result from highly mineralized water entering the Santa Fe from the east.

It is reasonable to suspect, therefore, that leakage from the north subbasin of Estancia Valley does occur. In the words of Meinzer (1911, p. 38): "The conditions here involved are so complex and obscure that it is impossible to form an estimate of the amount of leakage, but it may be a large factor." The hypothesis could, and because of its water-management implications should, be tested by hydrologic investigation along the route of probable leakage and by a quantitative inflow-outflow study of water in the north subbasin.

Modern Hydrologic Conditions

Recharge to the system is solely from rainfall and snowfall in the valley and surrounding hills and mountains. Precipitation ranges from a maximum of about 30 inches per year in very small areas on the highest mountain peaks, to a minimum between 11 and 12 inches in the central part of the valley, as is shown in the New Mexico State Engineer Office (1956) summary of U.S. Weather Bureau records for 1849 to 1954. R. Smith (1957, tables 1, 2) summarized the precipitation records for 12 weather stations in and near the valley. His annual averages, taken over the period of record to 1953, are about an inch higher than what is considered normal for each station by the U.S. Weather Bureau. The Weather Bureau calculates normal precipitation from averages of the 30-year period 1931 to 1960 (U.S. Weather Bureau, 1968). Average precipitation on the slope of the Manzano Mountains is about 20 inches a year, which is similar to precipitation at the Tajique weather station.

On the Pedernal upland, east of the basin, precipitation averages about 13 inches a year, and it is about 12 inches in the center of the valley at Estancia, Otto, and McIntosh. Progresso, at the south end of the valley floor, receives about 14 inches a year. Approximately half of the precipitation occurs in July, August, and September.

Higher temperatures prevail at lower elevations, and it is presumed that a greater percentage of the precipitation at low elevations evaporates before it can recharge aquifers. Lower precipitation, higher evaporation, and the fact that runoff rarely reaches the valley floor combine to substantially reduce recharge potential in the central lowlands of the valley. The drainage area on the west slope of the valley is nearly 3 times as great as that on the east slope. The larger area, greater precipitation, and lower evaporation rates on the west slope than on the east, require the conclusion that recharge is possibly as much as 3 to 5 times greater on the west than that on the east. The volumes of ground water flowing to the center of the valley from the 2 sides must be proportional to the recharge.

Assuming that distribution of topographic relief has remained nearly constant since the time at which Lake Estancia first formed, relative rates of precipitation and evaporation on the 2 sides of the valley may also have remained nearly constant. During times in which the lake filled the lower part of the valley, it flooded a larger percentage of the eastern drainage than the west. In these times, therefore, the relative amount of recharge on the west, hence the ground-water flow, may have been even greater than it is today.

On the slope of the Manzano Mountains recharge infiltrates the upper, permeable zone of the Madera Limestone. The depth of the water table and the few flowing streams in canyons high on the slope indicates that very little recharge is rejected for lack of storage capacity in the aquifer; lower on the slope, where the alluvium of the Estancia Valley formation crops out, no recharge is rejected. Ground water is transmitted toward the central part of the valley through both the upper, permeable part of the Madera and the alluvium. Most of the water that discharges upward from the Madera into the alluvial unit probably does so before reaching the edge of the Abo subcrop, for the Abo is generally tight, and flow through it across the bedding is necessarily very slow, and may be negligible.

Recharge to the central part of the valley from the east through the Yeso, Glorieta, and San Andres formations probably also discharges to the alluvium, although it is possible that some flow may take place through sandstone beds in the Yeso beneath the alluvium. Because permeability of the Yeso sandstones is much lower than that of the alluvium, and because the Yeso probably was faulted on the east side of the valley during subsidence that accompanied deposition of the alluvial unit, thus offsetting beds, the proportion of total flow from the east that may be carried by Yeso strata is thought to be very small.

Under the natural flow regime, prior to its disturbance by pumping activities of man that began about 3 decades ago, ground water left the basin by 3 routes; a) probable subsurface leakage outward from the north subbasin, b) evaporative discharge from the playas, and c) evaporation and transpiration from an extensive spring and seep line on the west side of the valley floor (fig. 19). The spring and seep line was located at the facies contact between clayey lacustrine sediment of the Dog Lake formation in the central part of the valley and the clastic facies of ~~the~~ lake sediment to the west. No analogous spring line is known on the east side of the basin, probably because of much smaller recharge rates there. No springs are known to have existed in the north subbasin, probably because of the postulated subsurface leakage.

Contrary to the opinion of R. Smith (1957, p. 52), who thought that the main area of natural evaporative discharge has always been restricted to the playas, it is concluded from this study that a significant amount of water evaporated or was transpired by phreatophytes along the spring line before the water table was depressed by pumping for irrigation. South of Estancia the spring line was a marshy area of heavy reeds and grass that reportedly was too soft in some areas for stock to walk on. The marshes are part of the childhood memories of most long-time residents. The marshy area may have been as much as a mile wide, and it extended south from Estancia for at least 7 miles. At Estancia and to the north, where the slope is slightly steeper, discharge was mainly from discrete springs, although broad marshy areas existed here too. Water flowing from the springs and seeps had come from the west slope, and therefore contained only small amounts of dissolved material in comparison to ground water toward the center of the basin. Some signs of springs still remain, but they are no longer prominent.

The position and elevation of the spring line controlled the pressure in the confined aquifers consisting of the Estancia Valley formation and the medial sand member of the Dog Lake formation. Ground water entered the artesian environments of the 2 aquifers by flowing under the springs, then passing beneath the edge of the confining beds consisting of the lower and upper members of the Dog Lake formation. The water then continued to flow eastward toward the point of discharge at the playas. The playas also discharged all water that entered the same aquifers on the east side of the basin, hence the amount of water that originally passed under the spring line was equal to the total playa discharge minus the volume of water contributed by the east side of the basin. The water that discharged at the springs consisted of that part of the flow from the west which exceeded the flow capacity of the alluvial and medial sand aquifers in the confined zone.

If it is assumed that the playas discharged equal amounts of water from the 2 sides of the basin, and that the total amount of ground water available on the west was 3 times the amount on the east, it can be estimated that evaporative discharge from the spring line approximately equalled that from the playas. The evapotranspiration then may have been 30,000 acre-ft annually, based on playa evaporation estimates discussed below.

Wells in the western part of Tps. 4-6N, R. 9 E. that produce from the alluvium beneath the west edge of the Dog Lake formation confining beds yield water similar in quality to those farther west (New Mexico State Engineer Office, 1966). In the central part of R. 9 E., but still west of the playas, the quality of ground water in the aquifer deteriorates, particularly in that sulfate concentration increases. The interface between fresh and brackish water is quite well defined (R. Smith, 1957, pl. 2), in most places lying 2 to 4 miles east of the facies contact between clayey and coarse-clastic sediment of the Dog Lake formation, and thus an equal distance east of the former spring line. If it is assumed that water beneath the confining beds of the lacustrine unit contained relatively high sulfate concentrations at the time of development of the depressions and initiation of discharge there, which is reasonable in view of the great length of time the ground water was stagnant while the lakes covered the valley floor, then it may be concluded that 2 to 4 miles is the distance that fresh ground water from the west had moved into the confined part of the aquifer between the time that discharge began at the playa depressions and the time that human activity disrupted the system.

Ground water in the medial sand aquifer west of the playas contains larger amounts of dissolved solids than that in the alluvial unit. A chemical analysis reported by R. Smith (1957, p. 172) for a shallow well in the SW¼SW¼SW¼ sec. 28, T. 6 N., R. 9 E. completed in the medial sand, shows a chloride content of 244 ppm and a specific conductance of 4,380 micromhos. One mile to the south, a well now known from information given by the owner to be producing from the alluvium, was reported by Smith to have a chloride content of 79 ppm and specific conductance of 1,980 micromhos. Several typical analyses of water in the 2 aquifers are tabulated in Appendix C. The high dissolved solids, particularly chlorides, in the medial sand are from evaporites that were deposited when Early Lake Estancia disappeared. The chemical interface between brackish water and fresh water in the medial sand is farther to the west than the interface in the alluvium. The rate of ground-water movement toward the playas in the medial sand thus is slower than that in the alluvium.

DeBrine (1971), using data collected from another phase of this project, has calculated that the annual evaporative discharge from the playa system is between 27,000 and 36,000 acre-ft. His calculations were based on 2 kinds of system measurements: a) ground-water inflow toward a single playa around which test holes had been constructed, and b) accurate measurement of microclimatic conditions near a playa surface and use of the data to calculate evaporation from open water, salt-crusted surfaces, and moist sediment surfaces. DeBrine's calculation is based on much more extensive data than were available to Smith, who earlier had calculated the discharge to be 50,000 acre-ft annually (R. Smith, 1957, p. 52).

Chemical analyses of water from playas (Appendix C), made for this project by the U.S. Geological Survey under a cooperative agreement with New Mexico Bureau of Mines & Mineral Resources, suggest that playa brines average 240,000 ppm dissolved solids. Thirteen analyses are included in the average, and samples were collected both when there was a crust and when there was none. Using Langbein's (1961, p. 3) approximation that the decrease in rate of evaporation due to high concentrations of dissolved salts is approximately proportional to the percentages by weight of the salt in solution, the evaporation rate from open water for the 240,000 ppm brine on the Estancia playas is 76 percent of the evaporation rate for fresh water.

The natural circulation pattern of ground water in the basin remained undisturbed until about 1946 when the effects of increasing pumpage for irrigation began to lower the water table on the west side of the valley (R. Smith, 1957, p. 53). The U.S. Geological Survey has measured changes in water levels in the valley since 1941. The results of recent measurements have been published by the State Engineer Office (Ballance, 1965; Busch, 1966; Busch and Hudson, 1967-1970; Hudson, 1971; Reeder and others, 1959). Heavy pumpage has been localized along the west side of the valley and at the north end because of better quality of the ground water in these areas and because aquifer permeability is high. The result has been to lower the water table an average of 15 to 20 ft to form a linear water-table trough; locally the water table has been lowered more than 40 ft. In the south subbasin the trough roughly coincides with the former spring line.

Lowering the water table at the spring line has stopped discharge from the springs and seeps, and it has also eliminated the head difference that was the driving force for eastward movement of fresh water toward the playas. Although there are no U.S. Geological Survey water-level observation holes in the main playa area, water-level data collected for this project at the test holes indicate that ground water in the central part of the basin is still under artesian pressure. The effect of lowering the pressure head on the west has apparently been partly compensated in the center of the valley by head differences to the east.

The direction of flow in the alluvium and the medial sand has already been reversed under the westernmost parts of the lacustrine confining beds in the fresh-water regime. It must be assumed that the pressure trough will continue to expand eastward, and that eventually the more highly mineralized water in the central part of the valley will begin to flow toward the pumped area, although to date there is no indication of westward movement of the interface. The State Engineer Office has taken this into account in developing its water-management policy for the basin.

SUMMARY OF BASIN HISTORY, QUATERNARY CORRELATIONS

Pre-Lacustrine History

The Estancia structural basin, underlying the southern part of Estancia Valley, and the Galisteo structural basin, underlying the northern part, were formed long before the present cycle of valley filling began. Following development of these structural basins, the land surface in the vicinity was beveled by erosion. The present cycle probably started in late Pliocene time with structural lowering in the area that is now the axial part of Estancia Valley, possibly accompanied by rejuvenation of uplift of the Manzano and Sandia Mountains to the west. The Pedernal block on the east probably remained stable. Subsidence of the valley against the stable Pedernal block took place by faulting with probable vertical displacement of 1,000 ft (Kelley, 1972). In the northern and southern parts of the present valley, the faults have been buried by subsequent accumulation of valley fill, but the west side of the Lobo Hill upland southeast of Moriarty is thought to be a fault scarp.

The assignment of late Pliocene age to the initiation of movement is based on previously recognized remnants of gravel and caliche correlative with the Ogallala, that lie high on the east and west sides of the Pedernal Hills (Darton, 1928; Bretz and Horberg, 1949; Fallis, 1958). The basal valley fill in Estancia Valley is correlated with the pediment gravel and with pediment gravel remnants up to 250 ft above stream valleys on the east slope of the Manzano Mountains that were mapped by Myers (1967). Although Myers considered the gravels to be Quaternary in age, present understanding of the valley history precludes the possibility of their formation during the Quaternary.

R. Smith (1957) was the first to propose late Pliocene(?) age for the valley fill on the basis of correlation with the upper part of the Santa Fe Formation north of Galisteo Creek. Evidence that substantiates this correlation consists of the relationship between 160 ft of coarse alluvial gravel on the north rim of Estancia Valley and the eroded remnant of its probable source rock at Cerro Pelon 5 miles to the north in the Galisteo valley.

Subsidence of the axis of Estancia Valley probably took place no more rapidly than alluvial sediment of the Estancia Valley formation could fill the valley. There is inconclusive evidence in deeper parts of the alluvium that one or more temporary lakes may have formed, suggesting that the lowering took place in pulses. During most of the time of accumulation of the alluvium, the valley was drained by a river that flowed southward down the valley, turning east at the present location of the community of Progresso to follow a great loop across what is now the topographic sill, and northeastward through the valley that connects Pinos Wells and Encino Basins (fig. 13). At Encino the river turned eastward, probably initially to flow to the Llano Estacado.

Deposition in late Pliocene(?) time and well into Pleistocene time resulted in the accumulation of more than 500 ft of alluvium in the valley. At the same time excess sediment was carried out of the valley and on to the east. If the ancient Estancia River was the headwater drainage of the river through the Portales buried valley on the Llano Estacado, then part of the alluvium that fills the Portales Valley had its origin in Estancia Valley.

Deposition probably finally ceased in Estancia Valley because of structural stabilization. This was followed by a period of erosion during which up to 200 ft of the formation was removed from a broad area on the floor of the valley. The degradation of the surface was allowed by erosional deepening of the river valley along its course through the present locations of Pinos Wells and Encino Basins.

In late Pleistocene time, downwarping lowered the contemporary floor of Estancia Valley, as measured at the top of the Estancia Valley formation, nearly 400 ft below the level of the river valley at the topographic sill north of Cedarvale. This established the present topographic closure of the basin. Shoreline features formed by the lakes that subsequently occupied the valley show that the valley has been structurally stable since. The latest date at which downwarping could have taken place was prior to impoundment of Early Lake Estancia, which is correlated with the Terry Pluvial on the Llano Estacado and Bull Lake Glaciation in the Rocky Mountains.

Lacustrine History and Correlations

The closed basin has been occupied by 2 major lake stages and a third shallow rejuvenation. Early Lake Estancia was large enough to fill the basin to above its sill level at 6,350 ft and overflow through the former river valley. Its maximum depth was about 380 ft. Late Lake Estancia rose to 6,225 ft, at and below which it cut well-preserved strandlines. It had a maximum depth of about 200 ft. The final shallow lake did not reach 6,150 ft, having had a maximum depth of about 70 ft.

Correlation of the sequence of Pleistocene events in Estancia Valley with lacustrine and glacial events elsewhere in the western part of the United States is based primarily on a few radiocarbon age dates reported by Lyons (1969) and Bachhuber (1971) from collections that they made in the valley. The correlations are shown in fig. 20. In particular the age interpretations of Bachhuber were relied upon, and a comparison with his work shows no essential correlation differences. The nomenclature differences between this report and that of Bachhuber, shown on fig. 18, are just that--nomenclatural. There are very real differences in inferred lacustrine sedimentary environments and other questions, however, that are not related to acceptance of a chronology. The correlations proposed here modify my earlier interpretation (Titus, 1969), principally by making Early Lake Estancia older and by lengthening the duration of each of the 2 major lake stages.

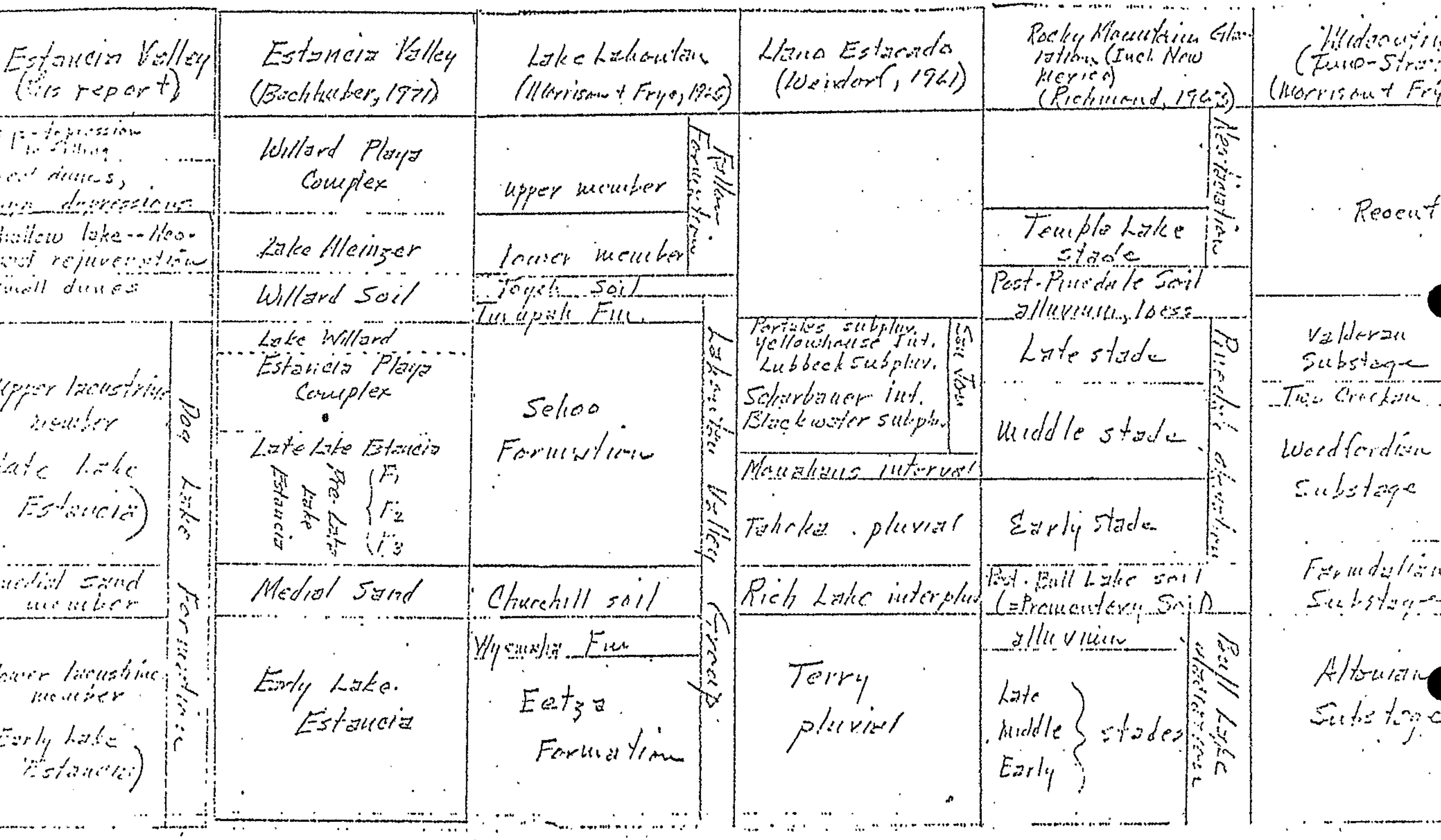


FIGURE 20 — Correlation chart for late Pleistocene and Recent time.

Early Lake Estancia, in which the lower member of the Dog Lake formation accumulated, probably occupied the basin during the period of Bull Lake glaciation in the Rocky Mountains, hence, at a time equivalent to the Altonian substage of the Wisconsinan in the Midcontinent area (Morrison and Frye, 1965, fig. 6). In the Llano Estacado the Terry Pluvial cycle was an equivalent event (Wendorf, 1961). Inasmuch as the initial formation of Early Lake Estancia may have been structurally controlled, not climatically controlled, its time of beginning cannot be deduced from the standard chronology.

After evaporation of Early Lake Estancia, the medial sand member of the Dog Lake formation was deposited during an interval correlated with the heavy erosion and soil formation throughout the west that followed Bull Lake glaciation. It is therefore equivalent to the Rich Lake interpluvial of the Llano Estacado (Wendorf, 1961), the Churchill Soil of the Lake Lahontan area, and the Promontory Soil of the Lake Bonneville area (Morrison and Frye, 1965, fig. 6).

The upper lacustrine member of the Dog Lake formation was deposited in Late Lake Estancia during the period of Pinedale glaciation in the Rocky Mountains. It is correlated with the Tahoka and San Jon pluvial events on the Llano Estacado. The dating of this unit is well established by 3 radiocarbon determinations on material collected by Bachhuber (1971). Fish bones from his zone E, about 14 ft below the top of the member, were dated 11,740 ± 900 B.P.; a foot or so below that, in his zone F_1 plant material was dated 12,400 ± 450 B.P. An estimated 15 ft deeper in the member, perhaps 10 to 15 ft above the buried base of the member, radioactively dead plant material was collected and analysed. Bachhuber concluded that the implied age of greater than 33,000 years was too old for the stratigraphic position, hence the radiocarbon had probably been removed by natural processes.

Lyons collected mammoth tusk samples from probable shoreline-marsh sites in the Big Sink area of the abandoned river valley that leads to the topographic sill. The sites are at an elevation that Lyons estimated to be about 6,250 ft (location: NE¼ sec. 33, T. 3 N., R. 11 E.). Radiocarbon dates of 6,000 ± 200 years B.P. and 7,950 ± 300 years B.P. were measured, but in transmitting the data the laboratory indicated that tusk material sometimes dates later than associated wood or bone. Lyons questions the validity of the radiocarbon dates both for this reason and because the dates are later than mammoth is known to have survived on the Llano Estacado (Lyons, 1973, personal communication). Wendorf (1961, p. 20, 116) indicates that the mammoth had disappeared from the Llano Estacado by 11,000 B.P. If, therefore, a true date for the Big Sink site is of the order of 12,000 years B.P., then at about the time the radiocarbon-dated fish and plant remains were being deposited in the lake center, Late Lake Estancia stood at or below 6,250 ft--perhaps at about the 6,225-ft level of the higher Late Lake shorelines. This date is equivalent to the Blackwater Subpluvial of the Llano Estacado.

The evaporative disappearance of Late Lake Estancia probably took place during the time of increasing aridity and soil formation that followed Pinedale glaciation. Gypsum crystals deposited widely on the then-dry lake floor were blown into dunes making up what are here called the small dunes. These correlate in time of origin with the post-Pinedale soil of the Rocky Mountains and the Turupah Formation and Toyeh Soil of the Lake Lahontan area (Morrison and Frye, 1965). Toyeh Soil formation ended about 4,000 years ago after having lasted about 1,000 years (Morrison and Frye, 1965, p. 19). The arid event in the Estancia Valley also correlates with the altithermal of Antevs.

A shallow lake rejuvenation is recorded in most western lake basins, the event correlating with Neoglacial advances in the Rocky Mountains. The shallow rejuvenated lake in Estancia Valley, which cut indistinct low-level shorelines, formed the gypsiferous offshore bar, and caused rounding and cementing on the surfaces of the small dunes, is therefore correlated with lacustrine sediments of the lower member of the Fallon Formation at Lake Lahontan and with the Temple Lake stade of Rocky Mountain glaciation. If the correlation is valid, and if the shallow rejuvenation of Estancia was contemporaneous with the first Fallon Lake maximum in Carson Desert (Morrison and Frye, 1965, p. 20), then the rejuvenation was near its maximum about 3,500 years ago. Such being the case, the playa depressions have originated and evolved to their present state within approximately the last 3,000 years.

Glaciation that occurred in the high mountains of New Mexico during the late Pleistocene was controlled by the same climatic conditions that controlled the lakes. Richmond has mapped moraines in the Sangre de Cristo Mountains north of the Estancia area and on Sierra Blanca Peak to the south, and has correlated these events with the established glacial chronology of the Rocky Mountains in Wyoming and elsewhere (Richmond, 1963). In the Sangre de Cristo Mountains, moraines indicate 2 stades of Bull Lake glaciation, 3 stades of Pinedale glaciation, and 2 stades of Neoglaciation. In the southern part of the Sangre de Cristo Mountains, only the earlier, or Temple Lake, stade of Neoglaciation left moraines, and no moraines of the Neoglacial were found on Sierra Blanca Peak. Moraines of the earliest glaciers in each area were left at the lowest elevations, and successively younger glaciers traveled shorter distances down the valleys. The longer glaciers were probably related to both higher precipitation and decreased evaporation during periods of colder climates. Leopold (1951) concluded that both factors were important for the existence of a lake in Estancia Valley. The successive decrease in sizes of the lakes is entirely consistent with decreasing length of successive glaciers in the mountains.

Water in Early Lake Estancia probably contained relatively low concentrations of dissolved material because of surface discharge over the topographic sill. It is likely that the early lake was temperature stratified, as sill elevation was well above the floor, and it is possible that it was chemically stratified as well. While quantitative chemical data for the basin are not sufficient for comprehensive analysis, the total salt load precipitated upon evaporation of the early lake does not seem to be great considering the volume of water that it contained. If this observation can be substantiated, the argument for fresh water at depth in Early Lake Estancia will be stronger. Even if the lake was entirely of fresh water, however, its total evaporation must have left significant amounts of salt on the valley floor. Part of the salt probably was incorporated in the medial sand, but most apparently redissolved when Late Lake Estancia formed.

During the interpluvial that followed Early Lake Estancia time, the basin was without a lake. Sand was transported onto the valley floor by streams to form the medial sand member of the Dog Lake formation. Eolian reworking of the sediment is suggested by the fine, well-rounded, loose sand that is so troublesome to drillers in the central part of the valley. Toward the end of the interpluvial, as the lake began to re-form, clay deposits alternated locally with sand.

Late Lake Estancia was never deeper than 200 ft and, as clayey sediment collected on the lake floor, the lake depth decreased to about 150 ft. Throughout this time the lake surface remained more than 100 ft below the level of the topographic sill, reaching a maximum elevation of

6,225 ft. Because of this lack of surface discharge from the lake, Meinzer (1911, p. 22) suggested that the lake level fluctuated widely as rates of precipitation and evaporation varied. The well-preserved beaches below 6,209 ft probably formed sequentially as the lake evaporated. Therefore, while Meinzer was probably correct, the lake stood near its highest level just before it disappeared.

Water in Late Lake Estancia probably contained high concentrations of dissolved gypsum and halite, derived partly from evaporative concentration and partly from solution of evaporites left by the earlier lake. Upon disappearance of the lake, gypsum and salt were deposited on the floor of the basin. Most of the halite appears to have subsequently been carried down into the sediment of the upper lacustrine member of the Dog Lake by recharge from precipitation. The gypsum that precipitated on the lake floor, however, was quickly blown into dunes that are the members of the small dune family.

The short-lived lake that formed after Late Lake Estancia and after formation of the small dunes covered only the central part of the valley floor and was never deeper than about 70 ft. It persisted at this level long enough, however, to round the surfaces of the dunes by current action, and to form beaches and long offshore bar from the gypsiferous sediment eroded from the dunes. Surge channels across the top of the bar indicate that strong winds periodically blew water into the eastern embayment. The poor definition on beaches at lower levels is probably due to the gentle slope of the lake bottom near the shore, and to wind-induced movement of water that caused oscillations in water level at the shore.

The shallow lake dried up perhaps only 3,000 years ago. Shortly after the lake evaporated, the playa depressions began to form and deepen, their locations being initially controlled by solution of gypsum in the Yeso Formation beneath 400 ft of alluvial and lacustrine strata. A subsidence zone extending upward through the almost impermeable clays of the Dog Lake formation provided proto-depressions on the exposed lake floor, and zones of increased vertical permeability through which ground water could leak from the underlying confined aquifers.

Under arid climatic conditions the leakage zones and initial depressions became sites of vigorous deflation, with deflation probably facilitated by the sediment-loosening and fluffing action of alternate wetting and evaporation from the playa surfaces. Deflation proceeded to deepen the depressions until the combination of decreased ground-water flow resistance and increased head difference, that resulted from thinning of the upper member of the Dog Lake formation, caused ground-water discharge rates to exceed the evaporation potential on the playa surfaces. The perennially moist playas could then no longer be deflated. Evaporation has continually increased the chemical concentration of water on the playas, and the increased concentration has reduced evaporation rates. Ground-water discharge has remained essentially constant, however, and the resulting increase in free water on the playa surfaces has caused the playas to begin infilling with both sediment carried into the basin and with crystals chemically precipitated from the evaporating water.

The general nature of the Estancia hydrologic environment as it exists today was already understood before this project started. Details of the interactions between geologic and hydrologic phenomena that control the flow of ground water had not been investigated, however. Furthermore, in this study the dimension of geologic time has been added to the special dimensions that have been the basis for previous hydrologic investigations; hydrologic and recent geologic phenomena in the basin have in this report been considered in the context of evolution of the hydrogeologic system.

REFERENCES

Anonymous, 1952, Stratigraphy of Paleozoic, Mesozoic rocks in parts of central New Mexico: New Mexico Geol. Soc., Guidebook 3rd Field Conf., Rio Grande country, central New Mexico, p. 106-126

Antevs, Ernst, 1954, Climate of New Mexico during the last glacio-pluvial: Jour. Geology, v. 62, p. 182-191

Atkinson, W. W., Jr., 1961, Geology of the San Pedro Mountains, Santa Fe County, New Mexico: New Mexico Bureau Mines Mineral Resources, Bull. 77, 50 p.

Bachhuber, F. W., 1971, Paleoliminology of Lake Estancia and the Quaternary history of the Estancia Valley, central New Mexico: Ph.D. dissert., Univ. New Mexico, 238 p.

Ballance, W. C., 1965, Ground-water levels in New Mexico, 1963: New Mexico State Engineer, Basic Data Rept., 143 p.

Bates, R. L., Wilpot, R. H., MacAlpin, A. J., and Vorbe, Georges, 1947, Geology of the Gran Quivira quadrangle, New Mexico: New Mexico Bureau Mines Mineral Resources, Bull. 26, 57 p.

Beede, J. W., 1911, The cycle of subterranean drainage as illustrated in the Bloomington, Indiana, quadrangle: Indiana Acad. Sci. Proc., v. 20, p. 81-111

Bjorklund, L. J., and Maxwell, B. W., 1961, Availability of ground water in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer, Tech. Rept. 21, 117 p.

Bretz, J. H., and Horberg, Leland, 1949, The Ogallala Formation west of the Llano Estacado: Jour. Geology, v. 57, p. 477-490

Bryan, Kirk, 1941, Correlation of the deposits of Sandia cave, New Mexico, with glacial chronology: Smithsonian Misc. Colln., v. 99, no. 23, p. 45-64

Bryan, Kirk, and McCann, F. T., 1950, The two high stages of Lake Estancia, New Mexico, and their relation to glacial chronology: unpub. manuscript, 35 p.

Busch, F. E., 1966, Ground-water levels in New Mexico, 1964: New Mexico State Engineer, Basic Data Rept., 130 p.

Busch, F. E., and Hudson, J. D., 1967-1970, Ground-water levels in New Mexico 1965-1968: New Mexico State Engineer, Basic Data Repts.

Dane, C. H., and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geol. Survey

Darton, N. H., 1928, "Red Beds" and associated formations in New Mexico; with an outline of the geology of the state: U.S. Geol. Survey, Bull. 794, 356 p.

Davies, W. E., 1960, Origin of caves in folded limestones: Natl. Speleol. Soc., Bull., v. 22, p. 5-18

Davis, S. H., and DeWiest, R. J. M., 1966, Hydrogeology: New York, John Wiley & Sons, 463 p.

Davis, W. M., 1930, Origin of limestone caverns: Geol. Soc. America, Bull, v. 41, p. 475-628

DeBrine, B. E., 1971, Quantitative hydrologic study of a closed basin with a playa (Estancia Valley, New Mexico): New Mexico Institute Mining Technology, Ph.D. dissert., 165 p.

Dury, G. H., 1973, Paleohydrologic implications of some pluvial lakes in northwestern New South Wales, Australia: Geol. Soc., America, Bull., v. 84, p. 3663-3676

Fallis, J. F., Jr., 1958, Geology of the Pedernal Hills area, Torrance County, New Mexico: M.S. thesis, Univ. New Mexico, 50 p.

Feth, J. H., and Brown, R. J., 1962, A method for measuring upward leakage from artesian aquifers using rates of salt-crust accumulation: U. S. Geol. Survey, Prof. Paper 450-B, Short papers in geology, hydrology and topography, p. B100-B101

Foreman, Fred, Clisby, K. H., and Sears, P. B., 1959, Plio-Pleistocene sediments and climates of the San Augustin Plains, New Mexico: New Mexico Geol. Soc., Guidebook 10th Field Conf., west-central New Mexico, p. 117-120

Foster, R. W., and Stipp, T. F., 1961, Preliminary geologic and relief map of the Precambrian rocks of New Mexico: New Mexico Bureau Mines Mineral Resources, Circ. 57, 37 p.

Freeze, R. A., and Witherspoon, P. A., 1966, Theoretical analysis of regional groundwater flow, I. Analytical and numerical solutions to the mathematical model: Water Resources Research, v. 2, p. 641-656

--------, 1967, Theoretical anaylsis of regional groundwater flow, II. Effect of water-table configuration and subsurface permeability variation: Water Resources Research, v. 3, p. 623-634

Frye, J. C., and Leonard, A. B., 1965, Quaternary of the southern Great Plains, in The Quaternary of the United States: Princeton, Princeton Univ. Press, p. 203-216

Galloway, Robert W., 1970, The full-glacial climate in the southwestern United States: Annals Assoc. Am. Geographers, v. 60, p. 245-256

Greene, F. C., 1909, Caves and cave formation of the Mithcell limestone: Indiana Acad. Sci. Proc, for 1908, p. 175-184

Hafsten, Ulf, 1961, Pleistocene development of vegetation and climate in the southern High Plains are evidenced by pollen analysis, in Paleoecology of the Llano Estacado: Santa Fe, Museum New Mexico Press, p. 59-91

Harbour, Jerry, 1958, Microstratigraphic and sedimentational studies of an early-man site near Lucy, New Mexico: M.S. thesis, Univ. New Mexico, 111 p.

Hibben, F. C., 1941, Evidences of early occupation in Sandia Cave, New Mexico, and other sites in the Sandia-Manzano Region: Smithsonian Misc. Colln., v. 99, n. 23, p. 1-44

Hudson, J. D., 1971, Groundwater levels in New Mexico, 1969: New Mexico State Engineer, Basic Data Rept., 74 p.

Hunt, C. B., Robinson, T. W., Bowles, W. A., and Washburn, A. L., 1966, Hydrologic basin, Death Valley, California: U. S. Geol. Survey, Prof, Paper 494-B, 137 p.

Johnson, D. W., 1902, Notes of a geological reconnaissance in eastern Valencia County, New Mexico: American Geol., v. 29, p. 80-87

Judson, S., 1950, Depressions of the northern portion of the Southern High Plains of eastern New Mexico: Geol. Soc. America, Bull., v. 61, p. 253-273

Kelley, V. C., 1963, Geologic map of the Sandia Mountains and vicinity, New Mexico: New Mexico Bureau Mines Mineral Resources, Geol. Map 18

----------, 1972, Geology of the Fort Sumner sheet, New Mexico: New Mexico Bureau Mines Mineral Resources, Bull. 98, 55 p.

Kelley, V. C., and Thompson, T. B., 1964, Tectonic map of the Ruidoso-Carrizozo region, New Mexico: New Mexico Geol. Soc., Guidebook 15th Field Conf., Ruidoso country, south-central New Mexico, p. 110-121

Keyes, C. R., 1903, Ephemeral lakes: Am. Jour. Sci., 4th ser., v. 16, p. 377-378

-----------, 1908, Geologic processes and geographic products of the arid region: Geol. Soc. America, Bull, v. 19, p. 570-575

Kottlowski, F. E., 1961, Pennsylvanian rocks in north-central New Mexico: New Mexico Geol. Soc., Guidebook 12th Field Conf., Albuquerque country, New Mexico, p. 97-104

Langbein, W. B., 1961, Salinity and hydrology of closed lakes: U. S. Geol. Survey, Prof. Paper 412, 20 p.

Leopold, L. B., 1951, Pleistocene climate in New Mexico: Am. Jour. Sci., v. 249, p. 152-168

Lyons, T. R., 1969, A study of the paleo-Indian and desert culture complexes of the Estancia Valley area, New Mexcio: Ph.D. dissert.,Univ. New Mexico, 355 p.

Meinzer, O. E., 1911, Geology and water resources of Estancia Valley, New Mexico; with notes on ground-water conditions in adjacent parts of central New Mexico: U. S. Geol. Survey, Water-Supply Paper 275, 89 p.

Meyers, J. S., 1962, Evaporation from the 17 western states: U. S. Geol. Survey, Prof. Paper 272-D, p. D71-D100

Morrison, R. B., and Frye, J. C., 1965, Correlation of the middle and late Quaternary successions of the Lake Lathontan, Lake Bonneville, Rocky Mountain (Wasatch Range), Southern Great Plains, and eastern Midwest areas: Nevada Bureau Mines, Rept. 9, 45 p.

Myers, D. A., 1966, Gelogic map of the Tajique quadrangle, Torrance and Bernalillo Counties, New Mexico: U. S. Geol. Survey, GQ-551

------------, 1967, Geologic map of the Torreon quadrangle, Torrance County, New Mexico: U. S. Geol. Survey, GQ-639

Needham, C. E., and Bates, R. L., 1943, Permian type sections in central New Mexico: Geol. Soc. America, Bull., v. 54, p. 1654-1656

New Mexico State Engineer Office, 1956, Climatological summary, New Mexico, precipitation 1849-1954: New Mexico State Engineer, Tech, Rept. 6, 407 p.

------------, 1965, Thickness of alluvium (valley fill and lake deposits), Estancia Underground Water Basin: New Mexico State Engineer, open-file map

------------, 1966, Specific conductance of ground water, Estancia Underground Water Basin: New Mexico State Engineer, open-file map

Northrop, S. A., 1959, Minerals of New Mexico: Albuquerque, Univ. New Mexico Press, 665 p.

Olsen, Siguard, 1944, Danish Charophyta, chronological, ecological, and biological investigations: Det K. Danske Vidensk. Selsk., Biol. Skr., bind 3, nr. 1

Peck, R. E., 1957, North American Mesozoic Charophyta: U. S. Geol. Survey, Prof. Paper 294-A, 44 p.

Phalen, W. C., 1919, Salt resources of the United States: U. S. Geol. Survey, Bull. 669, 284 p.

Piper, A. M., 1932, Ground water in north-central Tennessee: U. S. Geol. Survey, Water-Supply Paper 640, 238 p.

Read, C. B., Wilpolt, R. H., Andrews, D. A., Summerson, C. H., and Wood, G. H., 1944, Geologic map and stratigraphic sections of Permian and Pennsylvanian rocks of parts of San Miguel, Santa Fe, Sandoval, Bernalillo, Torrance, and Valencia counties, north central New Mexico: U. S. Geol. Survey, Oil and Gas Inv. Prelim. Map OM-21

Reeder, H. O., Herrick, E. H., Hood, J. W., and Gordon, E. D., 1959, Annual water-level measurements in observation wells, 1951-1955, and atlas of maps showing changes in water levels for various periods from beginning of record through 1954, New Mexico; in Part C, South-central closed basins and Rio Grande valley: New Mexico State Engineer, Tech. Rept. 13, p. 221-269

Reeves, C. C., Jr., 1973, The full-glacial climate of the southern High Plains, West Texas: Jour. Geology, v. 81, p. 693-704

Reiche, Parry, 1949, Geology of the Manzanita and north Manzano Mountains, New Mexico: Geol. Soc. America, Bull., v. 60 p. 1183-1212

Richmond, G. M., 1963, Correlation of some glacial deposits in New Mexico: U. S. Geol. Survey, Prof. Paper 450-E, p. E121-E125

Shuman, R. C., 1961, Genesis and classification of soils in the semi-arid region of central New Mexico: M.S. thesis, New Mexico State Univ., 156 p.

Smith, G. I., 1966, Geology of Searles Lake—a guide to prospecting for buried continental salines, in Second Symposium of Salt: Cleveland, Northern Ohio Geol. Soc., p. 167-180

Smith, R. E., 1957, Geology and ground-water resources of Torrance County, New Mexico: New Mexico Bureau Mines Mineral Resources, Ground-Water Rept. 5, 186 p.

Stearns, C. E., 1953, Tertiary Geology of the Galisteo-Tongue area, New Mexico: Geol. Soc. America, Bull., v. 64, p. 459-508

Stephenson, R. L., 1965, Quaternary human occupation of the plains, in The Quaternary of the United States: Princeton, Princeton Univ. Press, p. 685-696

Swinnerton, A. C., 1932, Origin of limestone caves: Geol. Soc. America, Bull., v. 43, p. 663-693

Talmadge, S. B., and Andreas, A., 1942, Carbon dioxide in New Mexico: New Mexico Bureau Mines Mineral Resources, Circ. 9, 7 p.

Talmadge, S. B., and Wootton, T.P., 1937, The non-metallic mineral resources of New Mexico and their economic features (exclusive of fuels): New Mexico Bureau Mines Mineral Resources, Bull. 12, 159 p.

Thrailkill, John, 1968, Chemical and hydrologic factors in the excavation of limestone caves: Geol. Soc. America, Bull., v. 79, p. 19-46

Titus, F. B., 1961, Ground-water geology of the Rio Grande trough in north-central New Mexico, with section on the Jemez Caldera and the Lucero Uplift: New Mexico Geol. Soc., Guidebook 12th Field Conf., Albuquerque country, New Mexico, p. 186-192

-----------, 1969, Late Tertiary and Quaternary hydrogeology of Estancia Basic, New Mexico: Univ. New Mexico Ph.D. dissert., 179 p.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Jour. Geophys. Research, v. 68, no. 16, p. 4795-4812

U. S. Weather Bureau, 1955-1968, Climatological data, New Mexico: v. 59-72

Weir, J. E., Jr., 1965, Geology and availability of ground water in the northern part of the White Sands Missile Range and vicinity, New Mexico: U. S. Geol. Survey, Water Supply Paper 1801, 78 p.

Wendorf, Fred (ed.), 1961, Paleoecology of the Llano Estacado: Santa Fe, Museum New Mexico Press, 144 p.

Wilpolt, R. H., MacAlpin, A. J., Bates, R. L., and Vorbe, Georges, 1946, Geologic map and stratigraphic sections of Paleozoic rocks of Joyita Hills, Los Pinos Mountains, and northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico: U. S. Geol. Survey, Oil & Gas Inv. Prelim. Map OM-61

APPENDIX A -- Selected Drillers' Logs of Water Wells
(from New Mexico State Engineer Office files)

Location: SE¼NW¼ sec. 18, T. 4 N., R. 9 E.
Owner: N. Knight

Sample description	Thickness ft	Depth ft
Lacustrine unit		
Surface soil	6	6
Gray clay	8	14
Alluvial unit		
Caliche	12	26
Caliche and gravel	13	39
Pale red clay	9	48
Gray clay, some gravel and sand	7	55
Pale red clay, gravel	9	64
Red clay, gravel, sand	24	88
Gray clay, gravel, sand	36	124
Gray clay	4	128
Red clay, gravel	4	132
Brown clay, gravel, sand	20	152

Location: SW¼SW¼SE¼ sec. 10, T. 6 N., R. 8 E.
Owner: Unknown

Sample description	Thickness ft	Depth ft
Lacustrine unit (?)		
Topsoil	3	3
Adobe clay	12	15
Alluvial unit		
Red clay, gravel	21	36
Water	2	38
Clay, gravel	7	45
Sand, gravel, clay	20	65
Yellow clay, sand	3	68
Yellow clay, sand, gravel	7	75
Red clay, gravel	12	87
Sand, gravel	3	90
Clay	10	100
Gravel, clay	10	110
Red clay	20	130
Sand, gravel, water	5	135
Clay	5	140
Gravel, clay, sand	5	145
Red clay	28	173
Boulder rock	2	175
Madera Limestone		
Red-bed clay	25	200

Location: SW¼ sec. 30, T. 6 N., R. 11 E.
Owner: W. Blackwell

Sample description	Thickness ft	Depth ft
Lacustrine unit and alluvial unit (undifferentiated)		
Soil	3	3
Gravel	7	10
Colored clay	18	28
Gray sandy clay and gravel	3	31
Gray and red clay with sandy clay	19	50
Gray and red sand with sandy clay, water	11	61
Gray and red clay	14	75
Gray sand and sandy clay, water	3	78
Red clay	1	79
Lost circulation (rock)	8	87

Location: NW¼NW¼SE¼ sec. 19, T. 7 N., R. 10 E.
Owner: H. Price

Sample description	Thickness ft	Depth ft
Lacustrine unit (?)		
Soil	3	3
Caliche	27	30
Alluvial unit		
Sandy shale	20	50
Sand and mud	65	115
Lime shell	15	130
Triassic rocks		
Red bed	30	160
Red sand rock	40	200
Red sandy shale	50	250
Red sand rock	50	300
Sandy red shale	5	305
San Andres Formation		
Broken lime	7	312

Location: NE¼NW¼ sec. 19, T. 7 N., R. 10 E.
Owner: H. Benefield

Sample description	Thickness ft	Depth ft
Lacustrine unit		
Surface	2	2
Yellow shale	36	38
Alluvial unit		
Caliche	7	45
Sand	45	90
Lime	2	92
Red sandy shale and gypsum	33	125
Triassic rocks		
Red shale	30	155
Sand	10	165
Sand and gravel	10	175
Red shale, sandy	25	200
Red shale, gypsum, shells	15	215
Red sandy shale	25	240
Red shale	10	250
Hard sand	4	254
San Andres Formation		
Yellow clay and gravel	26	280

Location: SE¼ sec. 3, T. 11 N., R. 8 E.
Owner: W. Richards

Sample description	Thickness ft	Depth ft
Alluvial unit		
Topsoil and caliche	17	17
Sand, brown	10	27
Brown medium sand	10	37
" " "	27	64
" " "	10	74
" " "	15	89
Brown sand and gravel	23	112
White rocks	9	121
Brown gravel and granite	17	138
Various gravel and boulder	24	162
Various boulders	132	294
Mesaverde Formation		
Light brown sandstone and sand	25	319
Light brown sandstone	97	416
Green shale	9	425
Blue shale	56	481
Blue and brown shale	50	531
Light brown sandstone	19	550

Location: SW¼ sec. 32, T. 11 N., R. 9 E.
Owner: B. King

Sample description	Thickness ft	Depth ft
Alluvial unit		
Topsoil	6	6
Caliche	14	20
Shale	70	90
Sand and gravel	110	200
Gravel	110	310
Sand and gravel	10	320
Gravel	65	385
Sand and gravel	20	405
Triassic rocks		
Red bed	55	460
Red rock	15	475
Red bed	15	490

APPENDIX B -- Sample logs from deep test holes drilled by New Mexico Institute of Mining & Technology

Location: NE¼NW¼SW¼ sec. 12, T. 6 N., R. 9 E.
Name: Means #1

Sample description	Thickness ft	Depth ft
Dune sediment		
Gypsum sand	10	10
Upper lake sequence		
Clay, silty, gray; laminated orange clay interbedded in middle of section; disseminated fine gypsum crystals below 26 ft	28	38
Clay, gray, pale-yellow to buff, sticky, yellow to buff clay loose; disseminated gypsum; organic fibrous material (charophytes?)	30	68
Medial sand sequence		
Sand, very fine to fine, clean, loose, well rounded, frosted, quartzose; little sandy clay in upper part, gray, yellow	19	87
Lower lake sequence		
Clay, sandy, gray, orange to buff; gypsiferous at top; few nodules orange to brown limestone near base	21	108
Alluvial unit		
Sand, fine to coarse, loose, very well rounded	1	109
Clay, partly sandy, brick-red to pale brick-red, few thin zones in upper 2 ft, cream; few flakes carbonized wood at 118 ft (soil zone?)	22	131
Limestone, sandy, white to tan, nodular; sand very coarse to medium, rounded; caliche	2	133

Location: SW¼SW¼SW¼ sec. 16, T. 6 N., R. 9 E.
Name: School Section #1

Sample description	Thickness ft	Depth ft
Upper lake sequence		
Clay, light gray to tan; contains fine gypsum crystals, fibrous organic material in lower part	60	60
Medial sand sequence		
Sand, fine, well sorted, rounded, frosted	18	78
Lower lake sequence		
Clay, gray, tan, little orange	24	102
Alluvial unit		
Clay, brown to reddish-brown; thin sand beds	28	130
Sand and clay, brown, red toward base	50	180
Sand, medium to coarse, very permeable	28	208
Clay, reddish-brown; thin sand beds	27	235
Sand, coarse, little very fine; thin granule gravel beds, partly cemented; orange clay beds near base	40	275
Sand, silty, red, fine; red, gray clay; silty gravel at 290 to 295 ft	25	300
Sand, very fine to coarse, partly cemented; little red, tan, white clay	20	320
Clay, brown, red	5	325
Sand, medium to coarse, partly cemented with calcium carbonate	5	330
Clay, silty, red, tan; very fine, silty sand beds	20	350
Sand, silty, tan, red, very fine, poorly cemented; red clay	10	360

Location: $SE\frac{1}{4}SE\frac{1}{4}NW\frac{1}{4}$ sec. 22, T. 6 N., R. 9 E.
Name: Berkshire #1

Sample description	Thickness ft	Depth ft
Upper lake sequence		
Clay, gray, pale-yellow to orange; disseminated small gypsum crystals; ostracods and charophytes	44	44
Medial sand sequence		
Sand, fine to medium, rounded, frosted, quartzose	11	55
Clay, sandy, tan; slightly gypsiferous; ostracods and charophytes	12	67
Sand, partly clayey, medium to very coarse, rounded, frosted, partly cemented	13	80
Gravel, very sandy, very fine, rounded, mostly quartz and limestone; small caliche fragments and thin clay beds in lower part	15	95
Lower lake sequence		
Clay, silty, tan, gray, some pale-green; contains small caliche fragments (allochthonous?)	10	105
Alluvial unit		
Sand, silty, tan to brown; very fine gravel size & caliche, rounded (allochthonous?)	15	120
Clay, silty, sandy, red to pink	10	130
Sand and red to pink silty clay interbedded	40	170
Gravel, very sandy, very fine to fine, rounded, calcium carbonate cement	38	208
Clay, silty, sandy, tan, reddish-brown, little pale-green; thin sand interbeds	27	235
Sand, fine, cemented	7	242
Clay, silty, reddish-brown, pale-green	8	250
Sand, reddish-brown, coarse, well sorted, subangular	7	257
Clay, reddish-brown, gray, sticky	23	280
Sand, very coarse to fine, rounded to subrounded, poorly cemented	8	288
Clay, gray, reddish-brown, sticky	12	300

Sand and very fine gravel, subrounded to subangular, sand fine to coarse, partly cemented with calcium carbonate; gravel contains few feldspar grains; interbeds of reddish-brown, gray clay	42	342
Limestone, clayey, light-brown, few chips mollusk shell, highly permeable (taking water), fresh-water limestone?; interbedded with coarse sand and gray to red clay	10	352
Clay, silty, partly sandy, red in top 5+ ft, becoming a yellow to gray below; contains unidentified black mineral grains and few chert fragments; seed pod from 360-362.5 ft; gastropod fragments	22	374
Yeso Formation		
Shale, very silty, sandy, red, little green clay; light-gray sandstone, white gypsum at base	16	390

Location: SE¼SE¼NW¼ sec. 20, T. 6 N., R. 9 E.
Name: Berkshire #2

Sample description	Thickness ft	Depth ft
Upper lake sequence		
Clay, light-gray, pale-yellow; small gypsum crystals	43	43
Medial sand sequence		
Sand, fine to medium, rounded, frosted	3	46
Clay, light-gray to white	6	52
Sand, fine to coarse, rounded; little light-gray clay in upper part, little light-red clay; fine gravel in lower part	28	80
Lower lake sequence		
Clay, tan to white, gray; thin beds of red silt near base	20	100
Alluvial unit		
Clay, gray, red; caliche	12	112
Clay, silty, red	16	128
Caliche; red clay	7	135
Sand, medium to coarse, rounded; interbedded red clay, silty, partly sandy; caliche bed at 181 to 184 ft	74	209
Caliche, sandy, white; little red sand	9	218
Sand, silty, red, coarse	6	224
Clay, silty, sandy, red to tan; thin sand layers interbedded	26	250
Sand, gray to red, coarse to very coarse; caliche fragments	12	262
Silt, clayey, sandy, red, gray; little fine gravel at 274 to 275 ft	21	283
Sand, tan to gray, coarse to very coarse, few feldspar grains	7	290
Sand, very clayey, silty, gray, dark-red, fine to coarse, quartzose, feldspar grains	19	309
Gravel, sandy, fine, rounded to subangular	11	320
Sand, clayey, silty, gray red, fine to coarse; clay, red, gray; little gravel, sandy, granules	10	330
Limestone, clayey, brown to light-brown, light-gray; coarse sand	10	340
Clay, sandy, red to dark-red; contains fragments of gastropod shells	10	350

APPENDIX C -- Chemical analyses of water from playas and from selected wells in Estancia Valley

(Analyses by U.S. Geological Survey, Albuquerque, New Mexico; constituents in mg/l)

Location	Date	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Total Solids
PLAYA SAMPLES									
North end, Laguna del Perro	5/ 3/67	1.2	25,400	65,000	2,500	-	20,250	177,000	443,400
same as above	6/22/67	42	34,000	52,100	2,630	1,010	78,500	126,000	294,000
same as above	8/ 8/67	680	5,330	37,400	624	321	30,200	50,800	126,000
same as above	9/ 7/67	333	20,000	112,000	2,260	734	95,000	160,000	400,000
same as above	1/ 2/68	540	3,170	27,000	402	156	15,100	39,500	86,400
same as above	5/21/68	20	16,000	114,000	1,630	416	94,000	151,000	377,000
NE¼SE¼ sec. 20, T. 6 N., R. 9 E.	2/ 6/68	695	636	5,800	71	126	4,600	8,700	20,900
same as above	4/30/68	1,200	1,380	11,600	138	62	8,800	17,600	40,800
W½ sec. 21, T. 6 N., R. 9 E.	6/22/67	843	4,500	26,500	409	148	13,100	45,500	91,000
same as above	2/ 6/68	570	9,380	61,500	840	320	30,500	101,000	210,000
NE¼NW¼ sec. 28, T. 6 N., R. 9 E.	2/ 6/68	620	13,700	21,800	916	1,580	29,500	60,400	137,000
same as above	4/30/68	39	39,900	73,600	3,500	3,940	107,000	147,000	373,000
SW¼ sec. 6, T. 6 N., R. 10 E.	6/22/67	701	7,160	57,800	497	114	13,000	103,000	182,000
NE¼NE¼SW¼ sec. 19, T. 6 N., R. 10 E.	6/22/67	485	620	3,260	107	53	1,640	6,750	12,900
WELL SAMPLES									
ESTANCIA VALLEY FORMATION									
N[illegible]SW¼ sec. 1, T. 6 N., R. 9 E.	4/26/50	228	107	226		252	780	336	1,830
sec. 11, T. 6 N., R. 9 E.	4/12/50	177	69	122		295	462	190	1,160
MEDIAL SAND MEMBER, DOG LAKE FORMATION									
SW¼SW¼SE¼ sec. 16, T. 6 N., R. 9 E.	2/20/68	174	203	670	16	524	1,150	774	3,290
NE¼NE¼SE¼ sec. 20, T. 6 N., R. 9 E. (Berkshire #3 test hole)	12/12/67	188	144	698	20	640	732	888	3,040
same as above	1/4/68	92	170	542	17	648	766	490	2,440
same as above	4/23/68	106	237	634	21	638	1,090	670	3,100