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PLAYA LAKE SYMPOSIUM

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:sonal pleasure in collaborating with of the Department of Geosciences nd planning for this work.

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:tor, International Center for
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PLAYA LAKE SYMPOSIUM

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SEDIMENTOLOGIC STUDIES IN THE WILLCOX PLAYA AREA, COCHISE COUNTY, ARIZONA

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Bernard W. Pipkin,[3] Richard C. Robinson,[4]
and Jan Carol Wilt[5]

Abstract

The Willcox Playa in Cochise County of southeastern Arizona is the desiccated vestige of Pleistocene Lake Cochise. Willcox Playa has an area of about 50 sq mi; Lake Cochise covered about 120 sq mi with a drainage area of 1,500 sq mi. The prominent preserved features include the playa floor, nearshore sediments, beach ridges on the east and west sides, and sand ridges and hills to the north, northeast, and east. In addition to surface sampling throughout the basin, over 200 auger and drill hole logs were obtained, and numerous water well logs were examined.

The playa floor lies at an elevation of 4,135-4,136 ft. From periodic wettings by rainfall and flooding along the west side, the surface is a mud-cracked crust of light brown clay. This crust when dry ranges from hard to soft and puffy. Sand-size playa crust fragments are easily eroded by storm winds and move across the surface as small dunes. Some of the fragments accumulate around the shrub *Suadea torreyana* to build up phreatophyte mounds of various sizes near the eastern edge. The largest playa surface feature is the polygonal pattern made by giant desiccation fissures.

Although very little sediment other than mud reaches the playa today, sedimentation was active during late Pleistocene times with streams transporting gravels, sands, and muds. The gravels reflect

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Numerous individuals and agencies contributed to the advancement of this project. We are grateful for the financial assistance from the National Science Foundation. Dr. Paul S. Martin made available samples from a 140-ft core obtained from the middle of the playa. Dr. Austin Long of the Geochronology Laboratories provided several radiocarbon dates. We were assisted in the laboratory by Floy Marie Anderson, Thomas N. Dirks, John Cintron, Jr., and Harvey S. Durand. M. L. Richardson of the Willcox office, U.S. Department of Agriculture, Soil Conservation Service, provided numerous services throughout the investigation. Finally we wish to thank the many Willcox Basin ranchers and farmers who answered our inquiries about their water wells, wind directions, local rainfall amounts, and flooding, and who otherwise assisted us with their knowledge of the basin.

the igneous, metamorphic, and sedimentary rock composition of the surrounding mountains; sands consist chiefly of quartz and feldspar.

In the playa muds illite dominates the clay minerals (-2 μ fraction) with minor montmorillonite, mixed-layer illite-montmorillonite, vermiculite, and traces of kaolinite and chlorite. The clays are of a detrital origin. Authigenic analcime is also common in the -2 μ fraction.

A 140-ft drill hole near the middle of the playa penetrated 10 ft of light brown oxidized mud before entering a black mud section that continued to 140 ft. Hydrogen ion (pH) and Eh measurements of the core gave pH values between 9.0 and 9.5 for all but a few of the 200 samples; Eh values below the oxidized surface zone were between -106 and -326 mv. Water well drilling suggests that the playa mud is at least 300 ft thick and that another 700-plus ft of basin-fill sediments underlie the mud.

Wave activity built up beach ridges on the east and west sides only because the north and south ends were sites of the influx of fluvial sediments during the late Pleistocene. Between the beach ridges and the central playa muds and at the north and south ends the sediments are more gravelly and sandy, displaying the usual coarse-to-fine facies change from lake edge to lake center.

Radiocarbon dates suggest pluvial conditions until about 13,000 years B.P., followed by desiccation and a return to pluvial conditions from 11,500 to 10,500 years B.P. Dry conditions then prevailed from 10,000 years ago to the present. As the lake level fell, storm winds eroded beach and nearshore sands and playa crust fragments to build extensive sand ridges and hills north, northeast, and east of the playa edge.

Introduction

During the late Pleistocene Epoch many lakes were present in the Basin and Range Province of western United States (Feth, 1964). Pluvial Lake Cochise, located in Cochise County of southeastern Arizona, was one of these lakes which later dried up; its remnant is now known as Willcox Playa or Willcox Dry Lake.

The Willcox Playa area was the subject of a number of sedimentation studies by University of Arizona students from June 1962 through June 1965. Since mid-1965 the senior author has continued the field and laboratory work intermittently. These studies have covered the sediment provenance, characteristics of the drainages, mineralogy of a 140-ft core from the middle of the playa, origin of the beach ridges, subsurface stratigraphy of the nearshore sediments, ancient and modern wind deposits, playa mud properties, and playa surface features.

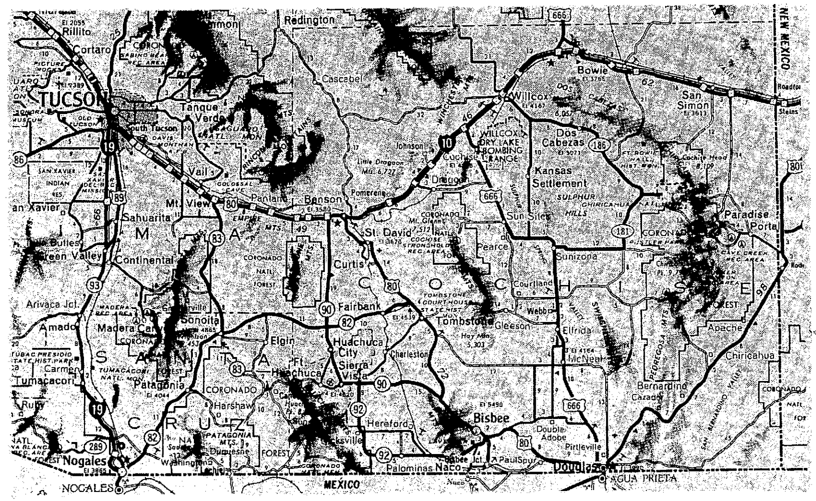

Fig. 1. Index map of southeastern corner of Arizona. Willcox Playa is designated "Willcox Dry Lake Bombing Range." Map reproduced with permission of Arizona Highways, Phoenix, Arizona.

The purpose of these studies was to provide a framework for the interpretation of the sedimentation history of the Willcox Playa area during the late Wisconsin and in post-pluvial times.

Location and Climate

Willcox Playa is located about 65 mi due east of Tucson and a few miles south of Willcox (Fig. 1). This barren flat is the lowest part of the Willcox Basin, which is the northern end of the Sulphur Spring Valley. The U.S. Geological Survey topographic map of the Cochise quadrangle depicts the playa and a small portion of the surrounding area.

Travelers proceeding from southern New Mexico to Benson and Tucson pass near the northern edge of the playa on Interstate 10 - State Highway 86 or directly over the northwestern corner of the playa on the Southern Pacific Railroad. Access to the western side of the playa is from U.S. Highway 666 which connects Douglas, Elfrida, and Pearce to Interstate 10 - State Highway 86 at a point 8 mi west of Willcox. Eastern access to the playa is by way of several dirt roads leading from the Kansas Settlement Road (Fig. 2). During dry weather a two-wheel drive vehicle is adequate to get out onto the playa, but during and for some time after rainy periods much of the playa is not traversible.

The climate of the area is semi-arid (Table 1). Over half the annual precipitation falls during the convective-type thunderstorms of July, August, and early September when warm, moist tropical air moves into the state from a southeasterly direction from the Gulf of Mexico. Winter precipitation includes rain and snow from frontal-type storms that move in from the Pacific Ocean across southern California. Both storm periods

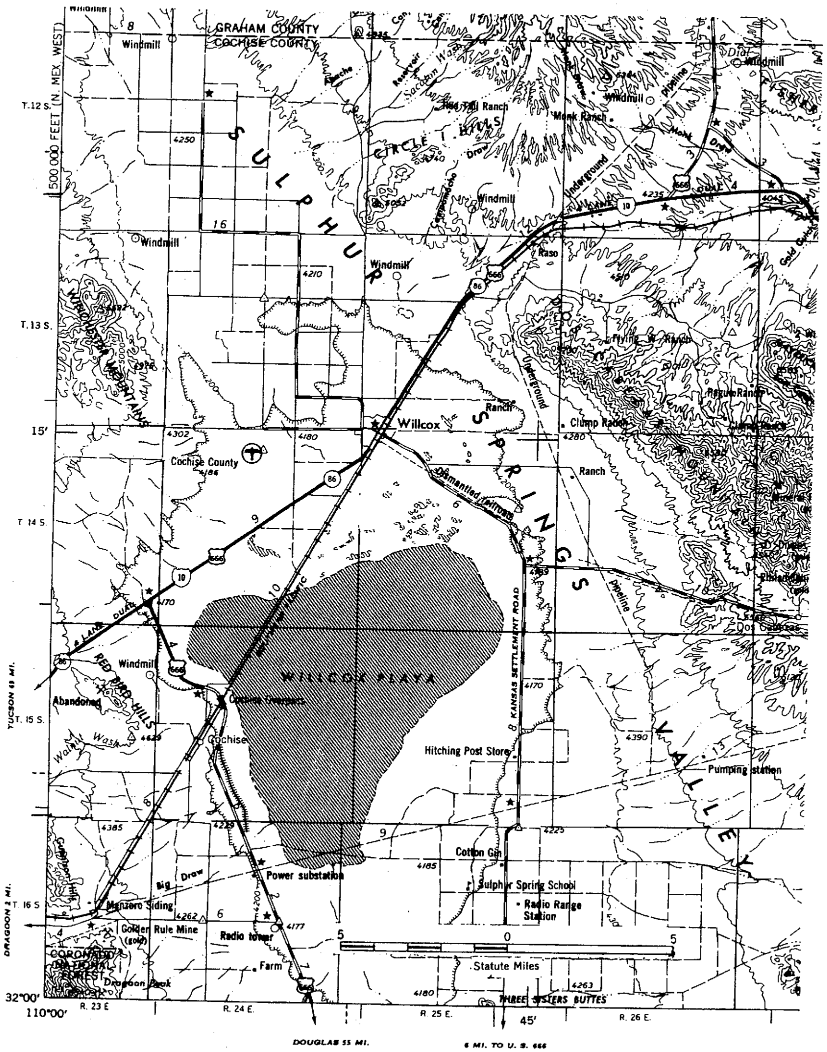

Fig. 2. Index map of the Willcox Playa area and part of Willcox Basin.

are accompanied by strong winds although they are usually of short duration. Summer temperatures for all locations frequently exceed 100°F, but average closer to 90°F. Winter lows for December, January, and February range from just above to several degrees below freezing; monthly means range form the low to high forties (Green and Sellers, 1964).

Studies Before 1962

The earliest geological investigations of the playa area were probably made by Thomas Antisell, M.D., a geologist on a railroad survey made from

Table 1. *Climatological data for the Willcox Basin*

Station	Mean Annual Precipitation in.	Mean Annual Temperature °F	Pan Evaporation in.[1]	Elevation	Period of Record[2]
Willcox	11.76	58.7	80.28	4,190	1899-1957
Cochise	13.35	59.9	-	4,180	1900-1954
Fort Grant	12.57	62.3	-	4,875	1900-1957
Chiricahua National Monument	18.63	57.6	-	5,300	1909-1957

[1] Evaporation from Weather Bureau Class A land pan for 1917-1935. Data from Green and Sellers, 1964.

[2] Data are averages for the period of record.

the Mississippi River to the Pacific Ocean in 1854-1855 (Antisell, 1857). At this time the survey party named the playa the "Playa de las Pimas." From Antisell's account it appears that the party camped at Croton Springs in the northwest corner of the playa.

O. E. Meinzer and F. C. Kelton studied the geology and water resources of the Sulphur Spring Valley in 1910-1911. The results were published as U.S. Geological Survey Water-Supply Paper 320 (Meinzer and Kelton, 1913). Meinzer did the geology, including a lengthy description of the Willcox Playa and surrounding area. He gave the name Lake Cochise to the Pleistocene lake that had once occupied the Willcox Basin. Throughout our field studies Meinzer's work was a constant guide and inspiration.

In 1920-1921 Kirk Bryan and J. W. Gidley visited three gravel pits located along the beach ridge on the west side of the playa in search of vertebrate remains; they found none but did have parts of a proboscidian described to them. At a fourth locality 5 mi west of Willcox and beyond the beach ridge they examined a debris pile from a dug well and the site of a drilled well. They found horse, camel, and bison teeth and part of a mammoth molar. They also examined a piece of tusk reported to have come from one of the gravel pits mentioned above (Bryan and Gidley, 1926).

The geology and groundwater resources of the Willcox Basin have been described in later separate short U.S. Geological Survey reports by R. S. Jones and R. L. Cushman (1947) and by D. R. Coates (1952).

U.S. Geological Survey Mineral Investigations Field Studies Map MF-231 by J. R. Cooper was published in 1960. This map covered four quadrangles of which the Cochise quadrangle was the southwest quadrangle. The reconnaissance geology of the playa and surrounding area are shown.

The first modern paper related directly to the sedimentary deposits of Lake Cochise was that of Hevly and Martin (1961) in which they described the pollen content of shore deposits in the Croton Springs area.

Studies Since 1962

During December 1961 Dr. P. S. Martin of the Geochronology Laboratories, University of Arizona, obtained a 140-ft core from the approximate middle of the playa. Martin (1963) later described the pollen of the core, recognizing a late Wisconsin pluvial in the upper part of the core. The senior author and Austin Long of the Geochronology Laboratories logged the core for lithology and color and made paired Eh and pH determinations over the entire length. The core sediments were further studied in the Department of Geology.

Under the supervision of the senior author, Gordon L. Pine studied the drainage and petrographic characteristics of the sediments moving toward the playa (Pine, 1963); Bernard W. Pipkin investigated the clay mineralogy of the playa and its drainage area (Pipkin, 1964); Richard C. Robinson described the sedimentology of the beach ridge and nearshore sediments (Robinson, 1965); and Mrs. Jan C. Wilt studied wind transport and deposits (Wilt, 1965).

Austin Long also obtained radiocarbon dates from playa sediments and materials adjacent to the playa. Based upon these dates he developed a chronology for the Willcox Playa and correlated this chronology with that of the New Mexico playas (Long, 1966).

Geohydrologic studies by the U.S. Geological Survey have continued in the Willcox Basin. Brown *et al.*,(1963) presented the basic groundwater data. Kister *et al.*, (1966) prepared maps showing fluoride content and salinity of the groundwaters. Brown and Schumann (1969) collaborated on a water supply paper, which, although brief, covers thoroughly the geohydrology in text discussion and with maps.

The Willcox Playa has been the target for photography from space during the National Aeronautics and Space Administration's Gemini and Apollo program flights. Many of the photographs have appeared in technical and scientific journals as well as in popular magazines. Copies of the photographs are available for study from the National Aeronautics and Space Administration or its designated distributors.

Soils mapping of farm lands and potentially irrigable lands in the Willcox Basin has been recently completed by the Soil Conservation Service; the final report is in progress (personal communication, 1970, D. L. Richmond, Willcox office, Soil Conversation Service).

Geologic-Physiographic Setting

The Sulphur Spring Valley, of which the Willcox Basin is the northern part, is in the Basin and Range Province of southern Arizona. Trend of

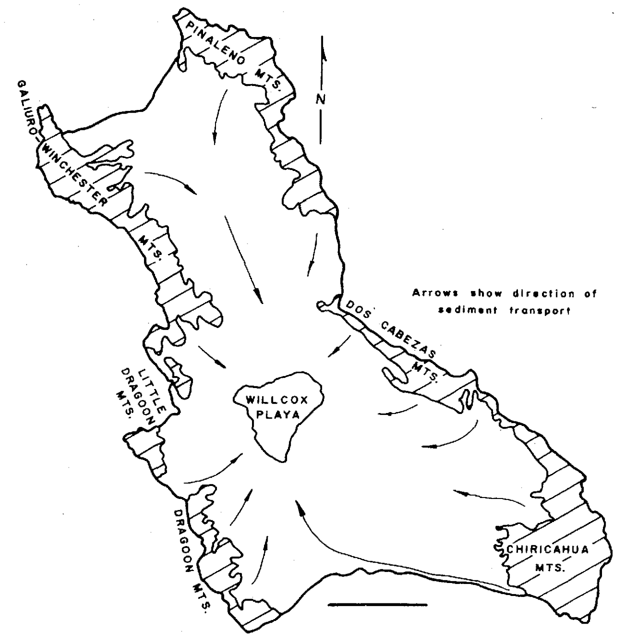

Fig. 3. Willcox Basin drainage area; black bar below southern basin boundary is 10 mi long.

the valley is about north-northwest with mountain ranges on both sides. The mountain ranges are the cumulative result of large-scale faulting and uplift during the mid-Tertiary. During and after this tectonism much detritus was eroded from the uplifted blocks and deposited in the adjacent valleys and basins (Cooley and Davidson, 1963; Pierce *et al.*, 1970).

The highest and most rugged range--the Pinaleno, Dos Cabezas, and Chiricahua mountains--lies on the east side of the basin (Fig. 3). Mount Graham in the Pinalenos (elevation 10,713 ft) is the highest peak in the drainage area. On the west the range includes the southern Galiuro, Winchester, Little Dragoon, and Dragoon mountains with Reiley Peak (elevation 7,631 ft) in the Winchester Mountains the highest point in these mountains. From the playa none of the mountains seem to be very high because the loftier range on the east is also a greater distance from the playa than the lower range on the west. If any one feature of the mountains stands out, it would have to be the two peaks of the Dos Cabezas Mountains, which are visible from many angles and distances.

The rocks of the mountain blocks range in age from Precambrian to Cenozoic and most all rock types are represented. Included are Precambrian granites and gneiss; Paleozoic sandstones, limestones, and shales; Cretaceous sedimentary rocks; Cretaceous-Tertiary granitic intrusives; volcanics of Cretaceous-Tertiary and Tertiary age; and late Cenozoic sedimentary rocks. The southern Galiuro-Winchester Mountains are almost entirely Tertiary volcanics. Across the valley to the east the higher Pinaleno Mountains are dominated by Precambrian granite and gneiss. The rocks in the Chiricahua Mountains portion of the drainage area consist chiefly of Tertiary volcanics of a rhyolitic composition. The remaining mountains are complex mixtures of sediments, igneous intrusives, and volcanic rocks (Wilson *et al.*, 1969).

The alluvial deposits that have filled the Willcox Basin consist of moderately consolidated conglomerate, sandstone, and mudstone of Tertiary age; poorly consolidated gravel, sand, silt, and clay of Quaternary-Tertiary age; unconsolidated stream deposits of gravel, sand, silt, and clay of Quaternary age; and the lake muds and associated sediments of the playa of Quaternary age (Brown and Schumann, 1969).

The deeper wells in the basin for which good sample logs are available penetrate more than 1,000 ft of gravel, sand, mudstone, silt, and clay. Because greater thicknesses of sediments (3,000 to 5,000 ft or more) are known in other nearby valleys and basins with similar histories, it is probable that the basin-fill sediments are actually much thicker than shown in the wells drilled to date in the Willcox Basin (Heindl and DeCook, 1952, p. 8).

The alluvial fan slopes between the mountains and the playa consist chiefly of the unconsolidated stream deposits cited above. Naturally the slopes are the steepest near the mountains, gradually becoming flatter toward the playa. To the east the alluvial slopes are much wider than those on the west side of the basin because the larger mountain range on the east has supplied a greater quantity of sedimentary debris. Thus this activity has moved the playa and valley axis closer to the west boundary of the basin (Meinzer and Kelton, 1913, p. 26).

The widest part of the basin is located south of the playa between the Dragoon and Chiricahua mountains; width is about 42 mi with a valley floor width of about 34 mi. The narrowest part of the basin is located north of the playa between the Winchester and southern Pinaleno mountains where the width is about 20 mi with an average valley floor width of about 12 mi.

Sedimentation has also been responsible for the formation of the drainage divides at the north and south edges of the Willcox Basin. To the north the Pinaleno Mountains, and probably the Galiuro-Winchester Mountains to a lesser extent, have shed sediments to form the divide with the Arivaipa Valley. From this divide southward the basin floor slope is very gentle and shows little erosion, but to the north of the divide Arivaipa Creek has eroded the basin fill extensively. Indeed, the north basin edge was once farther north than it is today (Meinzer and Kelton, 1913, p. 25-26). The southern drainage divide lies between the Chiricahua and Dragoon mountains with the divide taking a somewhat sinuous path south of the hills near Pearce and thence eastward on the south side of Turkey Creek.

The length of the basin between divides along the north-northwest axis is about 58 mi. Overall the Willcox Basin occupies about 1,500 sq

mi of which 950 sq mi are valley floor (Brown and Schumann, 1969). The playa occupies about 50 sq mi.

Playa Surface Features

Flooding and Crust Formation

Although the outstanding feature of the Willcox Playa is its apparent flatness, the surface does have a low gradient to the west-southwest. On the Cochise topographic quadrangle map the elevation for about two-thirds of the playa is 4,136 ft; however, elevations of 1 ft less occur along the west side of the playa. Runoff from intense summer storms in the drainages on the west side has but a short distance to travel and easily reaches the playa. Here the water may accumulate to a depth of several inches to almost a foot until lost by evaporation and/or infiltration. Depending upon the amount of runoff collected and rate of loss, the western playa surface may be flooded for periods up to several months.

The playa is actually flooded in two areas. One area is situated west of the Southern Pacific Railroad tracks in the northwest corner. The second area extends from the same railroad tracks south along the west edge to the southern playa tip; this water body has the shape of the letter J printed backwards.

None of the authors has ever heard of the entire playa surface being flooded at the same time. Several ranchers and farmers living on the west side have described to the senior author how a strong wind from the west-southwest moves water across the playa and holds the water there for several hours. Sediment traps located in the approximate middle of the playa have been flooded during the fall months; the lip of the trap opening was 6 in. above the playa surface. Ranchers and railroad workers have also described to the senior author how water has been blown up against the Southern Pacific Railroad track embankment to a depth of several feet.

These flooded areas are also the sites of salt accumulation after evaporation of the flood waters. From the air or the ground these areas have a definite whiteness to them. The salt may be derived from the sediments immediately adjacent to the playa as well as from the playa sediments themselves. Slightly brackish waters were repeatedly encountered in putting down many tens of auger holes between the beach ridges and the playa edge; salts could also be leached from the sediments augered from the hole. Many of the water wells in the same area, which penetrate to a depth of 50 ft or more, also produce slightly brackish waters.

In addition to the surface flood waters, the groundwater flow in the basin is toward the playa (Brown and Schumann, 1969). This water movement would then also bring dissolved salts toward the playa. Although the playa muds and clays are rather impermeable, over a period of several weeks the near surface sediments may be wetted from the flood waters. Around the playa edge many sands and gravels interfinger with the muds so that these coarser sediments could also serve as subsurface channels for movement of water into the muds.

Fig. 4. Playa crust dunes from the southeastern playa edge; dune height is 4 to 6 in. Winchester Mountains are in the background.

On the playa surface the ordinarily light brown muds become a light brownish gray (5YR 6/1 in the Munsell Soil Color Charts) to a very light gray (N8) and white (N9) after the surface waters have evaporated or after the salts have been moved to the surface by capillary discharge. Below the surface the moister sediment is a reddish brown color (2.5YR 4/4). Auger holes in the playa muds and clays would usually also be lined with arborescent sodium chloride crystals within a few inches of the surface after the hole had stood open for a week or two.

The Willcox Playa surface sediments (0-4 in. depth) consist of greater than 90 percent clay-size material and in most areas, when dry, form a hard crust. By "hard crust" is meant that automobile or truck tires leave but a slight rut or imprint on the surface. From the dry, hard crust the surface may grade into a dry, soft and friable or puffy crust. On this surface a vehicle tire may leave a rut several inches deep. Both kinds of crusts are involved in salt accumulation. The dry, hard crusts have almost a salt glace on the surface. They are more typical of the areas that have been covered by runoff waters that required some weeks or months to evaporate. The puffy surface sediments contain salt crystals that appear to have pushed sediment particles apart as crystals developed.

The distribution of puffy surfaces is somewhat irregular. In some areas a surface that was previously hard was noticed to have become puffy following late winter rains. Near the northeast corner and southern points of entry onto the playa vehicle tracks have been noted to be covered with a very puffy white crust while the surface on either side of a track was hard. The ruts probably channeled rain waters, and the waters subsequently evaporated.

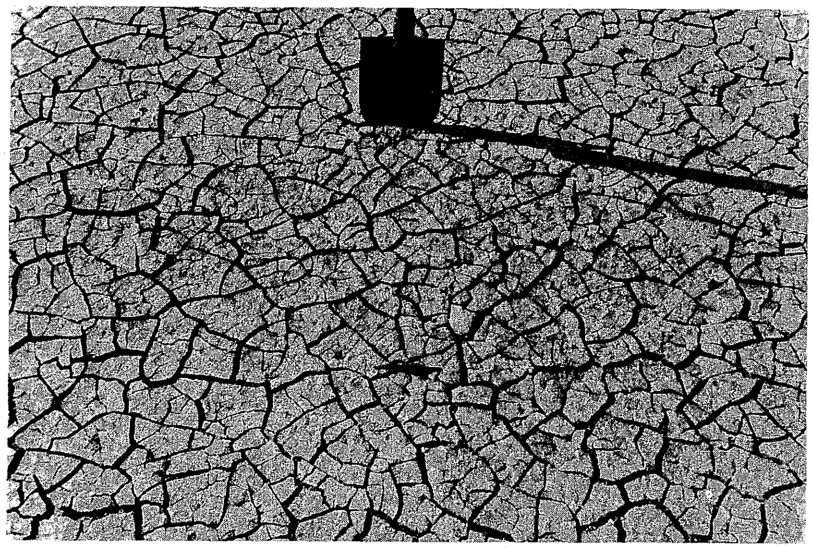

Fig. 5. Mud-cracked playa surface.

Playa Crust Dunes and Mudcracks

Another situation develops after the flooded playa surface has dried and mudcracks have formed. The cracked flaky playa crust is eroded by the wind, and the resulting fragments are transported across the surface to form small transverse dunes (Fig. 4). The dunes occur in patches a few yards to several tens of yards across. Later the winter rains–a slow, steady rainfall–wet the dune surface sufficiently so that when the areas do dry a puffy surface develops. Thus a portion of the playa surface will consist of hard crust and of soft and friable or puffy crust areas. As one drives from a hard crust to a soft, friable crust area there is a very noticeable drag on the vehicle's forward motion.

Mudcracks were mentioned above. They are common all over the playa surface, consisting primarily of irregular polygons which range in size from 1 or 2 to 18 in. across. Indeed, one large polygon is usually made up of several smaller ones (Fig. 5).

Phreatophyte Mounds

The playa surface is barren of plant life until the edges are reached. Here the salt-tolerant shrub *Suadea torreyana* appears (Martin, 1963, p. 437). On the east side of the playa *Suadea* plays an important role in trapping the playa crust fragments that have been transported across the playa by wind action. The fragments accumulate until a definite mound shape is formed, and then the mound continues to grow. The name *Suadea* mound or dune was first used, but Ward S. Motts' name "phreatophyte mound" is more descriptive (Motts, *in* Neal, 1965, p. 20). Motts describes their growth as follows:

Phreatophyte mounds appear to pass through a sequence of stages in their development that one could classify as youth, maturity, and old age. In the initial stage the individual phreatophyte grows and reaches maturity near the level of the playa surface. Windblown sand and silt begin to accumulate around the roots of the phreatophytes for two reasons: (1) the roots and the plants form a natural obstacle around which the windblown material accumulates, and (2) the discharge of water around the plant results in the precipitation of carbonate and salts which form a surface crust on the mound. The crust retards further wind and water erosion.

As the mound builds upward from the accumulation of windblown material, the plant continues to establish itself at the tip of the mound by extending its root system downward. In this manner the plant growth temporarily keeps pace with the sedimentation rate. The plant finally dies when the roots can no longer reach the water table. A drop of the water table could kill all phreatophytes growing on mounds within a playa area. Relict "phreatophyte-mound fields," where the plants on the mounds have died and no new phreatophyte growth is occurring, were probably caused by a drop of the regional water table.

The Willcox Playa phreatophyte mounds have a teardrop shape with a rounded nose windward and a tail leeward (Figs. 6 and 7). Mound height ranges from a few inches to 2 to 3 ft while length is extremely variable. When but a few inches in height, mounds may range in length from 3 to 10 ft. In another area a group of mounds about 3 ft in height measure 12 to 15 ft in length. In still another area a number of mounds averaging 18 in. in height measure 6 to 8 ft in length. Where *Suadea* bushes grow close together, the mounds will eventually coalesce to make a hummocky form.

The surface crust that develops is slightly resistant to poking with a finger. Beneath the crust the flaky sediments may be slightly moist with the moisture increasing with depth. Careful excavation of the mounds reveals layers of playa crust fragments separated by thin white lines of calcium carbonate and salts. One would not recognize the role of this crust or the mound structure without excavating a mound.

Since playa crust fragments are moved by strong storm winds blowing chiefly from the west-southwest, a *Suadea* mound may add a few to many layers in any one year. Therefore, no attempt was made to count layers in order to date or otherwise determine the age of the mounds.

A relict phreatophyte mound area is found on the east side near the intersection of secs. 2, 3, 10, and 11, T. 15 S., R. 25 E. *Suadea* bushes are absent, but the crust is intact. One mound is 8 to 10 ft in height and still shows the thin white lines of calcium carbonate and salts.

Fig. 6. *Suadea* phreatophyte mounds along the southeastern playa edge after about three months of growth.

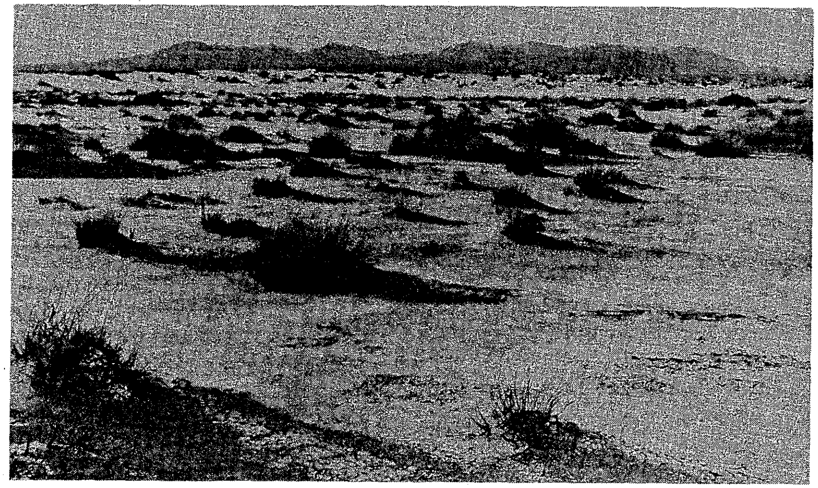

Fig. 7. Older and larger *Suadea* phreatophyte mounds in the northeastern corner of the playa.

Giant Desiccation Polygons

During the early planning stages of this project "giant mud crack systems" were noted in numerous areas of the playa on Army Map Service air photos taken in 1953. In July 1962 freshly opened cracks were encountered along the southeast edge. The cracks were 12 to 18 in. wide, about 4 ft deep, and from less than 100 to about 300 ft in length. A subsequent search of the literature led us to refer to these as giant desiccation features after the description of Willden and Mabey (1961) for similar features on the Black Rock and Smoke Creek deserts of Nevada.

James T. Neal (1965a, 1965b) and Neal, Langer, and Kerr (1968) made an extensive study of these giant desiccation features on Great Basin playas. The reader is referred to their papers for some of the details of their origin, shapes, and dimensions, and for influence of clay mineralogy on the playa sediments. Neal (1965b, p. iii) described the fissures as follows:

> Giant desiccation fissures observed on 39 playas (dry lakes) in the Great Basin are greater in size and causative rupture stress than are the typical, small, surface mud cracks. Giant open fissures may be a meter wide and more than 5 m deep, whereas the typical shallow mud cracks are a few centimeters wide and about 25 cm and more deep.
>
> The fissures form polygonal patterns that range from 15 to 100 m and more across, with intersections predominantly at approximately right angles. The fissures themselves follow sinuous, irregular lines. Thus, the patterns are for the most part "irregular random orthogonal polygons."
>
> The fissures form on hard, dry, compact playa crusts where desiccation has been rigorous and groundwater is fairly deep. The contractive stress producing the fissures results from loss of moisture and appears to develop over a period of several years; however, the rupture probably takes place in minutes. The greatest release of stress frequently appears to occur below the surface. Tectonic forces and basin subsidence may be a factor in fissure formation.
>
> Fissures follow a cycle of growth and destruction: fresh, sediment filled, vegetated, and relict fissures comprise the major geomorphic forms. The patterns can be easily identified on air photos, and can thus, through inference, offer reconnaissance information on the playa environment.

In December 1963 new fissures that had been partially filled in were observed along the southeast edge of the playa from the air. These fissures were about 300 ft long and formed a somewhat rectangular system in an area of older fissures. During the late summer rainy season of 1963 a "mud delta" was deposited in the northwest corner of the playa. The area was first observed from the air in October; at this time the surface looked to be fissured although still somewhat wet-appearing (Fig. 8). After it had dried for a time, the "mud delta" was visited in late December 1963. The fissures were filled but plainly visible (Fig. 9).

Neal, Langer, and Kerr (1968), after examining oblique air photos taken in 1963 and older vertical air photos, characterized the Willcox Playa fissures as occupying less than 10 percent of the playa with a polygon size of 15 to 30 m; polygons of irregular random orthogonal and oriented orthogonal shapes occur as relict "stains" and as partially filled and fresh fissures. The authors agree with these dimensions except for length because fissures about 300 ft long have been observed on the ground.

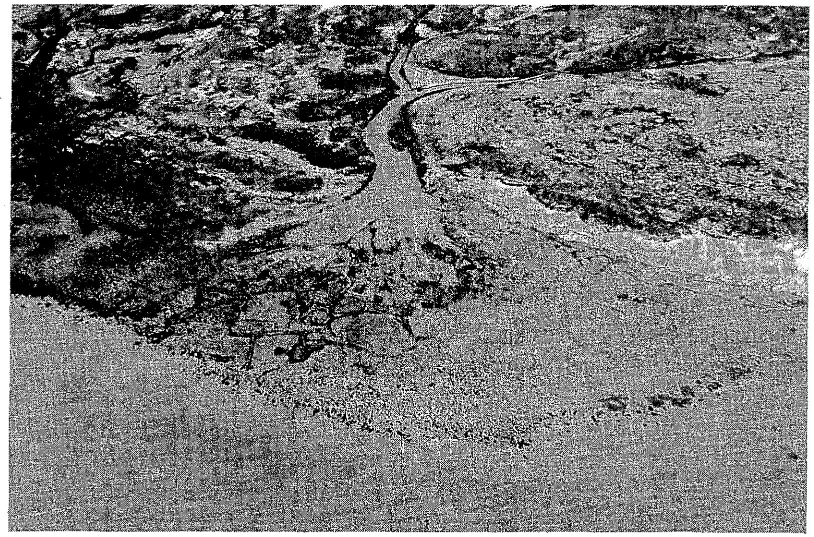

Fig. 8. Aerial view of "mud delta" in northwestern corner of playa; note fissured surface and polygonal system.

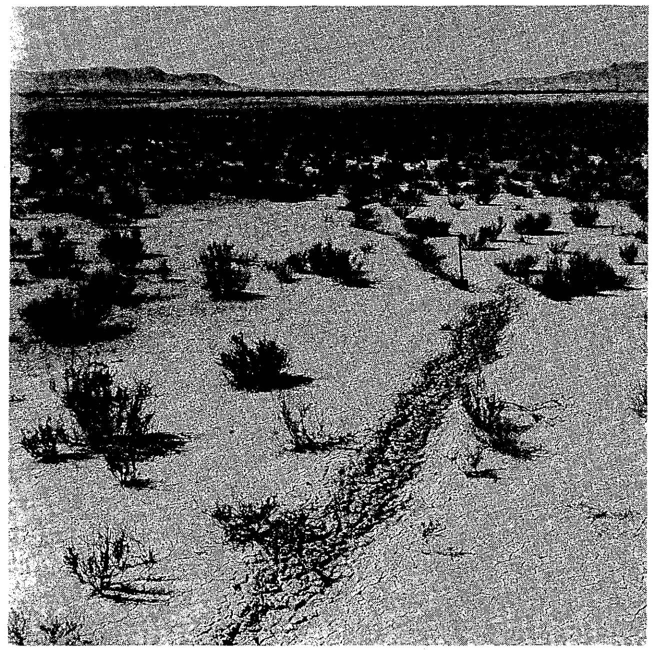

Fig. 9. Closeup view of filled fissure on surface of the "mud delta" in Figure 8.

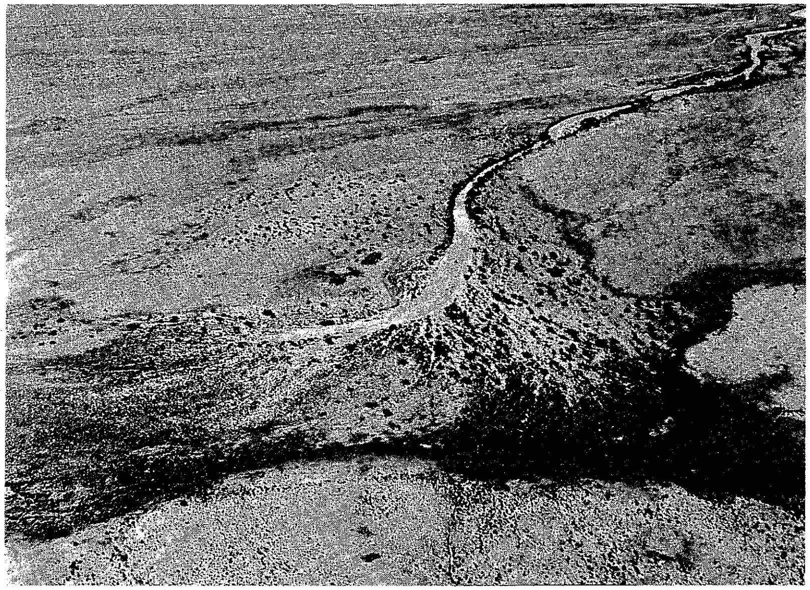

Fig. 10. Delta-shaped splay of fluvial sediments of Walnut Wash on the slope 3.5 mi east of Cochise in sec. 22, T. 15 S., R. 23 E.

Drainage Characteristics and Recent Fluvial Sedimentation

Stream flow in the Willcox Basin is intermittent with flow occurring during the winter rainy period and the summer thunderstorms. The drainage around the edges of the basin is characterized by rather high gradients. At the head of some streams in the mountains gradients may be as high as 1,000 ft/mi, but this gradient exists for only a short distance. Even in the lower portions of the drainages stream gradients are still high, averaging for most all drainages approximately 50 ft/mi. In but two channels is the gradient less, and here the gradients are still greater than 25 ft/mi. Individual channels are usually neither deep nor wide with depths of 1 to 3 ft and widths of 5 to 50 ft. The largest channel is Walnut Wash on the west side where one stretch of the channel is 8 ft deep and 250 ft wide.

Rainfall in the basin as described earlier amounts to about 12 in. per year, although this figure may be a few inches higher in the surrounding mountains. The summer thunderstorms are usually brief but provide the most rainfall. Many streams flow; however, only a few deliver water to the playa surface because the water is either lost by infiltration and evaporation or is retained by ranchers and farmers. They recognize the drainageways, whether small or large, and try to retain the waters behind dams or to divert the waters into cattle tanks for livestock and local flood control. Numerous dikes have also been built for flood control. Small reservoirs and cattle tanks are extremely abundant in the north, east, and west portions of the basin.

Several drainage areas are worthy of further description because they give a good picture of modern sedimentation in the basin. The northwest corner of the playa receives drainage from parts of the Winchester and Little Dragoon mountains. Although on air photos and topographic maps many channels may be observed heading towards the playa, stream flow is interrupted by several dams and one dike. Thus any sediment-laden waters leave their gravel and sand load higher on the slopes. Indeed, if any runoff does make it to the playa, only mud is deposited. The small mud deltas located in sec. 32, T. 14 S., R. 24 E. have been built by sediment-laden runoff from this drainage area.

Field evidence shows that even without the man-made structures, only muddy waters reach the playa. Some of the runoff from the Little Dragoon Mountains enters a single channel that parallels Interstate 10 on the south side and crosses U.S. Highway 666 just south of the Interstate 10 - U.S. Highway 666 overpass. Sediments from silt and clay to boulders are available to the waters by slope and channel erosion. Some coarser detritus is transported to within about 1 mi of the playa edge. At this point the coarse load splays out on the gentle grassy slope into a delta shape. The muddy waters continue playaward through the grass to contribute to the mud deltas described earlier.

Walnut Wash probably gives the most dramatic picture of the nature of sediment transport today. The drainage has its origin in the Texas Canyon area in the Little Dragoon Mountains and approaches the playa area after crossing Interstate 10 and winding around several low hills located about due west of the town of Cochise. At a point on the slope 3 1/2 mi west of Cochise on the Four Spear Ranch the coarser sediment load is deposited in a delta-shaped splay (Fig. 10). Muddy runoff waters continue eastward through a grassy draw, cause local flooding near Cochise, and finally channel into ditches that lead the waters onto the northwest corner of the playa near the Southern Pacific Railroad tracks. Other field evidence indicates that this wash once delivered coarse to fine detritus to the shores of Pleistocene Lake Cochise.

Big Draw separates the Little Dragoon and Dragoon mountains and drains the slopes of both mountain areas. During the Pleistocene this drainage also contributed gravel, sand, silt, and clay to Lake Cochise. The paleomeander belt is still visible on the surface, and the Pleistocene sediments may be viewed in gravel pits located along the southwest edge of the playa. Today Big Draw flows only after an intense thunderstorm in its drainage basin. The waters leave a well defined channel at the north end of the Dragoon Mountains at the Southern Pacific Railroad tracks and then follow the paleomeander belt about 6 1/2 mi to the playa (Fig. 11). If the flood waters do make it to the playa, they cross U.S. Highway 666 in a dip where local ranchers and farmers frequently observe depths of 3 to 4 ft of water. The muddy waters contribute silt and clay to the playa.

Flooding of the middle and lower basin slopes is also prevalent. The northeast slope of the Dragoon Mountains is subject to sheet flooding and delivers light reddish brown muddy waters to the south end of the playa.

Fig. 11. Paleomeander belt of Big Draw. This belt turns green after summer rains. Playa and Dos Cabezas Mountains are in the background.

Runoff from the Spike-E Hills area north-northeast of Willcox has periodically flooded the eastern part of Willcox. The waters are usually impounded in the sandy hills south of town where they infiltrate or are lost by evaporation. A similar situation exists just east of the Cochise County Airport. Runoff from the north and northwest causes local flooding which is lost by infiltration or evaporation while standing in the numerous alkali flats north of the playa.

The streams draining the north end of the basin, the Dos Cabezas Mountains on the east, and the Chiricahua Mountains to the southeast transport very coarse to fine detritus, but because of their greater distance from the playa, numerous dams, cattle tanks, and flood control dikes, stream flow and other runoff is lost before traveling very far. However, these areas were most important during the Pleistocene when climatic conditions were more favorable to sediment production and transport toward Lake Cochise.

Pleistocene Fluvial Sedimentation

Introduction

O. E. Meinzer was the first geologist to study the Sulphur Spring Valley in detail, recognizing the presence of one lake, suggesting an older, larger lake in the northern basin (Willcox Basin), and tentatively assigning the last epoch to the Pleistocene (Meinzer and Kelton, 1913, p. 74-76). Since Meinzer's field studies in 1910-1911, our knowledge of the Pleistocene

history of the Basin and Range Province has grown considerably. Much of this information has been obtained in the past 25 years using detailed geologic mapping, soils mapping, sediment analysis, radiocarbon dating, isotope studies, vertebrate and invertebrate paleontology, palynology, and paleoclimatology. From these studies we have a better understanding of the general concept of pluvial climates for the Basin and Range Province and similar regions around the world. The greater Pleistocene precipitation changes in the Basin and Range Province resulted not only in the formation of the pluvial lakes, but also in increased rates of weathering, soil formation, erosion, and sedimentation and provided a different environment for plants and animals.

Fluvial Sedimentation

Abundant evidence exists for fluvial sedimentation in the Willcox Basin during the late Tertiary and Quaternary in the form of the alluvial deposits described earlier. The oldest sedimentary rocks--moderately consolidated alluvium–and the younger, poorly consolidated alluvium have similar lithologic characteristics, but they may be differentiated in outcrop because the moderately consolidated alluvium has been deformed structurally by tilting and faulting (Brown and Schumann, 1969, p. 10). Brown and Schumann (1969, p. 12) further describe the older alluvium as follows:

> The moderately consolidated alluvium unconformably overlies the rocks of the mountain blocks and is overlain in most of the area by poorly consolidated alluvium and unconsolidated alluvium. The moderately consolidated alluvium consists of gray moderately indurated stream-deposited lenticular beds of gravel, sand, silt, and clay-size material derived from the adjoining mountains. The coarse-grained fraction of these sediments consists almost entirely of rhyolitic and andesitic volcanic fragments in a matrix of sand and fine-grained material. Northeast of Willcox intercalated basaltic lava flows occur in this unit (Cooper, 1960).
>
> The abundance of coarse-grained rhyolitic and andesitic volcanic fragments in this unit indicates that it was probably the first unit deposited in the present basin. The rhyolite and andesite represent the youngest rocks in the mountains; they were probably the first rocks to be removed by stream erosion and deposited in the central part of the basin as alluvium. The lithologic characteristics and the type of deformation of the moderately consolidated alluvium indicate it is similar to other units of Tertiary age in southern Arizona.
>
> Because the poorly consolidated and the moderately consolidated alluvium have similar lithologic characteristics, these units are difficult to differentiate in driller logs, which constitute the bulk of the subsurface data; . . . .

The consolidated alluvium is overlain unconformably by unconsolidated stream deposits that constitute much of the alluvial fan slopes and central valley floor. Based upon the examination of Arizona Highway Department drill hole logs from shallow borings east and west of Willcox, water well logs in the files of the Tucson office, U.S. Geological Survey, and interviews with well drillers in the Willcox area, the unconsolidated stream deposits probably range in thickness from a few tens of feet to over 600 ft. These deposits may be best studied north and south of the playa; closer to the playa these stream deposits interfinger with the clays and muds of Pleistocene Lake Cochise.

The presence of a wide stream meander belt in the basin north and west of Willcox is easily discernible on aerial photographs. The individual channels and meanders stand out because mesquite trees form dark patterns where they have put their roots down into the coarser, water-bearing sediments. About two dozen sand and gravel pits have been opened in the valley floor between Willcox and the Cochise County Airport, extending from Interstate 10 north for 5 mi. Most of these pits are now abandoned and only one or two pits have been active in recent years. Gravels and sands in this area have furnished fossil camel teeth and bones, horse teeth, mammoth bones, and one tusk.

A similar meander pattern occupies an area stretching southeast from the southern playa tip. This belt of stream meanders derived its flow from the southern Dos Cabezas Mountains and the Chiricahua Mountains as far south as Turkey Creek. Only one sand and gravel pit has operated in recent years, but local ranchers and farmers have put in numerous bulldozer cuts for the sand and gravel with which to make concrete to line their irrigation ditches.

The best exposures of the unconsolidated stream deposits close to the playa edge are those in several sand and gravel pits located on the southwest edge in the northeast corner of sec. 3, T. 16 S., R. 16 S. After these pits were started in early July of 1963 several cesspool pits were excavated to a depth of 12 ft in the south-central part of the same section. The pit walls showed the same stratigraphy as the sand and gravel pits. These sediments are part of the late Pleistocene Big Draw drainage.

In all areas where exposed, the unconsolidated stream deposits display typical fluvial sediment characteristics; cut and fill-type deposition; trough cross stratification in sands and gravelly sands; laminated fine-grained sands; and graded bedding in sands. To supplement the pit exposures during the 1962-1965 period of this study, Pine, Robinson, and Schreiber put down 105 auger holes on and adjacent to the playa to obtain detailed lithologic logs. These logs show most accurately the facies changes that developed between the coarser stream deposits and the finer-grained lake deposits.

Petrography of the Fluvial Sediments

The results of 53 size analyses for gravel, sand, and mud content are shown in Figures 12 and 13; also see Table 2. All samples are spot samples

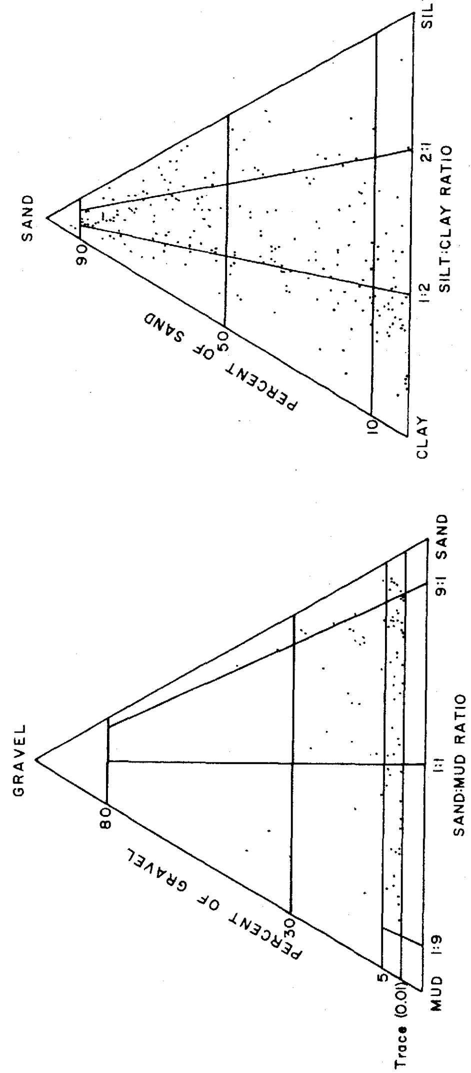

Fig. 12. Grain size nomenclature for textural groups as defined by the relative percentages of gravel, sand, and mud (a), and for nongravel-bearing materials for which silt:clay ratio was determined (b). Triangle *a* expanded at the base to plot mud, sandy mud, muddy sand, and sand that did not contain gravel. See Table 2 for textural names, which are modified slightly from Folk (1968).

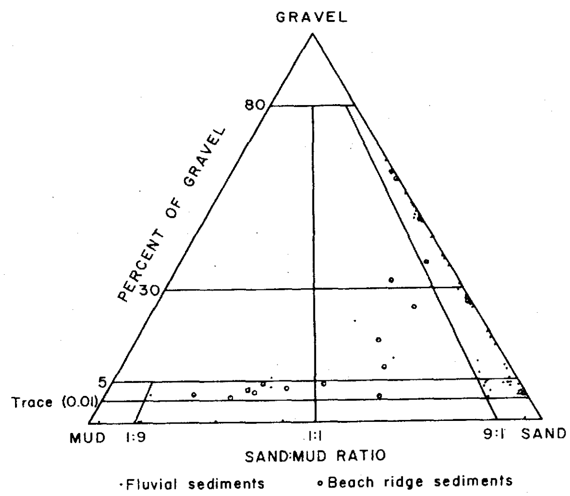

Fig. 13. Grain size nomenclature for fluvial and beach ridge sediments; refer to Figure 12 and Table 2 for textural names.

obtained from a pit wall and are considered to be representative of a sedimentation unit. Otto (1938, p. 575) defined the sedimentation unit at any sampling point as ". . . that thickness of sediment which was deposited under essentially constant physical conditions." Thus, laminated fine-grained sands in horizontal beds and cross-stratified gravelly sands or sandy gravels in a trough were sampled as individual sedimentation units.

The gravels fall chiefly in the pebble sizes (2-64 mm) and are dominated by gray and red volcanics, quartz, and quartzite. Limestone, chert, phyllite, mica schist, chlorite schist, granite, and basalt pebbles also occur. Naturally, the pebble composition in different parts of the basin reflects the rock types of the source areas. For example, in the gravel pits to the north of the playa it is easy to recognize the volcanic clasts from the Galiuro and Winchester mountains and the granite and metamorphic rocks from the Pinaleno Mountains. The pebbles are subrounded to well rounded; disc and blade shapes are most common.

The sand-size grains are composed of quartz, feldspar, rock fragments, and heavy minerals. Although all sand sizes occur, medium and fine sands dominate. Grains vary in roundness from very angular to rounded but are mostly subangular. Sorting is best in the sands and slightly gravelly sands with sorting values in the moderately well sorted to moderately sorted part of the verbal classification scale of Folk (1968, p. 46). Sandy gravels and gravelly sands are chiefly poorly sorted; all other samples are poorly sorted, very poorly sorted, or extremely poorly sorted. Heavy minerals are ubiquitous and usually either concentrated along planes between laminae in the sands or dispersed throughout the coarser gravelly sands and sandy gravels. Magnetite, ilmenite, hematite, pyroboles, epidote, clinozoisite, biotite, and zircon are abundant.

Table 2. *Textural names for mixtures of gravel, sand, and mud in Figure 12a and for mixtures of sand, silt, and clay in Figure 12b*

G.	Gravel
sG.	Sandy gravel
msG.	Muddy sandy gravel
mG.	Muddy gravel
gS.	Gravelly sand
gmS.	Gravelly muddy sand
gM.	Gravelly mud
(g)S.	Slightly gravelly sand
(g)mS.	Slightly gravelly muddy sand
(g)sM.	Slightly gravelly sandy mud
(g)M.	Slightly gravelly mud
S.	Sand
mS.	Muddy sand
sM.	Sandy mud
M.	Mud
C.	Clay
Z.	Silt
sZ.	Sandy silt
sM.	Sandy mud
sC.	Sandy clay
zS.	Silty sand
mS.	Muddy sand
cS.	Clayey sand

Note:

Gravel:	> 2 mm
Sand:	< 2 mm > 0.0625 mm
Silt:	< 0.0625 mm $> 4\ \mu$
Clay:	$< 4\ \mu$
Mud:	silt + clay (wet)

Lake Cochise Sediments

Introduction

The streams transporting the gravels and sands described in the previous section also transported silt and clay to Pleistocene Lake Cochise. Toward the middle, and presumably the deeper, part of Lake Cochise, clay and mud were deposited. Closer to the north and south ends, where the main streams contributed their loads, and along the western and eastern shores, the clay and mud mixed with sand or interfingered with sand, gravelly sand, and sandy gravel lenses and beds. These are the lithologies encountered beneath the playa surface to the north and the south and between the beach ridges on the east and west sides.

O. E. Meinzer (Meinzer and Kelton, 1913, p. 57-58) first described the thick clay beds of ancient Lake Cochise based upon the well log descriptions of local drillers. The information presented is quite accurate; he states "The black color is probably due to impregnation of the formation with sulphides, which become rapidly oxidized when they are brought into contact with the air, and the odor is probably due to the presence of hydrogen sulphide." He also correctly diagnosed the thick clay sequence as having been deposited from quiet waters, possible in a permanent lake. The University of Arizona Willcox Playa projects in the field and laboratory greatly extended the conclusions of Meinzer with the kind of general and detailed data that permitted a more complete description to be made of the late Pleistocene and Recent history and the sedimentary environments.

Sampling Activities

During the course of these studies a 140-ft deep hole was drilled in the middle of the playa approximately 3.87 mi due east of the Cochise Overpass on U.S. Highway 666. Except for the upper 10 ft which was oxidized to a brown color, the hole was entirely in the black clay described by Meinzer. A 4-in. inner diameter core barrel was used from the surface to a depth of 74.7 ft; from this point to total depth a 2 3/8-in. inner diameter core barrel was employed. Upon extrusion from the 5-ft core barrel the core slug was wrapped in commercial polystyrene film and sealed in plastic bags. This technique proved very satisfactory in preventing the oxidation of the black sediments. After several months' storage, most core slugs showed but little oxidation which consisted of yellowish brown or pale olive rims a few millimeters thick. Core recovery amounted to 85 percent.

Black clay was also sampled in two holes bored with a peat auger to depths of 19.85 and 16 ft, respectively. The deeper hole twinned the 140-ft hole; the shallower hole was located along the west playa edge opposite the Cochise Cemetery. Lake Cochise sediments were also sampled extensively in another 105 auger holes which ranged in depth from 10 to 22 ft.

In 1963 the Arizona Electric Power Cooperative put in over 200 holes to a depth of 7 1/2 ft for power line poles. The pole line crossed the southern end of the playa before following the southeastern edge for a distance of about 8 mi toward the northeast. Playa sediments left on the surface were examined. Several locations showed abundant ostracods in the clays; these sites were further sampled by augering to determine the subsurface position of the ostracod-bearing clays.

Sediment Characteristics

Size Distribution.--The Lake Cochise sediments sampled in the 140-ft hole and the two peat auger holes had a rather uniform size distribution. One hundred and thirty-four samples averaged 1 percent sand, 26 percent silt, and 73 percent clay. Based upon Folk's classification (1968, p. 28) this mixture is a clay. Actually 114 samples were clay and 20 were mud. The other 105 auger holes were located toward the north and south ends

of the playa and along the east and west sides playaward of the beach ridges thrown up by Lake Cochise waves. Here the sediments are more variable in their size distribution; in addition to sand, silt, and clay a number of samples contained gravel.

The cores from the 140-ft hole were the best samples for stratification studies. Laminations less than 1 mm thick were common but could be observed for intervals of a few inches only. Silt and sand layers could also be observed after detecting their presence by dragging a pointed pencil the length of a core slug. The silt layers were about 1/2 mm thick while the sand layers amounted to the diameter of the sand grains in thickness (generally less than 1/2 mm). This core is from what is regarded to be the deeper part of Lake Cochise. Auger holes put down toward the edge of the playa contain more sand in distinct layers or mixed with mud or clay.

Color.–The unoxidized muds and clays are black (N1). Oxidized surface and near-surface muds and clays however range from moderate yellowish brown (10YR 5/4) to light brown (5YR 5/6) and pale olive (10YR 6/2); colors are those of the Munsell system used in the Rock Color Chart (Goddard *et al.,* 1948). Depth of oxidation varies; depths of 3 to 5 ft are common near the edge of the playa and increase to 10 ft toward the middle of the playa. The oxidized muds and clays also change with depth to less oxidized light olive gray (5Y 5/2), greenish gray (5GY 6/1 and 5G 6/1), and dark greenish gray (5GY 4/1 and 5G 4/1) muds and clays before reaching the black (N1) sediments. Surface waters percolating slowly downward into the clays and muds are believed to be responsible for the oxidation.

Scattered through the 140-ft core below the depth of 10 ft the black clay and mud were mottled or streaked with dark greenish gray. Several intervals 1 to 2 in. in length also had vertical veinlets of dark greenish gray color. Many of the black muds in other auger holes contained the same dark greenish gray mottling and streaks. The dark greenish gray clays and muds are more oxidized than the black sediments based upon Eh measurements (discussed later in this section) and field observations.

Schreiber and Pine witnessed the drilling of several water wells about 1 mi southeast of Willcox. The wells penetrated the black lake clays and muds and when the well bailer was dumped, black sediment and black muddy water spilled into a pit. While the drill rig was shut down for a few days the pit surface muds oxidized to a light olive (5Y 6/1) to a greenish gray (5GY 6/1) color. At a depth of 2 to 3 in. the muds were dark greenish gray (5GY 4/1 and 5G 4/1) and at 4 to 5 in. the black color persisted. Thus the oxidized sediments seemed to form a protective blanket over the unoxidized sediments. The same experience of rapid oxidation was encountered in our augering when we left samples laid out in the open for several hours before logging them.

Eh-pH Measurements.–Over 200 paired Eh and pH measurements were made on the 140-ft core at the same time that the core was logged for lithologic characteristics. Austin Long of the Geochronology Laboratories made the determinations on the freshly unwrapped and split core slugs using a Beckman Zeromatic pH meter equipped with a Beckman No. 39170 fiber-type calomel reference electrode, a Beckman No. 41263 glass pH electrode, and a laboratory-made platinum electrode for millivolt potential determinations. The measurements were made directly on the moist fresh surface of the core slug. Reproducibility was to within 0.1 pH unit and 10 mv electrode potential.

Positive Eh values were measured for the upper 10 ft of oxidized sediment; pH values ranged between 8.8 and 9.6 and averaged 9.2. The rest of the core gave negative Eh values that ranged from -106 to -306 mv. Highest readings were for the blackest clays that gave readings near -300 mv. The greenish gray and dark greenish gray clays gave lower readings in the -106 to -206 mv range. With depth the pH values ranged from 8.7 to 9.6 but still averaged 9.2. One rather interesting but unexplained increase in pH readings did occur between 100 and 110 ft. Readings increased from the range of 9.1 to 9.2 through 9.3 to the range of 9.4 to 9.5. From 110 to 140 ft the readings were almost entirely in the 9.4 to 9.5 range. Long (1966, p. 11-12; 40-46) describes his procedure and interprets the results in some detail.

Organic Matter--Iron Sulfides.–The black and greenish gray sediments owe their color in part to preserved organic matter but chiefly to a black iron-sulfide mineral. Organic matter determinations were made by the reduction of chromic acid method of Allison (1935) using the factor 1.724 multiplied by percent organic carbon to obtain percent organic matter. Thirteen samples of black and greenish gray sediments from the 140-ft core ranged from 0.44 to 2.20 percent organic matter with an average of 1.02 percent. Organic matter for two greenish gray clays amounted to 0.44 and 0.58 percent, respectively.

By way of comparison, 15 samples from the upper 10 ft of oxidized sediments ranged from 0.30 to 1.93 percent and averaged 0.70 percent. This rather high average percentage for the oxidized sediments when compared to the greenish gray clays may seem incongruous. A possible explanation is that the oxidized sediments have been contaminated by surface waters bearing very finely divided organic carbon.

The presence of black iron-sulfide mineral is predicated on the black color, the strong evolution of H_2S when treated with dilute hydrochloric acid, negative Eh values, and oxidation characteristics. The iron-sulfide mineral could not be identified by X-ray diffraction techniques probably because of its low content, low degree of crystallinity, and masking by quartz, analcime, and clay minerals, but this mineral could be the ferrous sulfide hydrotroilite described from marine, marginal marine, and lacustrine sedimentary environments. Berner (1964) cites this literature in his study of iron sulfides formed from aqueous solutions at low temperatures and atmospheric pressure. He also suggests, based upon his research, that "The iron sulfide commonly referred to as hydrotroilite is at least in part poorly

crystallized tetragonal FeS." Other iron sulfides, such as pyrite, could also be present.

The formation of fine-grained iron sulfides in sediments has been described chiefly in marine and marginal marine environments (Berner, 1964, 1967, 1970; Love, 1964; Love and Murray, 1963), but the results of the studies and the requirements for iron sulfide formation may be applied to the lacustrine environment. Fine-grained lacustrine sediments must contain organic matter for the anaerobic bacteria to metabolize, a source of iron, and dissolved sulfate. All of these requirements plus highly alkaline conditions were met in Lake Cochise bottom sediments. Red and brown iron oxides are abundant in the sediments of the drainage area; the clay minerals of the lake bottom could be another source. Sodium sulfate is one of the two salts commonly found associated with the playa area sediments. Bacterial reduction of the sulfate produces H_2S which reacts with iron to form iron sulfide. The same authors describe the formation of pyrite from the iron monosulfide and elemental sulfur. This stage of sulfide development has not been observed in Lake Cochise sediments.

Black iron sulfides in lacustrine sediments deserve further study. The senior author has observed and studied black muds from other Pleistocene and Recent lakes in Arizona and in deep cores from Great Salt Lake (Schreiber, 1958). Many lacustrine environments may be more accessible and easier to study than some marine and marginal marine environments.

Clay Mineralogy.--The mineral compostion of the clay-size fractions of the 140-ft core and playa surface samples was studied in detail by X-ray diffraction techniques and supplemented by electron microscope photographs. All mineral identifications were made on the -2 μ fraction. The clay minerals are dominated by illite with lesser amounts of montmorillonite, mixed-layer illite-montmorillonite, and vermiculite in decreasing order of abundance. Only traces of chlorite and kaolinite were detected with the kaolinite occurring in but four samples near the top of the core.

Illite also dominates the playa surface samples almost to the exclusion of other clay minerals. Expansible phases constitute less than 5 percent and are, in order of abundance, mixed-layers, montmorillonite, and vermiculite. Traces of kaolinite and chlorite were found in a few samples. It is interesting that 33 playa surface samples averaged 1 percent sand, 6 percent silt, and 93 percent clay-size materials.

The clay minerals of the lake sediments and playa surface are judged to be of detrital origin because of their similarities to the clay minerals of the drainage area. All terrains contribute illite which also dominates most samples. Soils and channel samples high in chlorite and vermiculite come from the Dragoon Mountains where phyllites, schists, and granite crop out. Northward, on the west side of the playa, montmorillonite increases as the influence of the granitic terrain of the Little Dragoon Mountains is felt. A soil sample from Texas Canyon in the Little Dragoon Mountains contained montmorillonite as the dominant clay mineral. From the complex terrain north of the playa chlorite, chlorite-kaolinite, and montmorillonite are produced. These samples were all from stream channels and are a good representation of material being carried toward the playa from the north. The samples from Precambrian granites in the Dos Cabezas Mountains are high in montmorillonite with minor chlorite and kaolinite. Northward the mixing of sedimentary and extrusive igneous rocks is reflected in less montmorillonite and more chlorite and chlorite-kaolinite. South of the playa samples with relatively high proportions of kaolinite and kaolinite-chlorite were found. Some of these samples may represent reworked lake sediments.

The very high percentage of illite and low amounts of other clay minerals is puzzling when one considers what is available from the drainage basin. Several factors operating in the Willcox Basin might help to explain this discrepancy. The fact that very few streams deliver water to the playa surface (and thus little sediment) has already been described. A second factor involves the downward percolating meteoric waters which oxidize the near-surface clays and muds. These same waters could selectively transport fine colloids downward and strip potassium from illite. This would explain the low montmorillonite content of the surface and the relatively high mixed-layer content of the surface and near-surface materials. The third factor involves wind action on the playa surface where very fine colloidal montmorillonite could selectively be deflated, particularly from a minutely mud-cracked surface. Strong winds and "dust devils" are common not only on the playa but also on the adjacent slopes. Since many of these slopes are plowed fields covering many square miles, much fine clay (perhaps illite) could be picked up from the fields and then be deposited as a blanket over the lower parts of the basin. Or perhaps "dust" comes from a more distant source bringing in clay minerals, quartz, iron oxides, calcite, etc.

The clay mineral distribution at the surface of the playa cannot be explained by normal sedimentary processes. Certainly some form of quasi-equilibrium has been reached between geologic processes, mainly wind and meteoric waters, and the surface sediments.

The zeolite mineral analcime is another important constituent of the -2 μ fraction and is related to the clay mineralogy. It occurs throughout the lake clays and muds where its abundance has been calculated to be 5 to 10 percent. The analcime occurs in equant crystals and is believed to be of an authigenic origin through the diagenetic destruction of kaolinite for the following reasons:

1. An origin through the reorganization of volcanic glass in alkaline lake waters is excluded because volcanic glass has not been identified in the lake beds.

2. Petrographic and geochemical data indicate low dissolved silica concentrations which would rule out crystallization of precipitated aluminosilicate gels to form analcime.

3. Kaolinite is unstable in an alkaline environment (all but a few of the 218 pH measurements obtained were between 9.0 and 9.5). Kaolinite is forming in minor amounts in the drainage area today and probably formed at a higher rate during a Pleistocene pluvial yet is absent in the core below a depth of a few feet.

Calcium Carbonate Content.--Calcium carbonate in the form of the mineral calcite is ubiquitous in the Lake Cochise sediments. It occurs in all size grades from the clays through sand. In the clays and muds it is not visible but may be detected by its effervescence in dilute hydrochloric acid or by X-ray diffraction techniques. Many of the sand samples contain small white calcium carbonate lumps resembling caliche, gastropod shell fragments, and ostracod valves. Numerous sandy mud samples from the power pole holes located along the southeast edge of the playa contained only ostracod valves as the sand fraction. One auger sample with a volume of 324 cm^3 furnished 23 g of ostracod valves for radiocarbon dating. Calcium carbonate content is extremely variable; 18 samples from auger holes had a range of 1.7 to 34.0 percent with a mean of 15.2 percent.

The calcite in the 140-ft core, which occurs in all size grades in the core and constitutes as much as 80 to 90 percent of the sand fraction in some samples, was studied in detail. It is primarily, if not entirely, the product of authigenic crystallization and biological activity. Angular fragments of translucent sculptured ostracod valves are prominent in both the silt and sand fractions. Shell fragments have served as nuclei for radial growth of calcite crystals with prismatic and scalenohedral habit. These crystals are very fine grained and contain much included organic matter. They exhibit parallel extinction, high birefringence, and effervesce vigorously in dilute hydrochloric acid. Aggregates of tiny crystals occur in several forms. White, saccharoidal, spherical grains in the coarse fraction were found to be composed of radial groups of calcite crystals. Much more common are light-brown, spherical and rod-shaped aggregates of crystalline calcite, ostracod fragments, and detrital minerals. These range in size from 0.04 to 0.15 mm in diameter and show varying degrees of effervescence in acid. Some effervesce vigorously and appear to be aggregates cemented by calcite. Others effervesce sluggishly, and the nature of the insoluble residue suggests these are fine mineral grains agglutinated by organic matter. The rod-shaped pellets resemble closely the fecal secretions reported in modern marine sediments (Moore, 1939). Several samples contained reddish-brown spongy aggregates that had evidently been oxidized and redeposited from desiccated margins of the lake. Overall, cemented and agglutinated grains formed the bulk of the sand fraction of the core.

Beautifully developed calcite euhedra occur at a depth of 80 ft and in varying amounts to the bottom of the core. They appear as elongate nearly perfect single crystals with well-developed prisms and scalenohedrons terminated by rhombohedrons. Less commonly, rhombohedral crystallization occurs alone. Many are without inclusions and are perfectly clear, whereas others contain considerable amounts of organic matter. These crystals are definitely authigenic as they show little evidence of mechanical wear, and they are larger than the detrital grains with which they occur. Crystals a few tenths of a millimeter long were the rule, although some from a depth of 100 ft measured 1 to 2 mm long.

Other Sand Fraction Mineralogy.–Quartz and feldspar are abundant constituents of many sand fractions. Texturally the sands are chiefly fine to very-fine grained, moderately well sorted where not mixed with silt and clay, and angular to subangular with some rounded and well-rounded grains. Quartz-feldspar ratios are variable with the coarser samples having the higher ratios (3:1 to 5:1). The low percentage of feldspar in the coarser grade sizes probably reflects the abundance of vein quartz in some rocks and coarse-grained granite in part but also the ease with which feldspar grains cleave. This cleavage of feldspar to a smaller size seems rather plausible because the quartz-feldspar ratios are nearer to one or less than one for the finer grained samples.

Studies were also made of the quartz-feldspar ratios of sediments derived from different rock types in the drainage basin. In general, samples obtained from streams which derive their materials from granitic, sedimentary, schistose, and gneissic rocks, or younger alluvium contain more quartz than feldspar. The ratios range from slightly more than 1:1 to approximately 3 1/2:1. Sediments derived from rhyolites or mixed rhyolite-andesite sources had ratios well below one.

Heavy-mineral suites were separated from the sand and coarse silt fractions of samples from the 140-ft core and auger holes and examined with a petrographic microscope. Pyroxene and amphiboles were grouped (pyroboles), as were epidote, clinozoisite, and zoisite (E-C-Z). The frequency of mineral groups and species was visually estimated; the results for the 140-ft core are tabulated in Table 3.

Primary bentonitic material overlooked in the visual examination of the core might be detected in heavy-mineral suites. Euhedral apatite, zircon, and biotite, with or without sphene, are typical of silicic volcanic ash (Weaver, 1963). A few samples had so little coarse material that the heavy-mineral separates were too fine-grained for microscopic examination. The remainder contained abundant minerals with a decidedly mafic character. Zircon, tourmaline, rutile, sphene, and garnet are rare or present in small amounts, whereas pyroboles, chlorite, biotite and E-C-Z are abundant. Tourmaline is the brown variety typical of low-rank metamorphic rocks, and strongly pleochroic brown basaltic hornblende forms a significant proportion of the total pyroboles. Dark-brown and green biotite are common, and much of the brown biotite has been leached to a pale golden brown. Sedimentary chlorite was distinguished from green biotite by the mottled appearance imparted to chlorite from abundant inclusions. Except for a few zircon euhedra, all the minerals showed the effects of weathering and mechanical abrasion.

The heavy mineral suites from auger hole samples showed the same relative abundances. Because the auger holes were located nearer to the

Table 3. *Heavy minerals of the 140-ft core*

Sample No.	Depth (ft)	Pyro-boles	Zir-con	Tour-maline	Rutile	Garnet	Apatite	Chlorite	Biotite	E-C-Z	Other Minerals – Comments
203	1.5	x								x	Very poor suite
208	3.0	c	r		r	r	r	vc	s	vc	Basaltic hnb. present
212	5.0	c					r	vc	s	vc	Sphene (r), bas. hnb.
216	8.5	x						x	x	x	Very poor suite
17	17.8	c						c	vc	c	
19	19.4	x			x		x	x	x		Very poor suite
25	21.6	vc						c	c	vc	
34	28.0										No heavy minerals
43	33.7	x					x			x	Very poor suite
46	35.9										No heavy minerals
51	39.4	vc						c	c	vc	Fluorite
55	43.1	vc							vc		Fluorite
59	45.0										No heavy minerals
69	50.0	x				x					Fluorite(x), olivine(x)
78	55.6								x		Very poor suite
86	60.9	vc	r				c	s	c	c	Very fine grained
93	65.0	a		r				c	c	c	Fluorite(r), bas. hnb.
106	73.3	c						c	c	s	Fluorite(c), bas. hnb.
114	80.3	vc	s				s	s	c	c	
118	85.1	c		r		s	c	c	s	c	Bas. hornblende
125	90.0	a	s				r	s	s	vc	
135	97.6	vc				r	r	c	c	vc	Bas. hnb., sphene(r)
139	100.0	vc	r					r	vc	s	Poor suite
142	104.0	vc		r		r	c	s	s	c	Bas. hnb., sphene(r)
147	108.0	vc	s	r		r	r	s	c	vc	
150	109.0										No heavy minerals
155	113.0	vc		r			s	c	c	vc	Green tour., bas. hnb.
161	117.0	vc	r			r	s	c	c	c	Bas. hornblende
166	120.0	c	r				s		c	c	Poor suite
172	123.0	vc		r		r	r		c	vc	
177	126.0	vc	r			r	r		c	vc	
187	132.0	a	r				r	s	s	c	
195	137.0	vc		r			s		c	c	Brown tour., bas. hnb.

Explanation: a = 50-75%; vc = 25-50%; c = 10-25%; s = 2-10%; r = few grains; x = too few grains for statistical estimate.

edge of the playa, and in some instances beyond the edge, their samples are better for determining the provenance of the heavy minerals. Based upon the study of the drainages from various rock types in the basin, the following generalizations can be made about the characteristic heavy minerals. Source areas of gneissic rocks yield sediments containing large quantities of pyroboles; high biotite counts are obtained from sediments derived from rhyolitic rocks; and samples high in E-C-Z and pyroboles and low in other heavy minerals are derived from schistose rocks. High zircon counts from a sample indicate a granitic or sedimentary source area. Rhyolitic and andesitic source areas yield sediments containing large amounts of apatite; granitic rocks also yield significant quantities of apatite.

A striking feature of the heavy-mineral assemblage is the paucity of stable minerals and an abundance of more labile constituents. The predominant minerals are those one would expect from a mafic-igneous and metamorphic rock terrain. However, the low frequencies of zircon, rutile, sphene, and garnet do not adequately represent contributions from silicic igneous rock areas. These minerals are the most dense heavy minerals, and because of hydraulic factors operating in this low-energy environment, they are not found in the coarse-size fractions examined. The frequencies of apatite probably better represent the sediment contributions from silicic igneous terrains which lie east and west of the playa. Even allowing for hydraulic factors, it is apparent that the heavy-mineral suites are influenced mainly by detritus from mafic-igneous and metamorphic rock terrain to the north. Again the northerly drainage area stands out as an important source of sediments for the basin and Lake Cochise.

Salts and Gypsum.–The occurrence of arborescent halite crystals on the walls of auger holes left standing open has already been described. The senior author encountered a similar situation in a study of a number of Great Salt Lake, Utah, cores that had been taken inside plastic tubes. Upon drying, the sediments had shrunk and the space between the inner wall of the tube and the core face was occupied with similar arborescent halite crystals.

Although halite was the only readily soluble salt detected in the core sediments, halite, thenardite, and burkeite occur in the soluble white crusts of the playa surface and nearby sand dune areas.

Gypsum was encountered in only one sample from an east side auger hole. The crystals measured up to 5 mm in length and since they enclosed sand grains, they are deemed authigenic.

Beach Ridges

Location.–Beach ridges border the playa on the east and west sides and are the major preserved shore features of Pleistocene Lake Cochise. The ridges stand out when viewed both from the ground and from the air because they support a good growth of mesquite trees and yucca (Fig. 14). Of the 50 mi of shoreline, only about 29 mi are defined by this

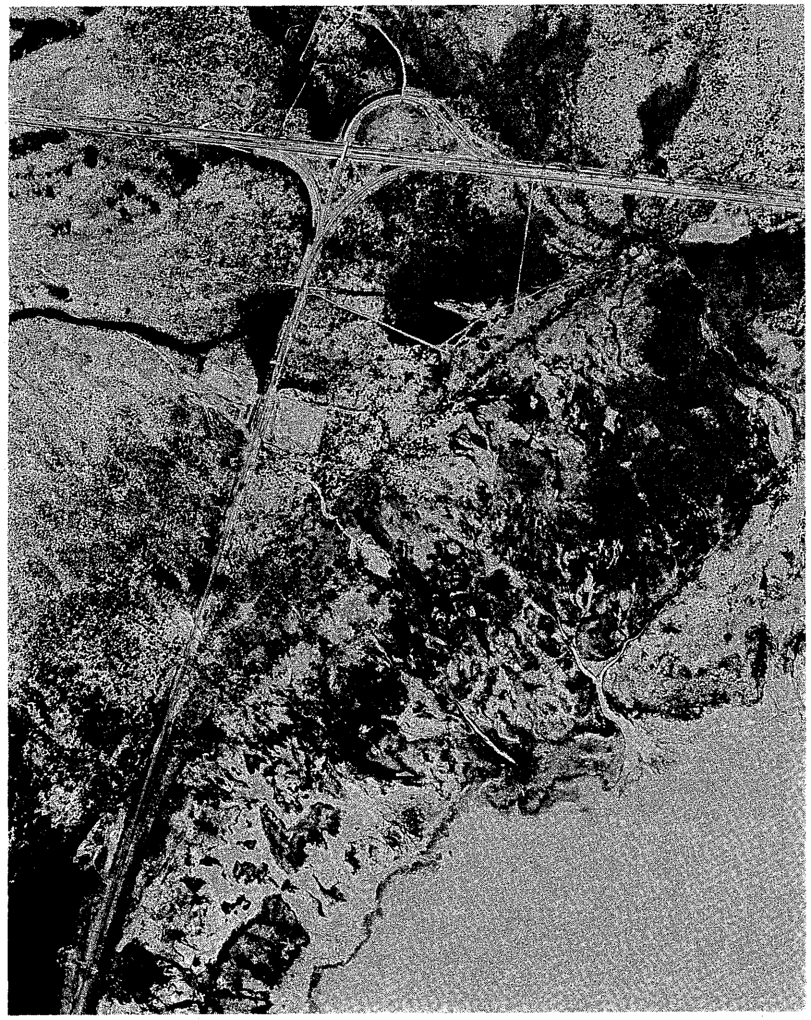

Fig. 14. Vertical air photo of the northwest corner of playa near the Interstate 10 - U.S. 666 overpass. The beach ridge is located by the thin dark line of mesquite trees that parallel U.S. 666 for a short distance before swinging north. Croton Springs is the light-colored area of sand at bottom of photo.

shoreline feature. The beach ridge is about 15 mi in length on the west side. On both sides the ridges follow the 4,175-ft contour, although their crests are 5 to 10 ft higher. At the north and south ends of the playa it does not appear that the ridges were ever built because these were the sites of the influx of fluvial sediments during the late Pleistocene. Meinzer (Meinzer and Kelton, 1913, p. 34-37) describes the east and west beach ridges as being somewhat shorter than the 14 to 15 mi indicated above; he also mentions a beach ridge on the north side of the playa. Air photos show the beach ridges to be longer, however, and Meinzer's beach ridge on the north side is actually an aeolian feature.

West Beach Ridge.–The west beach ridge extends from sec. 17, T. 14 S., R. 24 E. in the north to sec. 25, T. 16 S., R. 25 E. in the south (Fig. 15). Along this length the ridge is as much as 400 ft wide although the width is difficult to measure because the ridge slope on the playa side grades into the lake sediments without too sharp a break. Of the two slopes, the foreshore slope is much steeper and shorter than the back slope. In sec. 33, T. 15 S., R. 24 E., 1 1/2 mi south of Cochise, the steeper foreslope is about 100 ft wide whereas the backslope is about 300 ft wide.

The height of the beach ridge is equally difficult to measure because of the lack of a sharp break in the foreslope to form a base of the ridge or of good exposures showing beach gravels resting on lake muds and clays. At a locality 2 1/2 mi south of Cochise in the SE 1/4 sec. 33, T. 15 S., R. 24 E. in a man-made cut through the beach ridge, 10 ft of unconsolidated beach ridge sediments overlie 5 to 6 ft of cemented beach sandy gravels that rest on an unknown base. About 100 ft playaward the same gravels rest on a base of lake clay. From other field observations, this 10-ft height is probably about average for the maximum developed areas on the west side. Maximum elevation of the beach ridge on the east side is 4,185 ft but is 5 ft less on the west side. However, it is estimated to have been about the same on the west side because road construction is known to have utilized the beach ridge sediments and thus lowered the height by about 5 ft. U.S. Highway 666 occupies the beach ridge opposite the northwest corner of the playa.

Beach ridge sediments are partially exposed in numerous natural and artificial cuts across the ridges. The best localities are in a stream channel on the south side of the gravel pit in the SW 1/4 sec. 31, T. 14 S., R. 24 E.; at the culvert on U.S. Highway 666 in the north-central part of sec. 7, T. 15 S., R. 24 E. (Fig. 15); in a deep drainage ditch and abandoned gravel pit alongside the Southern Pacific Railroad track in the SE 1/4 sec. 17, T. 15 S., R. 24 E.; and in the 2 mi length of beach ridge shown on the Cochise topographic quadrangle map in secs. 28 and 33, T. 15 S., R. 24 E. Other pits have been opened in the beach ridge for sand and gravel, but they are not well exposed because of surface wash, slumpage of the walls, and their use as refuse dumps.

The beach ridge sediments range in composition from relatively mud-free gravelly sands to slightly gravelly sandy muds (Fig. 13). For most of its length the beach ridge surface is gravelly because the fines have been washed away. Roller and disc shapes dominate the pebbles.

East Beach Ridge.–The beach ridge on the east side is not as well developed as the west one. Measuring dimensions on the east side is also very difficult because the ridge is in such gradational contact with the lake sediments that across the width the beginning and end of the ridge cannot be determined with any certainty. This ridge has gentler foreshore and

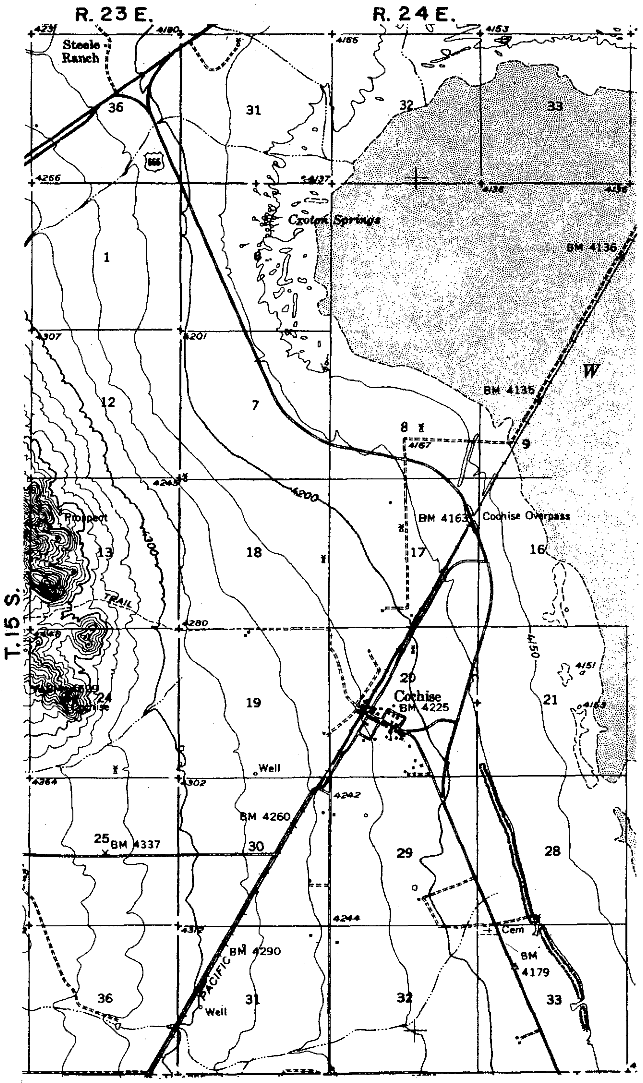

Fig. 15. Index map of west side of playa; beach ridge follows 4,175-ft contour and is shown in secs. 28 and 33, T. 15 S., R. 24 E.

backshore slopes, and therefore is about half as high as the west beach ridge. Toward the southern end the beach ridge splits into three smaller ridges separated by lower troughs.

Gravels are less abundant in the east beach ridge, possibly because the eastern source is farther away from the east beach ridge than the western source is from the west beach ridge. In the only good exposure, a borrow pit at the east edge of the Kansas Settlement Road in sec. 12, T. 15 S., R. 25 E., the unconsolidated beach ridge sediments rest on marly sediments.

Origin.--Since the west beach ridge has the best exposures, most of the following remarks are based upon field studies on the west side. The beach ridge sediments are structureless but rest on bedded, cemented sandy gravels. Any discussion of the origin of the beach ridges begins with a description of the formation of the bedded beach sediments.

Prior to actual beach ridge formation, beach sands and gravels were supplied by the streams entering Lake Cochise. For the west side the sediment sources were relatively close. Longshore drift and waves were responsible for sediment transport and mixing. Periodically storm waves built up the beach level more rapidly. At the culvert locality on U.S. Highway 666 (Figs. 16 and 17) the bedded sands and gravels display cross-stratification and dip towards the playa a few degrees. In an artificial cut in SE 1/4 sec. 33, T. 15 S., R. 24 E. the bedded sands and gravels dip westward a few degrees and probably represent backshore deposits. At all three localities cited earlier the sediments are cemented with calcium carbonate which was probably precipitated from the lake waters in this zone of wave activity. East from the culvert locality the coarse beach sediments become finer grained sandstones which are also cemented with calcium carbonate.

The unstratified and unconsolidated beach ridge sediments present a real contrast to the underlying bedded, cemented sediments. Meinzer (Meinzer and Kelton, 1913, p. 34-35) describes an origin for these beach ridges based upon the studies of topographic features of lake shores by G. K. Gilbert (1885, p. 87-88); Meinzer states:

> Along the shore of any lake or other body of standing water the waves and shore currents are active in handling the sediments which they erode from the banks or which are supplied to them by the inflowing streams. These sediments may be spread along the shore to form a beach or may be built into bars, spits, hooks, or other shore features. Where the lake bed near the shore slopes very gently and the water is consequently shallow, the sediments handled by the waves are likely to be built into a low symmetrical ridge that lies some distance from the shore and runs approximately parallel to it. The lakeward side of a beach ridge assumes all the characteristics and functions of a beach. The belt of shallow water imprisoned between the beach ridge and the shore forms a lagoon, which in the course of time is filled with sediment and converted into a marsh. If the slope of the lake bed near the shore is steep and the water deepens rapidly, the waves are more likely to beat on the shore with full force and to cut into the mainland, forming cliffs and terraces.

Meinzer's proposed origin certainly fits the conditions he observed during

Fig. 16. Outcrop of stratified, cemented beach ridge sediments along U.S. 666 at culvert in N 1/2 sec. 7, T. 15 S., R. 24 E.

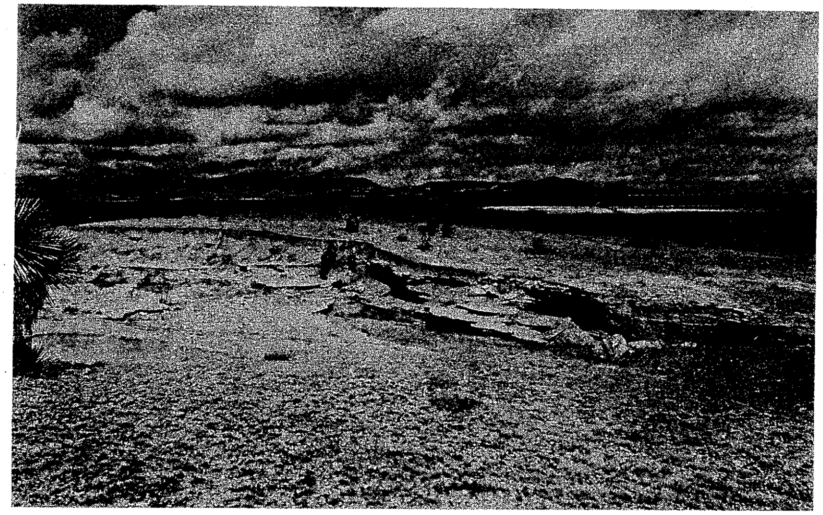

Fig. 17. View of the same locality as shown in Figure 16; photograph taken in 1935 before road construction. This view looks northwesterly along beach ridge with the Winchester Mountains in the background. Playa is to the right. Photograph courtesy of the Arizona State Museum.

the course of his field work. However, today we have additional exposures of the beach ridges and thus can assemble a more complete stratigraphic-sedimentologic picture. Several questions must be answered.

It is quite plausible that the beach ridge began as a subaqueous bar and subsequently built up above lake level. The size analysis data (Fig. 13) shows a considerable mud content. With the anticipated wave and current activity of this shoreline area why are the sediments not better winnowed of the mud fraction? A second question that must be answered is why is there such a pronounced break between the beach ridge sediments and the underlying cemented sediments?

The unstratified and unconsolidated beach ridge sediments could be the product of intense storm wave activity where large amounts of lake mud were carried shoreward, mixed with sand and gravel, and finally thrown up helter-skelter onto the cemented beach sediments. Very rapid mixing and sudden deposition seems to be the only plausible way to obtain this large mass of unstratified muddy sediment around the lake margins. If the ridge was constructed rapidly, and thus built up above lake level, then winnowing of mud would also be at a minimum.

A further explanation may lie in a falling lake level toward the end of the last pluvial period. With waning precipitation the supply of sediment to the lake would also be decreased. As the nearshore lake waters became somewhat shallower, waves started breaking at a greater distance from shore, eroding previously deposited muds. These muds then moved shoreward with the intense storm wave activity to become part of the beach ridge.

The break between the beach ridge sediments and the underlying cemented sediments may represent a minor unconformity. Calcium carbonate precipitated from the lake waters cemented the gravels during deposition as cited earlier. With a decrease in sediment supply the beach could no longer grow, and with a falling lake level the sediments that were supplied would form a meager deposit lakeward of the cemented beach sediment. Later, during the storms, these clastics would be combined with lake muds to form the beach ridge.

The lagoonal areas that formed between the beach ridge and the land were recognized by Meinzer (Meinzer and Kelton, 1913, p. 63) and studied in the field by the present authors. Although cut up extensively by road construction and other human and animal activities, the lagoons appear as broad, flat areas behind the beach ridge. Two areas were augered and shown to consist of coarse to fine sediments. One hole encountered a marly section about 1 ft thick; the calcium carbonate content was due principally to ostracod valves and abundant gastropod shells of pond-dwelling types.

Nearshore Facies Changes

The nearshore sediments are defined as those that are in an indefinite zone extending lakeward from the shoreline to somewhat beyond the breaker zone and include the sediments in the area from immediately in front of the beach ridge to the somewhat transitional zone where the sands give way completely to the lake mud. The distance involved is about 1/2 mi. These sediments must have been deposited in rather shallow waters.

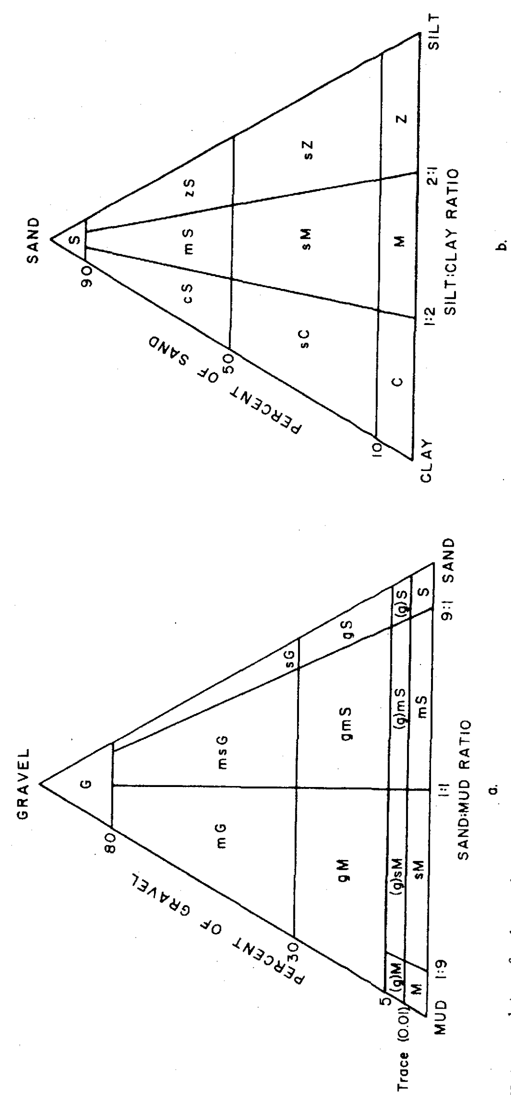

Fig. 18. Grain size nomenclature for lacustrine sediments from auger holes in the north and south ends of the playa and in the near shore areas on the east and west sides. Refer to Figure 12 and Table 2 for textural names.

The nearshore sediments were studied along four lines of auger holes totaling 38 holes. Two lines were located in sec. 35, T. 14 S., R. 25 E. on the east side; these lines were 1,100 and 2,520 ft long, respectively. A third line, 3,250 ft long, was located in secs. 5 and 6, T. 15 S., 24 E. in the Croton Springs area on the west side. The fourth line, 2,000 ft long, was also on the west side on the section line between secs. 28 and 33, T. 15 S., R. 24 E., and opposite the Cochise Cemetery.

These areas were selected because they represent locations where the distance between the beach ridge and the edge of the playa is at a minimum; they are readily accessible with a four-wheel drive vehicle; and they were thought best to show the nearshore facies changes.

The lithologic types involved in the facies changes are mixtures of gravel, sand, and mud (Fig. 18). The auger hole samples from the east side lines were dominated by muddy sand and sandy mud. The west side lines were closer to the beach ridge and therefore contained gravels. In general, the sediments decrease in grain size toward the playa. A typical facies relationship is one of interfingering and gradation between lithologies.

The Pleistocene Lake Environment

Lake Characteristics.--Lake Cochise covered about 120 mi in the northern Willcox Basin, extending from a few miles north of Willcox to about 4 mi south of the present southern tip of the playa. An estimate of the depth of the lake can be made if the thickness of the unstratified sediments forming the top of the beach ridge can be presumed to represent material deposited above the highest lake level. Using an average beach ridge elevation of 4,180 ft with a 10 ft drop to the highest lake level and a playa surface elevation of 4,135 ft, the lake was thus about 35 ft deep. These figures help to visualize Lake Cochise as a long, wide (about 11.3 by 20 mi) and very shallow lake.

Streams transported clastic sediments and other debris and dissolved materials to the lake from all directions, with the largest amounts of sediment probably coming from the north and south-southeast. Gravel, sand, and mud were dumped into the lake transport system. The gravels were left near shore or drifted along the beaches with sand. Storm wave activity built up the pronounced beach ridges. In an offshore direction sands were deposited as relatively clean sands or mixed with muds. Still farther offshore muds and clays settled out.

Lake waters must have been somewhat brackish judging from the sodium chloride and sodium sulfate content of the sediments. However, the waters were not so brackish as to prevent ostracods from thriving in the lake. The waters were also alkaline enough to permit the ostracod valves of calcium carbonate to grow and persist and to promote the precipitation of calcium carbonate in sizes ranging from mud to crystals of 1 to 2 mm length.

It cannot be determined with any certainty that these lake waters were stratified physically or chemically. The organic matter content of the lake muds suggests deposition in a low oxygen to reducing environment at least in the bottom waters, or perhaps the organic matter was buried rapidly enough to become part of the very reducing diagenetic environment. Once part of the mud, the organic matter was metabolized by the anaerobic bacteria which in turn converted the sulfate to hydrogen sulfide.

Climatic Episodes.--P. S. Martin (1963) studied the fossil pollen in the 140-ft core from the middle of the playa and interpreted the vegetation history of the surrounding region in terms of Pleistocene climatic changes. To Martin high pine pollen counts indicate a cool-wet (pluvial) climate, and relatively low pine counts or poor pollen preservation and oxidized sediments indicate interglacial or interpluvial climates.

The upper 6.9 ft of the core contained no pollen except for the modern pollen rain at the surface. From 6.9 to 69 ft the core sediments contained very high pine pollen; this is interpreted as a pluvial episode affected by Wisconsin glaciation in northern latitudes. Martin also includes the next 8 ft (to a depth of 77 ft) in this Wisconsin section of the core, though lower in pine pollen. Below 77 ft to total depth, but particularly from 77 to 96 ft, there are numerous samples that were too poor for the recovery of pollen for a 200-grain count. However, grass pollen is very abundant below a depth of 96 ft. For the core section below a depth of 77 ft he proposes two interpretations. The interval from 77 to 95 ft may represent the Sangamon interglacial episode when the lake dried up periodically, destroying the pollen by oxidation. From 95 to 140 ft the high grass and low pine pollen counts equate climatically with the Illinoisan glacial stage. The other interpretation is that the entire core below 77 ft is a Sangamon record.

One of the present authors (Pipkin, 1964, p. 124) made a comparison of the petrographic data for the core with Martin's vegetative-climatic history; it shows some interesting differences as well as areas of agreement.

> Large calcite euhedra appear at 80 feet and continue to the bottom of the core. They formed during a warm-dry or hot-dry episode during which the degree of saturation of $CaCO_3$ increased. Partial desiccation of the lake was indicated at depths from 113-117 feet and at 123 feet. This was manifest in abundant spongy, highly oxidized calcareous accretions occurring with unoxidized aggregates and clear authigenic calcite rhombs. Apparently marginal sediments were exposed to subaerial processes and then redeposited in a deeper part of the lake. Only one of these samples lacks pine in the pollen assemblage. This is not surprising since the modern pollen rain on the dry lake bed contains 2-19 percent pine. There is no indication in the sediment record of dilution of Lake Cochise during a pluvial-glacial episode from 95-140 feet as proposed by Martin. Rather, progressively warmer conditions conducive

to increased carbonate deposition are indicated by the occurrence of larger and better developed euhedra through the interval 100-140 feet.

Long (1966, p. 39-40) commented on Pipkin's interpretation and proposed a different model for calcite crystal growth as follows:

> Pipkin (1964) suggested a climatic interpretation for the occurrence of the large euhedral calcite crystals below the 80 foot level, implying that warmer conditions tended to saturate the solution in $CaCO_3$ and precipitate the calcite. Actually the situation is more complex. No doubt warmer conditions are conducive to more rapid precipitation of $CaCO_3$, but the effect of temperature on the original size of crystals is questionable. The sediment microenvironment is already saturated in $CaCO_3$ with respect to calcite shortly after deposition as evidenced by the presence of the ostracod valves in the core. The fine crystallites indicate that calcium or CO_2 or both were added to the system after deposition. In such a small crystallite the surface free energy becomes important in determining the crystal energy, and the smaller the crystal the greater the surface area to volume ratio and the greater the molar free energy of the crystalline $CaCO_3$. Since the system will tend toward lower free energy, larger crystals will form given sufficient time. Thus the sediments lower in the core quite naturally contain the larger crystals independent of any climatic changes at the surface.

Thus the problem is a complicated one that must be approached by several disciplines for a solution.

In summary, on the evidence from pollen analysis and carbonate deposition in Lake Cochise, a cycle of one pluvial and one interpluvial episode can be recognized.

Age of Lake Cochise Sediments

O. E. Meinzer first suggested a late Pleistocene age for the last lake epoch of the northern Sulphur Spring Valley (Meinzer and Kelton, 1913, p. 76), but it remained until the application of palynological techniques and radiocarbon dating that a more definite age could be assigned. To complement Paul S. Martin's pollen studies, Austin Long obtained the first radiocarbon dates. Seven dates for Lake Cochise clays are given in Table 4. The ages for samples A-221 and A-351 can be rejected for the reasons stated, *i.e.*, low organic content and modern contamination, respectively. Regarding samples A-352 and A-363, Long (1966, p. 120) states that they ". . . may represent the age of the sediments, but because of groundwater movement in the area and the extremely small size of the carbonate crystals, mixing is probable." Samples SI-176, SI-177A, and SI-177B are also from

Table 4. *Radiocarbon dates–Lake Cochise sediments*

Sample No.	Location and Remarks		Age, Years B.P.
A-221	N 1/2 sec. 1, T. 15 S., R. 24 E., near center of playa; depth–5 ft; very low organic content necessitated dilution; age is a minimum one.	>	20,000
A-351	E 1/2 sec. 12, T. 15 S., R. 24 E.; 140-ft hole; ground elevation 4,136 ft; carbonate fraction; depth–19 to 27 in. below surface; above water table with modern contamination; minimal age.		8,615 ± 110
A-352	Same location as A-351; depth–75 to 84 in. below surface.		23,000 ± 500
A-353	Same location as A-351; depth–92 to 101 in. below surface.		22,000 ± 500
SI-176	SW 1/4 sec. 35, T. 14 S., R. 25 E.; ground elevation 4,143 ft; ostracod fragments; depth–42 to 48 in. below surface.	>	30,000
SI-177A	SW 1/4 sec. 35, T. 14 S., R. 25 E.; 270 ft from SI-176; ground elevation 4,138 ft; ostracod fragments; depth–63 to 72 in. below surface.	>	30,000
SI-177B	Same location as SI-177A within 70 ft; depth–63 to 66 in. below surface.	>	30,000

Data from Long, A., 1966, Appendix 1.

shallow depths along the eastern edge of the playa. Again some mixing with groundwater is possible at these locations.

Long (1966, Appendix 1) also obtained radiocarbon dates on marls, caliche, carbonate nodules, and organic matter from the beach ridge and surfaces above the beach ridge at localities chiefly on the east side but also from localities on the west side and north end. The highest samples came from a slope above the beach ridge on the east side at an elevation of 4,220 ft. The youngest date was 5,000 ± 100 B.P. and the oldest date was 27,600 ± 900 years B.P. A complete discussion of the geological and geochronological significance of the materials dated and all the dates obtained is beyond the scope of this paper. However, Long (1966, p. 82) infers the following sequence of fluctuations in the level of Lake Cochise:

1. Pluvial conditions from before 30,000 until about 13,000 years B.P.; lake was above 4,230 ft until about 13,000 years B.P.

2. Nonpluvial conditions with probable desiccation of lake and arroyo cutting between 13,000 and 11,500 years B.P.

3. Pluvial conditions from 11,500 to 10,500 years B.P. with lake rising close to the elevation of the beach ridges (circa 4,175 ft); pluvial conditions ended abruptly.

4. From 10,000 years ago to present we have had dry conditions.

The only paleontological data for the Lake Cochise clays come from the recent study of the ostracods of the lake cores and other lake clays by Mrs. J. D. Cameron, Arizona State University. Mrs. Cameron describes 6 genera and 15 species and assigns a "latest Pleistocene--probably of Wisconsin glacial and Sangamon interglacial" age (personal communication, 1971).

When one considers Martin's pollen chronology, Long's radiocarbon dating, and the above data, it seems logical to state that the Lake Cochise sediments beneath the present playa surface are the product of sedimentation in a late Wisconsin lake and that older lake sediments exist to an unknown depth. Additional subsurface drilling and coring, bulldozer cuts in the beach ridges, other field work, sedimentologic analyses, and radiocarbon dating are desirable to work out a more precise geologic history of Lake Cochise.

Wind Deposits Adjacent to the Playa

General Characteristics

The wind deposits occupy an area of 40 to 50 sq mi located north, northeast, and east of the playa edge. This area is not a solid sheet of sand with typical dune forms displayed; rather it is an area of low sand ridges and hills anchored by salt grass and yucca and separated by numerous depressions and isolated ponds. These ridges parallel the edge of the playa and on air photos appear as a roughly concentric system with each other and the playa edge. Some of these ridges are continuous for 2 or 3 mi, but the majority are less than 1/2 mi long. The widths are very small with respect to the lengths. Commonly the ridges are a few tens of feet in width although a few ridges are 150 to 600 ft wide. Heights are less than 25 ft with one exception.

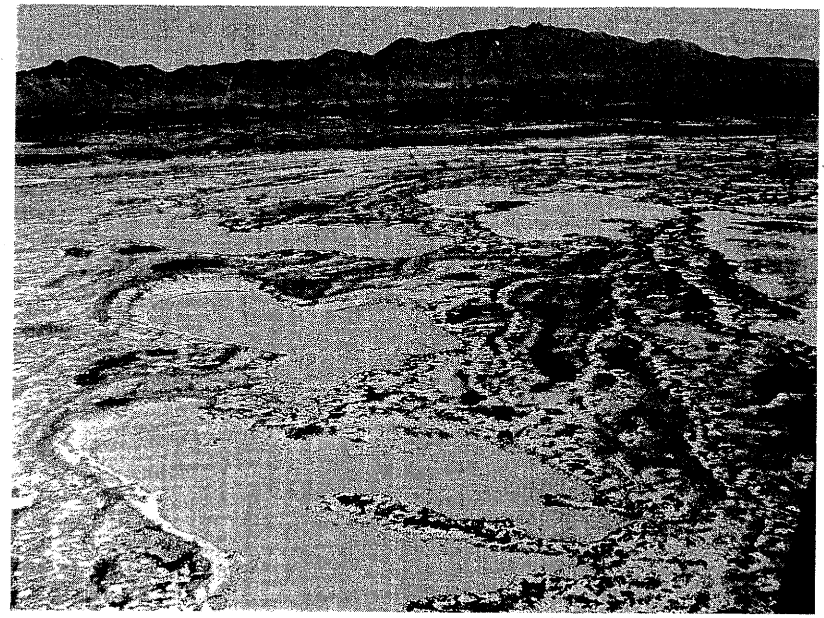

Fig. 19. Aerial view of water-filled depressions or "blowouts" in sandy ridges and hills on north edge of playa in secs. 16, 17, 20, and 21, T. 14 S., R. 25 E.

The largest of these sand ridges is located in sec. 14, T. 14 S., R. 25 E. about 3 mi northeast of the playa; it is approximately 75 ft high, 2 mi long, and 1/2 mi wide. This large dune-like feature is probably one of the oldest in the area because caliche has formed in the red sands and silts. Radiocarbon dating of the caliche yielded an age of 7,160 years for this large stabilized dune and an age of 3,660 years for an apparently younger active dune approximately 1 1/2 mi to the northwest (Long, 1966, p. 116). Although this ridge has a barchan dune shape, indicating a wind direction from the northeast, it seems probable that this shape is the result of erosion. Ancient and modern prevailing storm wind directions from the southwest support this interpretation. The gently sloping southwest side of this feature and the steeper northeast or outer side of the crescent are significant because barchan dunes exhibit the opposite form and have their steepest side on the inner flank of the crescent. Several rounded cobbles and boulders of granitic, rhyolitic, metamorphic, and sedimentary rock composition were found on top of this hill. Because none of these could be found within the hill, it is reasonable to assume that they were carried to the top of the hill by man.

The ridges closer to the playa are much lower and narrower than this large dune-like feature and average 15 ft in width and 10 ft in height. This area, especially north of the playa, is characterized by many rounded, barren depressions or "blowouts" which are filled with water in the rainy seasons (Fig. 19). The depth of these blowouts is only a few feet and

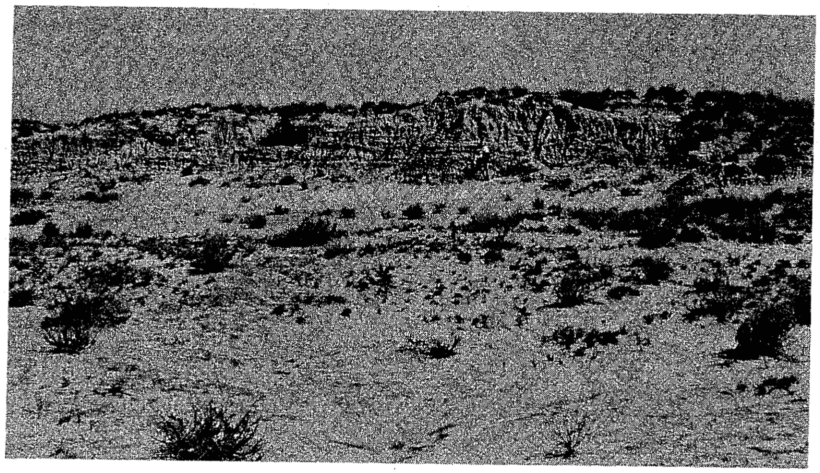

Fig. 20. Cliff face eroded in dunes on the east edge of playa in sec. 35, T. 14 S., R. 25 E. showing differential erosion in layers of sand and muddy sand.

is limited by the depth to the water table or by the presence of a resistant clay layer.

West of the east beach ridge near the margin of the playa a steep cliff face has been eroded into the dune sands. This dune cliff face is about 20 ft high on the eastern edge of the playa and ranges down to a few feet high along the northern edge. This cliff follows the 4,150-ft contour rather closely, although many gullies have been cut into the face and appear as V-shaped indentations on the contour line. The cliff face has exposed a section of aeolian cross-bedding which is emphasized by alternating layers of sand and muddy sands (Fig. 20). The cross-bedding has a prominent northeasterly dip. Erosion by running water, raindrops, and wind loosens the sand which drops to the base of the cliff; further erosion and transport by running water moves the sand a short distance toward the playa. Winds can then pick up this sand and transport it back to and over the dune cliff-face.

Origin

O. E. Meinzer (Meinzer and Kelton, 1913, p. 39-40) used records of the United States Weather Bureau for the Willcox area to tabulate and diagram wind directions in the Sulphur Spring Valley. The prevailing winds over a five-year period were found to be from the south about 33 percent of the months, from the west 25 percent, from the southwest 20 percent, and from the southeast 10 percent. However, it must be emphasized that the prevailing winds are not nearly as important to the aeolian deposits as are the storm winds.

The effect of these southwesterly storm winds upon the small phreatophyte mounds near the eastern and northeastern margins of the playa

is quite dramatic. They are invariably lined up with their long direction parallel to the direction of the storm winds (S. 60° W. ± 20°). Playa crust dunes are also driven by these same winds. The location of the sand dunes on the northeastern side of the playa is additional evidence for citing the southwesterly winds as the most prominent storm winds influencing the development of the sand dune. These dune sand deposits are absent on the south and west sides of the playa.

An experiment with sediment traps was tried as follows. Four traps were placed on the playa at the southwest corner of sec. 6, T. 15 S., R. 25 E. Each trap consisted of the standard rectangular one-gallon-size paint thinner can. A 2 by 4 in. hole was cut in one end and the can mounted on a wooden stake so that the bottom lip of the opening was 6 in. above the playa surface. The four cans were first installed on November 23, 1962, with the openings pointing northeast, southeast, southwest, and northwest. When visited on June 6, 1963, the trap pointed southwest was nearly full (and actually could not retain any additional sediment because of the slope on the sediment face at the opening). The trap pointed northwest was one-third full; the trap pointed southeast was one-half full; and the trap pointed northeast was almost empty. After each trap was cleaned, they were remounted and then not visited until November 1, 1963. During the five-month period the traps had been flooded by the waters blown across the playa surface. All of the cans contained some dried mud. Each trap was again cleaned and remounted. On December 28, 1963, the trap pointing southwest contained enough playa crust fragments to cover the bottom of the can; the trap pointing northeast was empty; the other traps each contained but a few cubic centimeters of sediment. Although the experiment was run for less than one year the results seem to bear out the importance of the storm winds from a southwesterly direction.

Similar sand dunes are located on the northeastern sides of playas in New Mexico and northern Chihuahua (Meinzer, 1911; Melton, 1940; Schwennesen, 1918). This indicates that a large region was characterized by a southwesterly storm wind direction at the time the pluvial lakes in the southwestern United States began to dry up.

The sand dunes were probably formed to a small extent while the waves from pluvial Lake Cochise were still active, even though the lake level was receding, because sand could be picked up from the beach and the newly exposed nearshore bottom area.

The slow change from pluvial conditions still allowed large amounts of sediment to reach the lake in the early stages of drying up. The waves sorted this material and deposited the coarse sand nearest the shore where it was the first to be dried out as the lake continued to shrink. This continuing accumulation, together with the reserve of sand already built up when the lake was at its maximum extent, insured a sand supply sufficient for the formation of a large dune area. When the lake bottom was completely dry, even the beach sands from the west side could have been blown across the dried surface to the northeast.

Much evidence indicates that most of the dune formation took place after Lake Cochise began to dry up. The most convincing proof consists of well-log data showing sand deposits above the lacustrine silts and clays (Meinzer and Kelton, 1913; Robinson, 1965). The presence of laminae of playa crust material in the dune cliff face also furnishes impressive evidence. The sediment trap studies indicate that there is still quartz and feldspar sand and playa crust material movement today. Personal experiences in a sand and dust storm on November 7, 1963, and on March 8, 1964, left no room for doubt that large quantities of sand, silt, and clay are moved by modern storm winds.

In summary, it has not been possible to recognize any of the usual dune shapes in the Willcox Playa area because it appears that many ancient features were probably obliterated by erosion. One gets the impression from ground observations and aerial photograph examinations that the area is a sheet of sand with irregular water- and wind-eroded forms.

The sediment materials transported by the wind today are the same as the materials in the older dunes. Dunes are not forming beyond the playa edge today.

Textural Properties

The majority of the 28 samples of blowing sand, playa crust fragments, and dune ridge sediments have a mean grain size in the fine sand grade size (the statistical parameters "graphic mean size" and "inclusive graphic standard deviation" of Folk, 1968, were used in all the grain-size studies). The samples included small amounts of very coarse and coarse sand, larger amounts of medium and fine sand, and smaller amounts of very fine sand, silt, and clay. The blowing sands and playa crust fragments had inclusive graphic standard deviation (sorting) values chiefly in the moderately sorted range. One playa crust fragment sample from a sediment trap was very well sorted. Dune ridge samples were also chiefly fine grain sands, but the sorting was more variable, ranging from well sorted to poorly sorted. This spread in sorting is to be expected because the dunes contain not only laminae of sand but also sandy muds, muddy sands, and playa crust fragments of a mud composition. Thus the problem was one of sampling. No doubt sampling of individual laminae, if possible, would produce the better sorting values characteristic of most aeolian and dune deposits.

Deflation of the Playa Surface

The radiocarbon dates of Long (1966) for the dunes northeast of the playa are decisive evidence of a long period of wind erosion of Lake Cochise beach and nearshore sands and the playa surface. In the dunes the abundance of individual playa crust fragment laminae or mixed quartz-feldspar-playa crust fragment laminae is also good evidence that the playa surface has been deflated over a long period. The deflation is still going on in the form of the playa crust fragments being moved by strong winds and as frequent dust storms during all seasons of the year.

It is also interesting that Long has no radiocarbon dates younger than about 20,000 years B.P. for the playa near-surface sediments. Since Long (1966, p. 82) also proposes pluvial conditions until about 10,500 years ago, why do we not obtain younger dates? The answer may lie in the deflation that has taken place over many thousands of years.

During our field studies we plane-tabled a number of areas on the east and west sides of the playa. These surveys started on the paved roads at the beach ridges and continued across beach-nearshore sand areas onto the playa. When the surface of the beach-nearshore sand area is projected playaward, the projected surface is found to lie several feet above the present playa surface. Based upon these projections we estimate that at least 2 ft and perhaps as much as 4 ft of playa sediments have been removed by deflation so that today we walk upon Pleistocene lake clay and mud.

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LATE QUATERNARY LAKE LEVEL FLUCTUATIONS IN THE NAKURU-ELMENTEITA BASIN, KENYA

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The Nakuru-Elmenteita basin lies in the Eastern Rift Valley of Kenya just south of the Equator. At present the basin contains two small (less than 10 feet deep) highly alkaline lakes. The basin (Fig. 1) is defined by the approximately north-south faults bounding the Rift Valley and is crossed by many small faults of similar alignment. Volcanic activity can be traced from the Middle Pleistocene to the last few hundred years; large volcanoes of probable Middle Pleistocene date close the basin at either end (Menengai to the north, rising to 7,475 feet, and Eburu to the south, rising to 9,365 feet). Younger cones and lava flows are also found, particularly in the Badlands area south of Lake Elmenteita. Lacustrine sediments ranging in age from Middle Pleistocene to Recent occur in the basin; many of these are diatomites and diatomaceous silts. Periods of lacustrine sedimentation appear to have been separated by periods of faulting and vulcanicity. Breaks in the sedimentation record, particularly of the older sediments, do not necessarily imply an arid climatic phase.

Research in this area was first done by Leakey (1931a, 1931b) and Nilsson (1931, 1940) in the late 1920's and early 1930's. Their results do not agree in every particular, but both recognized a large number of former lake shorelines at various elevations above the present lakes. Leakey interpreted these shorelines as evidence of several periods of high lakes (pluvials) separated by drier periods of low lakes (interpluvials), according to the following scheme:

Nakuran post-pluvial wet phase--
shoreline at 145 feet above present lake--
(youngest)
Dry interval

Makalian post-pluvial wet phase--
shoreline at 375 feet above present lake
Dry interval

Gamblian pluvial, with three peaks--
shoreline at 510 feet above present lake
shoreline at 600 feet above present lake
shoreline at 750 feet above present lake--
(oldest)

The surface of Lake Nakuru is at present at an altitude of 5,774 feet (May 1970); when Leakey took the lake as datum in the late 1920's, its level was 5,776-5,777 feet.

The Gamblian, Makalian, and Nakuran were considered as climatic fluctuations that might be traced all over Africa, and correlations of

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