OPEN FILE REPORT 55

Regional Hydrology and Evaporative Discharge as a Present-day Source of Gypsum at White Sands National Monument, New Mexico

Roger J. Allmendinger and Frank B. Titus

8 May 1973

OPEN-FILE REPT #55
Contents (W.J. Stone)

ABSTRACT

Lake Lucero, a modern playa, is the southernmost and lowest of a 30-mile long system of alkali flats and playa depressions lying in the western portion of the Tularosa Basin of south-central New Mexico. Many hypotheses have been proposed but few data-supported conclusions have been advanced to describe the mechanism of formation of Lake Lucero, the associated alkali flats, and the gypsum comprising the White Sands dunes.

The present study, centered on Lake Lucero, indicates that subsurface hydrologic processes have been actively transporting and concentrating gypsum and other salts since late Pleistocene time. Surface waters were important in the past when ancestral Lake Otero was dwindling in size because of a change of climate, possibly less than 10,000 years ago. During this time, the bulk of the gypsum was deposited as thinly bedded lacustrine deposits and large selenite crystals.

Data obtained during the summer of 1970 show that modern surface waters which occasionally cover the playa add little gypsum to the system. No salts precipitate from this ponded water until the evaporation-infiltration processes have left the playa surface essentially dry. A later efflorescent crust indicates that the concentrated remnant waters eventually reach equilibrium with the predominant gypsum phase of the near-surface playa deposits. Presumably these waters are then drawn upward by capillary action and evaporate at the surface where a brilliant white gypsum crust forms.

Although surface waters were important in the past, it seems likely that today regional ground-water dynamics play the most important role.

ACKNOWLEDGMENTS

We are ~~I am~~ grateful to the New Mexico Bureau of Mines and Mineral Resources for funding the project as well as for providing transportation and chemical analyses. The work was supported in part by funds provided through the New Mexico Water Resources Research Institute, by the Department of the Interior, Office of Water Resources Research as authorized under the Water Resources Research Act of 1964 (Project B-013-NMex-3109-106).

Dr. Frank Kottlowski was kind to review the manuscript and offer considerable, helpful suggestions.

We are ~~I am~~ thankful for the assistance, interest, and enthusiasm of all the Park Rangers and especially Head Ranger, Hugh Bozarth, White Sands National Monument. The naturalist division spent much time collecting the weather data essential to this report. This tedious and time-consuming effort is gratefully acknowledged.

Personnel at the White Sands Missile Range helped by allowing access to the field area.

I appreciate the field assistance given to me by my fellow graduate students Starr Lanphere, David H. Swenson and William W. Wilkinson, Jr.

INTRODUCTION

The Tularosa Basin is an arid, intermontaine depression typical of the basin and range physiographic province of western North America. The basin encompasses an area of 6,500 square miles (Fig. 1). In 1909 Richardson divided what was formerly called the Hueco Bolson into two portions. The northern portion, the Tularosa Basin, is separated from the southern portion, the Hueco Bolson of Texas, by a very slight topographic divide just north of the Texas-New Mexico border. The complete structural basin extends 200 miles south from Carrizozo, New Mexico across the corner of Texas and into Mexico. Its width ranges from 24 to 60 miles.

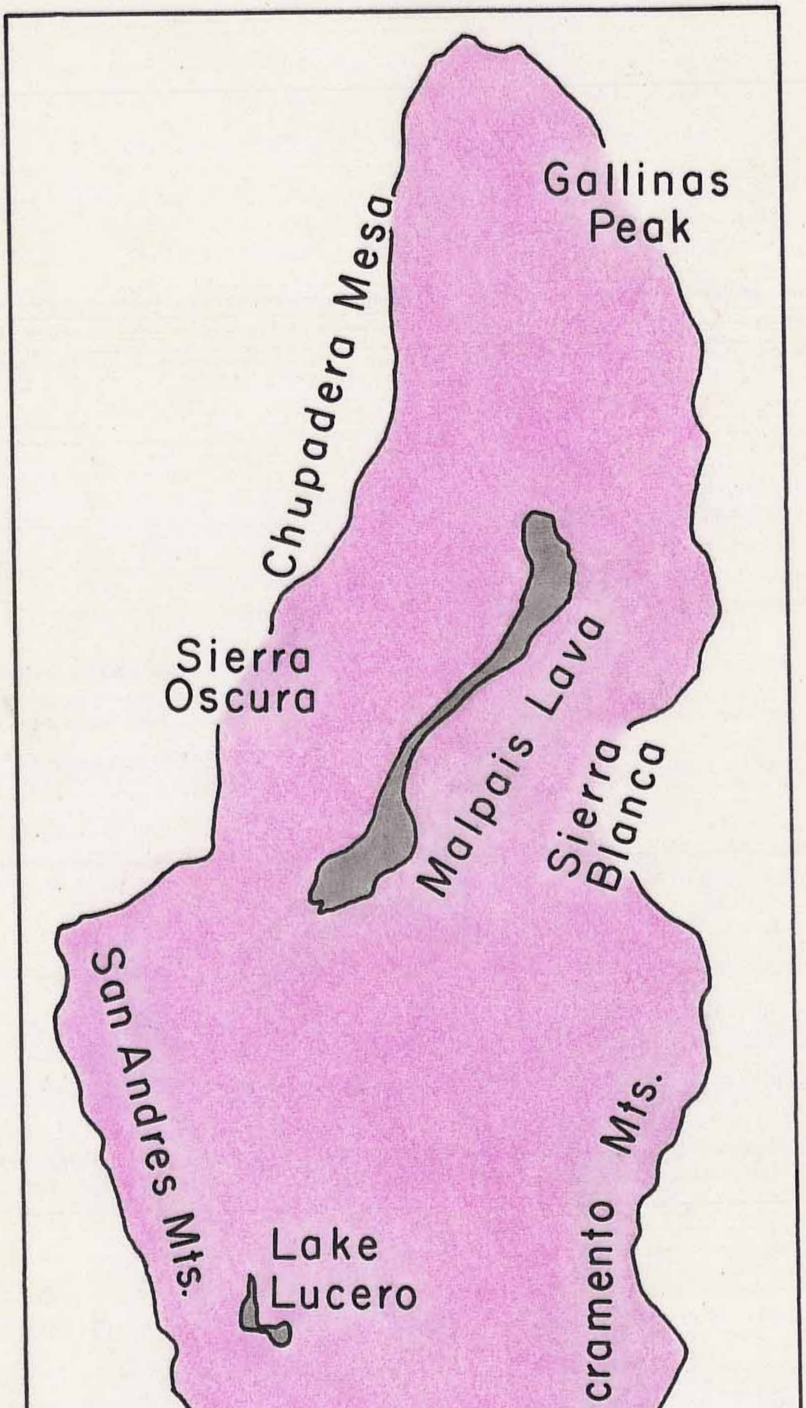
Elevations range from over 12,000 feet above sea level at Sierra Blanca, on the east, to less than 3,900 feet in the southwestern part of the basin. The basin is bounded by the Franklin, Organ, and San Andres Mountains and Sierra Oscura and Chupadera Mesa on the west; by a broad topographically high region on the north; and by Gallinas, Patos, and Tuscon Peaks, Sierra Blanca, and the Sacramento and Hueco Mountains on the east. The gentle divide on the south requires that all drainage within the Tularosa Basin be interior.

The climate of the basin is typical of arid regions of the Southwest. Rainfall ranges from 7 inches at Holloman Air Force Base and White Sands National Monument Headquarters area, to 12 inches in the foothills regions, to over 25 inches per year in the mountain regions (Hood, 1959).

The low relative humidity, frequently falling below 10%, the high temperatures, and the persistant southwest winds combine to give the central basin area an evaporation potential of over 100 inches per year (Hood, 1959, p. 238).

TULAROSA
BASIN
WATERSHED

24 MILES



Modified
from
J. S. McLean
1970

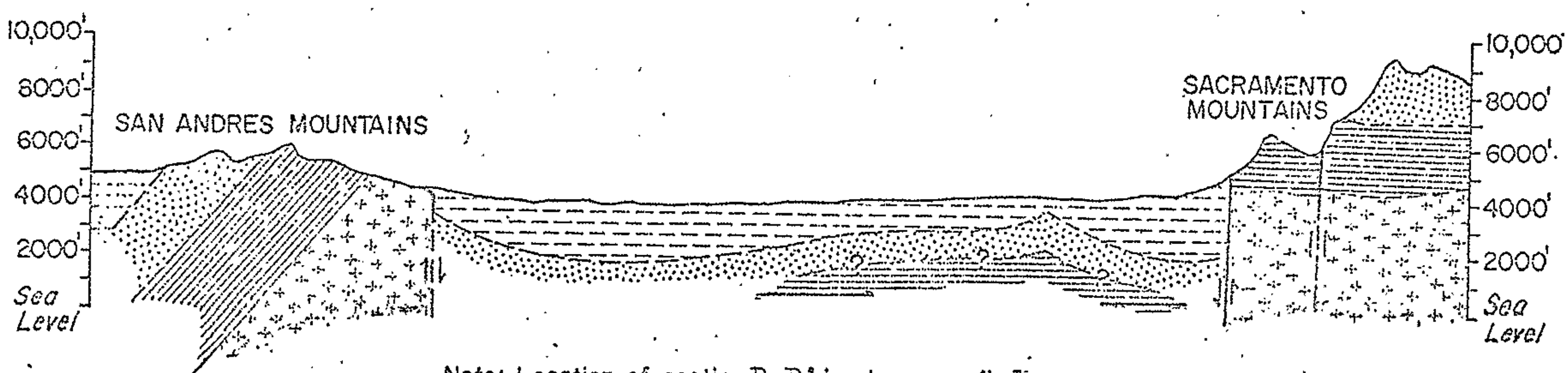
Fig. 1

The malpais, a recent basaltic lava flow, lies in the northern half of the basin, west of Carrizozo, Oscura and Three Rivers (Fig. 1). This flow plays an important role in the near-surface hydrologic circulation pattern. About 35 miles to the south-southwest lies the playa named Lake Lucero, and related alkali flats. Northeast of the playa and alkali flats the dominant southwest winds have covered 275 square miles (McKee, 1966) with nearly pure gypsum sand dunes. The immediate gypsum source is obviously the playa and alkali flats.

The area of research (66 sq. miles) lies entirely within the Co-use area of the White Sands National Monument.

Lake Lucero is normally a dry playa whose subsurface strata consist primarily of clay and crystalline gypsum. Occasionally summer storms furnish enough runnoff water to cover the playa surface.

Lake Otero existed during the Pleistocene times as a body of water covering a much larger portion of the Tularosa Basin than present-day Lake Lucero. Gypsum probably precipitated out of the lake as a dryer climate followed the latest Pluvial.



Note: Location of section B–B' is shown on fig.I

0 5 10 MILES

Vertical exaggeration 6.35:1

EXPLANATION

Cambrian, Ordovician, Silurian, Devonian Mississippian, and Pennsylvanian age

Permian age

Cenozoic alluvium and lake deposits

Intrusive rocks of Tertiary, Cretaceous or Precambrian age

Fault
Dashed where approximate, arrows indicate relative movement

Figure 2
Geologic divisions west to east through the Tularosa Basin.
(J.S. McLean, 1970)

Reduce to 1/4 page?

Structure of the Tularosa Basin

The Tularosa Basin is a structural trough formed by the downfaulting of a large central block of a north-south trending anticline (Fig. 2.). Anticlinal deformation ceased in the late Tertiary when a release in compressional forces led to tension and consequent normal faulting (Sumner, 1969, p. 2).

The western limb of the anticline dips 10 to 20 degrees into the assymmetrical, southward plunging syncline of the Jornada del Muerto. The anticlinal axis trends nearly north-south along the western portion of the basin and extends through Mockingbird Gap. The eastern limb of the anticline dips very gently into the Pecos River some 80 miles to the east.

The fault scarps of the east face of the San Andres Mountains and the west face of the Sacramento and Oscuro Mountains delineate the fracture zones which formed the graben. Total vertical movement along these fault zones has been several thousand feet (Kottlowski et al., 1956, p. 73).

The main fault zone of the San Andres Mountains trends slightly west of north but is offset to the east in places by oblique faulting. Here the total displacement is as much as 5,000 to 10,000 feet. On the east side of the basin, the fault scarps of the Sacramento Mountains also trend west of north and rise about one mile above the valley floor in two successive steps. Figure 2 is a generalized illustration of the approximate stratigraphic relationships in the basin; it is not intended to accurately represent the structural geology. The attitude of the bed rock and basin fill is probably more closely related to normal faulting than is suggested by the figure (Kottlowski, 1973, pers. comm.).

Stratigraphy of the Tularosa Basin Borderlands

The fault scarps of the bordering mountains expose thick sections of Pennsylvanian and Permian Rocks. Strata of most interest in this study are the evaporites of the Yeso and San Andres Formations, which constitute the most likely primary source of the gypsum now found in the subsurface of the interior basin.

The Yeso Formation, consisting of gypsum, limestone, and some sandstone is primarily Leonardian in age with the lowermost portion being upper Wolfcampian. Overlying the Yeso is the San Andres Formation, a massive to medium-bedded limestone of Leonardian (?) and Guadalupian age. The Yeso and San Andres Formations are separated by the Glorieta Sandstone in the northern San Andres Mountains. The Glorieta Sandstone probably correlates with the Hondo Member of the San Andres Formation as it is mapped in the Sacramento Mountains.

to end of section ?

When faulting exposed the strata along the graben perimeter, meteoric waters began dissolving the soluble evaporites and transporting them to the basin.

Kottlowski et al. (1956, p. 53) have described the Yeso as it crops out in the San Andres Mountains. Here the Yeso thins from 1,580 feet in the Rhodes Canyon area to only 324 feet in the Love Ranch area about 45 miles to the south. This increase in thickness to the north seems to be due to an increase in both the number and thickness of gypsum units (Kottlowski, 1963, p. 66).

Wilpolt and Wanek (1951) reported a maximun thickness of 1,651 feet for the Yeso Formation in the eastern Sierra Oscura. Several of their cross sections indicate that the Yeso may obtain about 25 percent gypsum and anhydrite in this area.

Pray (1961, p. 111) described the Yeso Formation in the northern

(Tularosa Canyon) and southern (Orendorf Peak) parts of the Sacramento Mountains and noted a decrease in thickness from 1,800 feet in the south to about 1,350 feet in the north. It is noteworthy that the percent gypsum in the formation increases significantly to the north. Farther north, in the Carrizozo quadrangle, the gypsum content of the Yeso decreases while that of the San Andres Formation increases.

The Standard of Texas No. 1 Heard oil test in Section 33, T. 6 S., R. 9 E., at the north end of the Tularosa Basin, penetrated a complete section of Yeso consisting of 4,265 feet of interbedded limestone, salt, gypsum, sandstone, and mudstone. Nine hundred feet of this section is halite.

Evidence for solution of evaporites

Several authors have noted the effect of fresh water on the above described evaporites.

Weir (1965, p. 19) identified cavernous sections in the Torres Member of the Yeso in the subsurface of the northern Tularosa Basin as being the primary source of water for domestic use.

Weber (1964, p. 103) reported that surface water drains into solution cavities in gypsum and limestone on the west side of the Malpais lava flow. These waters appear to percolate deep enough to leach the salt beds encountered in the Heard test. The waters issuing from Malpais Spring at the southern tip of the basalt flow have a high sodium chloride content (conc. Na^+ = 3,550 ppm and Cl^- = 13,000 ppm) and may be part of this circulation pattern.

The basal beds of the San Andres Formation where exposed in the Carrizozo quadrangle display random strikes and dips owing to solution of the underlying evaporites and consequent subsidence and draping of the rocks. One section of the Malpais basalt flow collapsed into a solution cavity in gypsum breaking through more than 150 feet of basalt. This large amount of solution probably is a direct consequence of the damming effect of the basalt flow. The lava flow blocks runoff water from the west and north which ponds up and infiltrates faster and in larger quantities than it would otherwise.

Herrick (1904, p. 187) described a similar situation east of the White Sands. Here the sand dunes dam storm waters which flow westward from the Sacramento Mountains and accelerate the solution of the underlying Quaternary lacustrine saline deposits. Herrick reported many sinkholes and caverns where arroyos from the east encountered the dunes.

Basin fill

Basin fill refers to the unconsolidated rocks of the basin interior which were deposited by alluvial, lacustrine, and eolian agents. Strain (1969, p. 122) suggested early Miocene as the time when basin filling began. These unconsolidated deposits thicken from north to south. North of U.S. Highway 380, deposits are thin, but they thicken to 6,015 feet in the vicinity of a test hole east of the White Sands Missile Range Headquarters as reported by Doty and Cooper (1970, p. 21-24). Data on the thickness and lithology of the valley fill on the west side of the basin ~~is~~ are scarce.

A section of basin fill was encountered in the test well reported by Davis and Busch (1965, Table 17) drilled in Sec. 17, T. 19 S., R 5 E. Sediments penetrated are mostly clay, some sand lenses, and appreciable amounts of gravel. The top 112 feet in this test was almost entirely gravel with some sand. No gypsum was reported in this drill hole.

GEOLOGY OF LAKE LUCERO AND THE ADJACENT WHITE SANDS AREA

Areal geology and geomorphology

The geologic map (Fig. 3) is compiled from field mapping, air-photo interpretation, and data from the literature. Good aerial-photographic coverage was obtained from 35 mm slides taken at low altitudes in a light plane. These slides in conjunction with a large, controlled, aerial mosaic (approximately 1: 30,000) supplied by the Engineering Division, White Sands Missile Range, simplified compilation of the map. The following map units are discussed in their approximate order of deposition or formation.

Lacustrine Deposits. - Herrick (1904, p. 179) described the "Otero marls" as "... a succession of gypsum and saline beds intercalated in gypsiferous marls," which he believed to be Tertiary in age. The "Otero marls" are the saline, lacustrine deposits of late Pleistocene, Lake Otero, deposited physically and chemically during concentration of salts derived from the Permian marine evaporites.

Herrick estimated that Lake Otero covered 1,600 to 1,800 square miles at its greatest extent. Weber and Kottlowski (1959, p. 40) give no estimate of size but believe that the lake may have existed during the latest Pluvial, only 12,000 to 24,000 years ago.

The lacustrine deposits on the western side of the lake comprise interbedded lenses of clay, silt, sand, and gravel. These deposits are reddish-brown to greyish-green, fairly well bedded, and heterolithic in nature. This sequence probably represents a time when alluvial processes were depositing detritus in a marginal lacustrine environment. This would account for the poorly-bedded clays as well as the poorly-sorted sands and gravels.

Fig. 5. Well-defined, horizontal bedding exposed in an impact crater on the playa.

OMIT ?

Lateral variation in this sequence supports this hypothesis. The average grain size decreases from west to east, and bedding becomes well defined (Fig. 5). In the lacustrine deposits on the south end of the playa and extending around the eastern periphery, the bedding is from 1 to 2 inches thick, horizontal, and well defined. Here the sorting is good. The lithology is almost 100 percent white to medium-gray gypsum of fine sand size. The lacustrine deposits underlie everything north and west of the playa and a narrow zone around the south and west. Samples taken from holes drilled with an auger in and around the playa show that these deposits average 10 to 25 feet thick. Below this depth they become interbedded with clays and sands typical of a lacustrine sequence.

Lacustrine and Eolian Deposits. - These deposits, found in the north and central sections of the area, are dissected lacustrine deposits, similar to those just described, capped by gypsiferous eolian dunes. These dunes may correlate with the old dune field in the southeast of the study area. Deflation has carved enough relief to expose lacustrine deposits which underlie, in places 15 to 20 feet of eolian deposits. These eolian deposits were once probably actively migrating dunes similar to those now found to the east. At the present the strong southwest winds are gradually reducing them to the level of the surrounding alkali flats. Cross-bedding is very obvious in these deposits of light, reddish-brown gypsum sands, and small blowouts are common.

Playa Deposits. - The area on the map labelled Lake Lucero represents present-day playa deposits. If summer storms attain sufficient numbers and intensity, discharge from the mountains reaches the playa by both surface and subsurface routes. Most of the surface water comes from the west since sand dunes of various ages hinder flow from the south and east and a succession of small playa depressions in the alkali flats intercept most of the water which might come from the north.

The surface water which does reach the playa brings with it a considerable sediment load as well as some dissolved solids. The sediment, and, to a lesser extent, the dissolved solids, differentiate the playa regime from that of the alkali flats described next. Surface water cannot leave Lake Lucero since it occupies one of the lowest closed depressions in the Tularosa Basin. Winds blowing across the water surface create currents strong enough to transport sediment from the west side of the playa to the east side by both traction and suspension. A rough estimate of the flow velocity gave 40 ft./min. or 0.4 mi./hr. as an approximation. This process evenly distributes a stratum of fine silt and clay over most of the playa surface. For this reason the playa is a site of sedimentation.

During most of the year, when the playa is not flooded, it becomes a surface of deflation, as is shown by the topographically higher lacustrine deposits on all sides of the playa. Present day observations of the wind actively scouring the playa floor and blowing sediment high into the air also makes deflation appear to be the obvious cause for this depression.

The thickness, and even presence, of playa deposits is dependent on short-term climatic conditions. When present these deposits lie directly on lacustrine deposits.

Alkali Flats. - The alkali flats resemble the playa area in many ways. Both the alkali flats and the playa are source areas for the White Sands by eolian deflation and transport; both lie directly on the

Fig. 6. Aerial photograph of large blowout.

Note well-developed blowout dunes.

lacustrine deposits of Lake Otero, both have very low relief and both are subject to the processes imposed on them by shallow, saline ground waters.

The alkali flats differ from the playa in that they are not sites of sedimentation during periods of flooding. They are instead susceptible to sheet wash and accompanying erosion although arroyos and rills are absent. The alkali flats may be a more important source of detrital gypsum because they are exposed to eolian erosion more frequently than the playa.

Blowouts. - Blowouts occur where wind action has been especially effective in removing sand deposits. These depressions were formed entirely by wind action and commonly have blowout dunes on their leeward margins.

Several small blowouts and one large one have been carved from the lacustrine and eolian deposits. The best developed blowout lies between the two segments of Lake Lucero on the interdunal plains (Fig. 6).

Alluvium. - The areas mapped as alluvium are primarily alluvial fan deposits, mainly unconsolidated cobble- to clay-sized, heterolithic rocks derived from the San Andres Mountains. The material west of Sec. 2, T. 18 S., R. 5 E. is primarily fine-sand and silt size and was deposited as nearly level mud flats.

The alluvium overlies lacustrine deposits which occasionally crop out where erosion has reduced this alluvial cover.

Neher et al. (1970, Fig. 3) mapped some dunes in the area the writer has termed alluvium. They describe the dunes as consisting of 75 to 95 percent reddish-brown silica sand, averaging 3 to 10 feet in height. The sand forming these dunes is derived from the alluvial fans and stream channels.

The writers believe~~s~~ that the primary mode of transport for these sands is alluvial, however; eolian processes have aided in the formation of ~~these~~ mesquite-capped mounds (Fig. 4). The sand size particles in the alluvium are transported by the wind; when the wind encounters a mesquite bush, its force is diminished and the sand is deposited. The sand builds up around the mesquite bushes as they grow, until some have attained heights of over 10 feet.

Selenite Crystals. - The selenite-crystal horizon closely follows the marginal zone between lacustrine and alluvial deposits. This occurrance is a clue to the origin of these crystals.

The top of the selenite horizon is about 30 feet above the playa while the bottom lies somewhere near but below, the playa surface. The crystals are dark-brown to golden-yellow near the top of the zone and lose their color with depth, until within a few feet of the playa they are light-gray to nearly colorless.

Some of the crystals have reached dimensions of over four feet. The size decreases while the apparent amount of crystal dissolutioning increases with depth. At the top of the selenite zone the crystals have sharp boundaries and distinct cleavage surfaces; near the bottom of the zone the crystals are pitted and etched deeply by solution.

Kerr and Thomson (1963) described recent gypsum deposits in Laguna Madre, Texas, which resemble the selenite found in this study area. Padre Island (110 miles long) separates Laguna Madre, a linear coastal lagoon from the Gulf of Mexico. The presence of this long island combined with low precipitation and runnoff isolate the lagoon from any significant source of non-saline water while high evaporation rates concentrate the already saline sea water.

Fig. 4. Mesquite-capped mounds as they occur west of Lake Lucero

= Coppice Dunes (WJS)

Most of the crystals west of Lake Lucero have incorporated very little matrix, however; a small percentage have incorporated sand-size clastics. Several crystals grew with one end in sand and the other in mud and clay, thus resulting in a specimen which is one-half relatively clear selenite and one-half "sand crystal" (Figs. 7 & 8).

One way of visualizing how this may occur is by comparing a walk along a sandy beach with one through a muddy swamp. The sandy beach offers solid resistance to weight, while the mud in the swamp is easily displaced. The force of gravity may be analogous to the force of crystallization of the selenite crystals. Crystals which grew in a mud environment displaced the sediments; the sand strata however, offered more resistance and therefore became incorporated into the selenite.

The environment envisioned for the formation of these crystals at Lake Lucero is depicted in Figure 9. The selenite seems to prefer the marginal alluvial-lacustrine deposits for growth to large size. This region was described earlier as a region where alluvial processes were depositing detritus in a lacustrine regime. This process would create a shallow-water environment which would be subjected to the same wind-induced water-level variations as those found at Laguna Madre.

The similarities in the formation of these two selenite deposits are numerous; both developed in an environment of high evaporation potential; both developed into large crystals and rosettes; both formed in a marginal terrestial and saline water environments; and both incorporated sand-size particles while displacing finer matter. Therefore, the Laguna Madre deposits may be a modern day analog of the selenite beds at Lake Lucero.

Sand Dunes and Interdunal Plains. - Aerial photographs were used

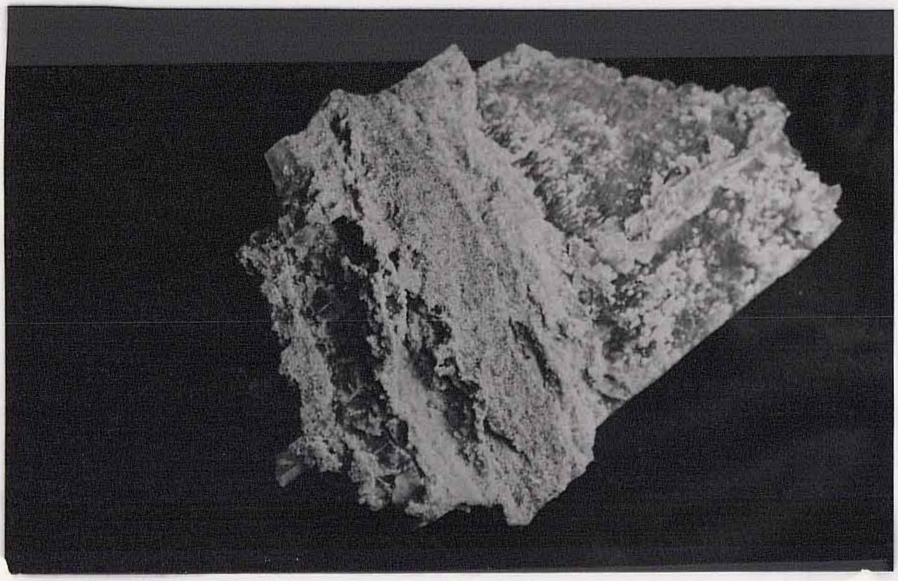


Fig. 7. Gypsum crystal showing sand inclusions.

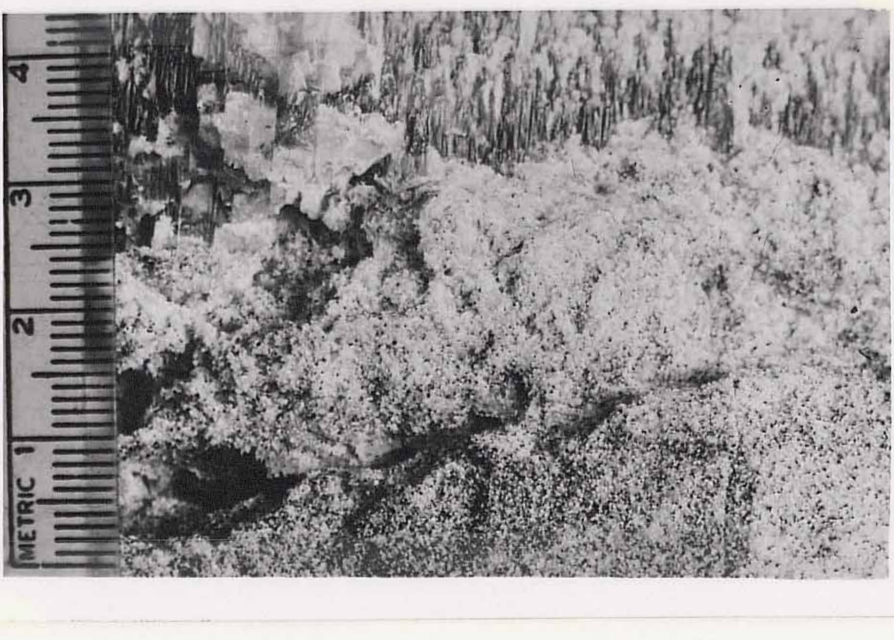


Fig. 8. Close up of above crystal

exclusively in mapping the sand dunes and interdunal plains. The strong contrast afforded by the White Sands simplified this procedure greatly. The interdunal plainss are areas that are devoid of any significant, active, eolian deposits. A few scattered dunes do exist in this area as do a few interdunal areas in regions mapped as dunes.

The older dune field occupies only a small segment of the mapped area and consists of well stabilized dunes which have developed a poor soil zone and have been subject to some erosion.

Stratigraphy of the playa subsurface (lacustrine deposits)

In the spring of 1969, 51, four-inch test holes were drilled by truck mounted, continuous-flight auger around the periphery of Lake Lucero. These holes, drilled for hydrologic purposes, supplied stratigraphic data in the form of grab samples taken at five-foot intervals.

Most samples show gypgum grains or crystal fragments as making up the bulk of the upper 10 to 25 feet. Some small amounts of clays occur in these beds and near the western margin some sands and silts are included. This unit is thinly bedded and very compact; most of the grains are sub-angular but quite spherical. These are probably the "Otero marls" discussed by Herrick.

Below this unit lie more typical lacustrine deposits of sand, silt, and clay. Selenite still remains a significant constituent in these deeper deposits but the fragments are much smaller. Well-developed crystals are often found in clays, suggesting that they grew in place by precipitation from concentrated brines. These crystals, transparent and colorless, often form swallow-tail twins ten to twenty-five millimeters in length, thus differing from the selenite found in the beds marginal to the playa. Many places on the playa surface are covered with crystals of this nature suggesting that they were once common in finer grained strata that have now been removed by eolian processes. If these crystals occurred in sufficient quantities in the past, they could well have been the source of most of the gypsum now comprising the White Sands. Observations of some of the lacustrine deposits surrounding the playa show that this type of gypsum is indeed very abundant.

Playa mineralogy

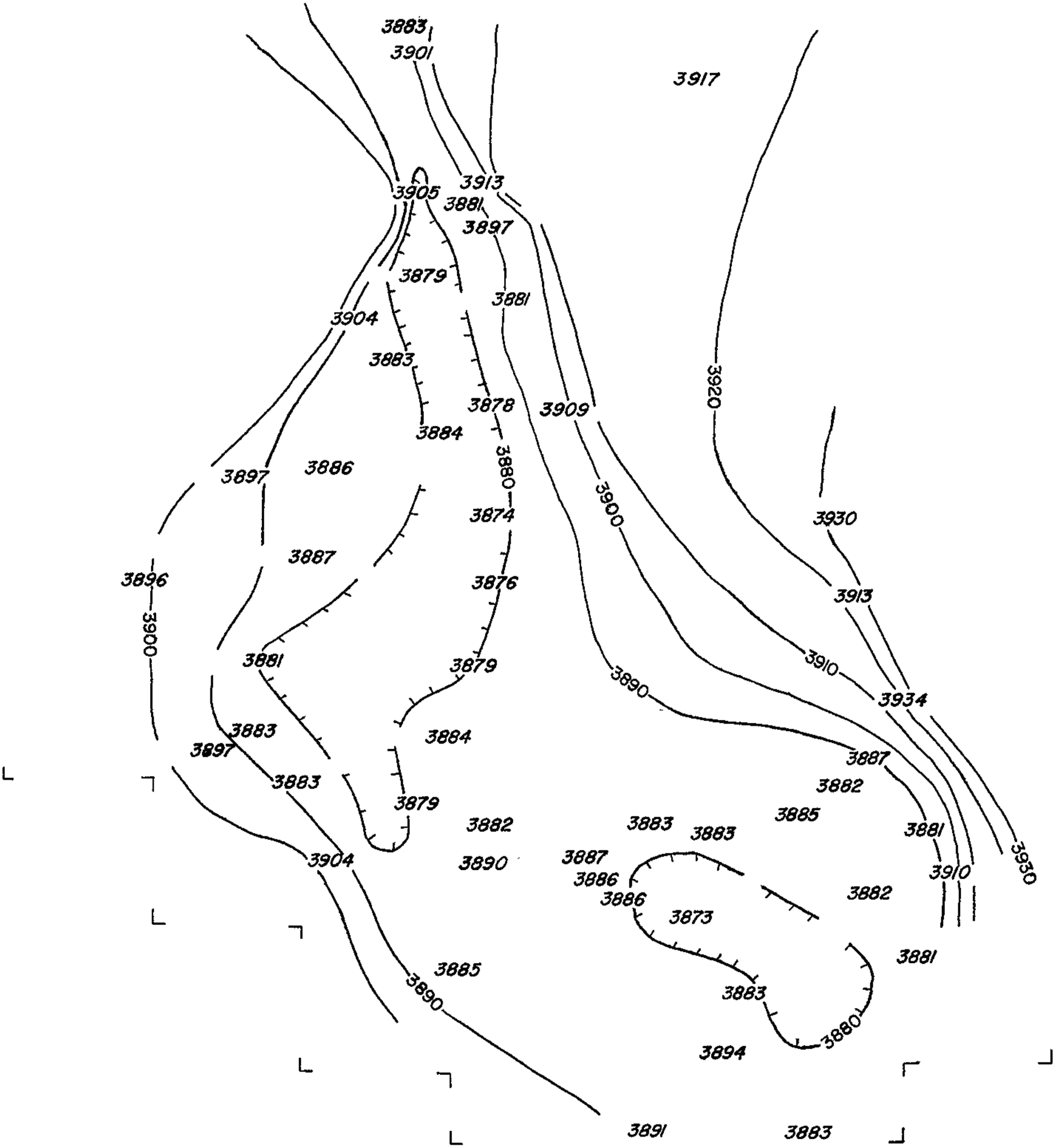
Preliminary investigations show that gypsum (selenite), thenardite, and halite are the primary surface minerals with gypsum and bloedite being the primary evaporites in the subsurface. Gypsum is, by far, the most common mineral in the study area; thenardite, halite, and bloedite occur only rarely. Meinzer and Hare (1915, p. 72 and 180) noted the occurrence of sodium chloride, sodium sulfate, magnesium sulfate, sodium bicarbonate and sodium carbonate in the Tularosa Basin. Not all necessarily occur in this study area and only those mentioned have been definitely identified.

Theory of ground-water motion as it applies to the Tularosa Basin

McLean's water-table map (1970) suggested the possibility of a water-table depression in the vicinity of Lake Lucero. A more detailed survey of water levels shows that there is indeed a water-table depression. This information was obtained from water levels measured in the test holes shown in Fig. 10. This represents the lowest position of the water table since this project began, because surface flooding during the summers of '69 and '70 caused the water table to rise. Figure 10 is a contour map of the water table showing definite water-table depressions as measured in the spring of 1969.

A depression in the water table indicates a ground water sink, similar to a cone of depression around a pumped well. This means that ground water flows radially inward towards the center of the depression and (assuming water loss by evaporation) upward towards the water table. Ground water must therefore be lost at the land surface. The most reasonable and likely explanation for this phenomenon is capillary rise and evaporation at the surface. A shallow depth to water and very fine-grained, compact nature of the strata would facilitate this process as would a high evaporation potential.

The water table, as shown in Figure 10, usually lies less than ten feet below the surface of the playa, and more commonly falls between two and four feet below land surface. This is within the range of capillarity for the very fine sand to silt size material. The grain size of the strata between the water table and the land surface falls in the 0.05 to 0.02 mm range which Meinzer (1944) cited as causing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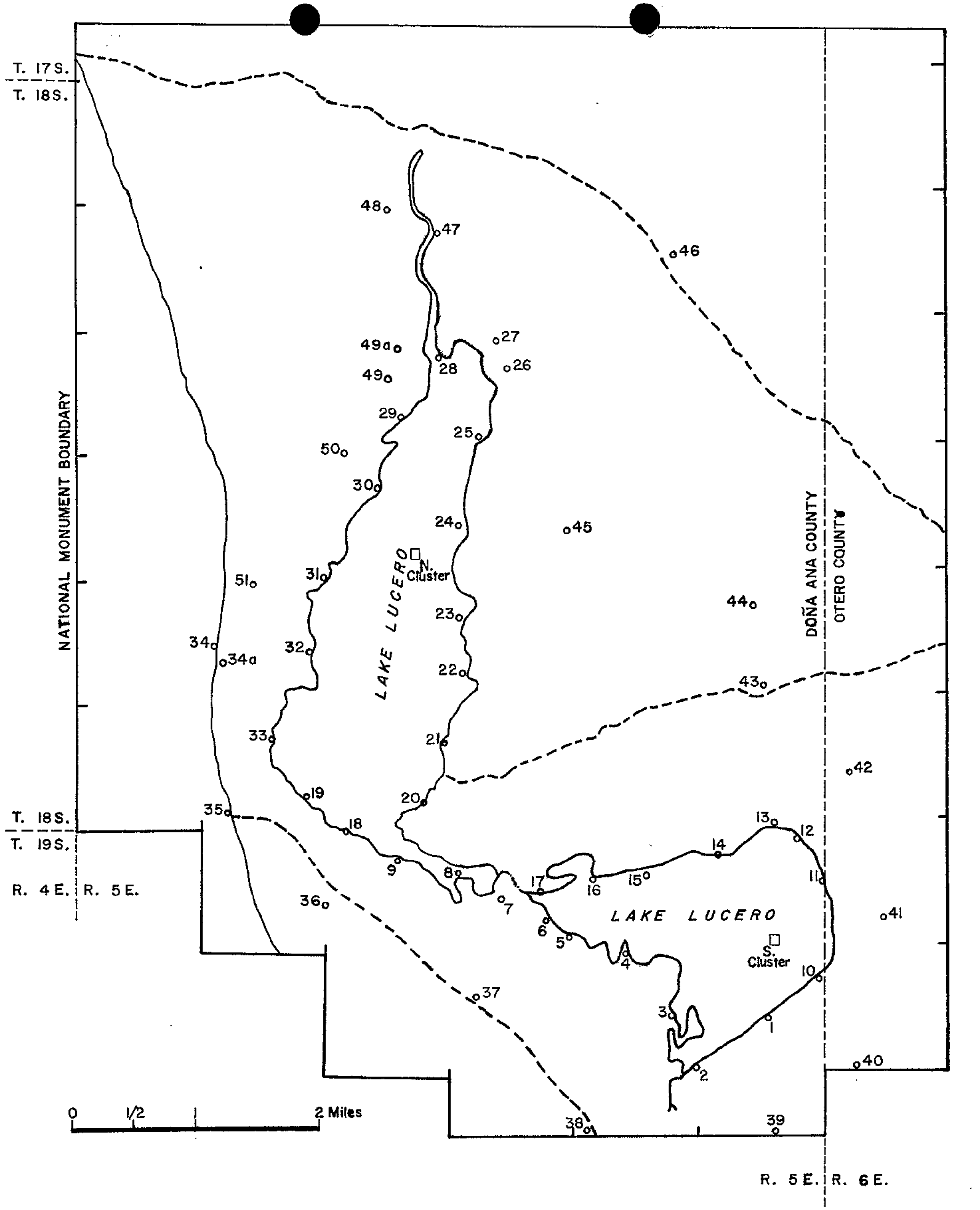

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T. 18 S.
T. 18 S.
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R. 4 E.
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NATIONAL MONUMENT BOUNDARY
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OTERO COUNTY
LAKE LUCERO
N. Cluster
LAKE LUCERO
S. Cluster
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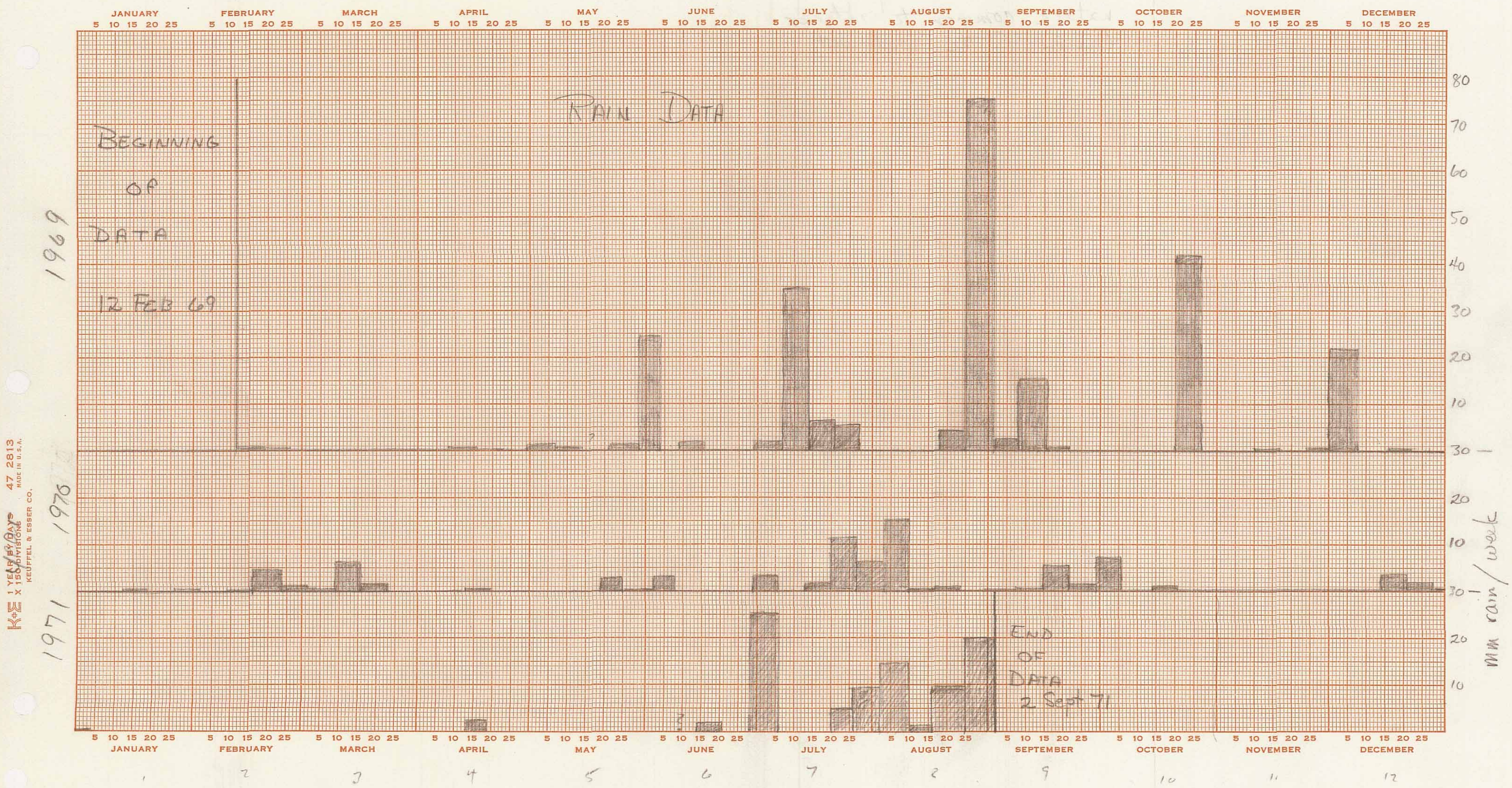
Fig 11. Graph of weekly rainfall accumulation showing sporatic nature common to interior basins of the Southwest.



JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
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AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
RAIN DATA
BEGINNING OF DATA
12 FEB 69
1969
1970
1971
END OF DATA
2 Sept 71
80
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60
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mm rain / week
K+E 47 2813
1 YEAR BY DAYS X 150 DIVISIONS
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a capillary height of 200 cm. This suffices to supply water to near the surface where evaporation readily takes place.

As Ripple et al. (1972) point out, there are two factors which control the amount of evaporation from a shallow water table below bare soils. The first factor to be considered is the potential evaporation. This is the amount of evaporation which would take place from a constantly saturated soil surface. The soil factor is the second which includes the height of soil above the water table and its hydrologic properties.

The hydrologic properties of the playa deposits are unknown and therefore only an estimate of the potential evaporation can be obtained. The combination method of Van Bavel (1966) was used to convert the meteorologic data to potential evaporation. Van Bavel describes and experimentally verifies this combination concept.

Data used for calculating the potential evaporation were collected by personnel of the White Sands National Monument on a weekly basis from February 12, 1969 to September 2, 1971. These data were collected from a weather station maintained on the southern margin of Lake Lucero, directly adjacent to the playa. Table 1 expresses these data as monthly averages for the 2½ year period. The rain data are plotted separately on a weekly basis to demonstrate their sporatic behavior. (Fig. 11).

Figure 12 is a plot of the potential evaporation calculated from these averages. As expected the highest evaporation rates occur during June and July while December and January are the lowest. The total potential evaporation calculated for this time period is about 230 cm. per year. This is equal to 2,300 l. per m.^{2}

Turk (1970, p. 1213) has measured the effect of salinity on evaporation at Great Salt Lake, Utah. His data, presented as percent equivalent evaporation of fresh water, show that in the range of total dissolved solids of ground water below Lake Lucero, evaporation may be decreased by 15 to 30 percent. This results from the fact that dissolved solids lower the vapor pressure of a solution. Salinity lowers the maximum possible evaporation to about 1870 liters per m^2.

In conjunction with the evaporation potential calculated from the meteorological data, an estimate of the actual evaporation was obtained from a lysimeter. Figure 13 shows the records taken from a constant-head lysimeter constructed and installed during the summer of 1970. The lysimeter column is 1.05 m. long (approx. 3.5 ft.) and has a surface area of 325 sq. cm. (about 50 sq. ins.). The sediment column is a core taken in situ with as little disturbance as possible. The sediments are fine-grained, very compact, gypsum and clay. These strata probably have the lowest hydraulic conductivities of the playa subsurface and therefore will yield a lower limit on the actual evaporation.

Figure 13 shows that the rate of evaporation from the lysimeter is about 6 liters per year. Expanding this datum over a square meter gives 185 liters per square meter per year as a lower limit for evaporation. These data combined with data on the chemistry of the near-surface ground water allow calculation of salt accumulation rates.

Samples from near-surface and deeper ground waters indicate that Ca^{++} concentrations vary from about 400 to 700 milligrams per liter. Sulfate ions are well in excess of this number (about 8500 to 88,000 mg/l.). Assuming that all the calcium is precipitated as gypsum, and that the above estimates are correct, the limits on the amount of gypsum which may be precipitated as the result of evaporation are 250 to 4880 grams per square meter per year. The upper limit is based on the maximum calcium concentration and the maximum possible evaporation rate, and is probably an unrealistic number. The lower limit, however,

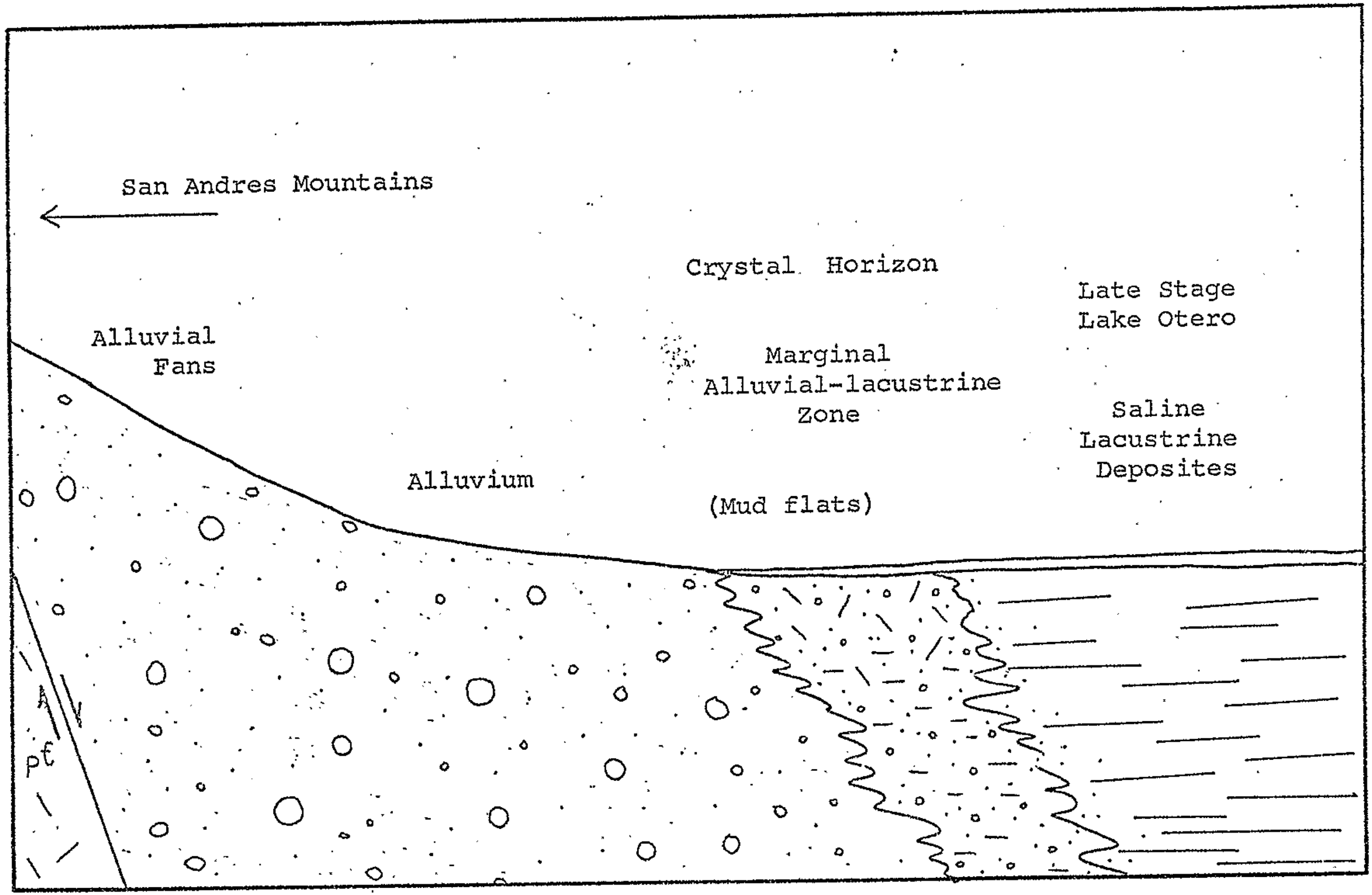

Figure ~~13~~ 9. Environment of formation of large selenite crystals.

Reduce to 1/4 page?

Water table?
(WJS)

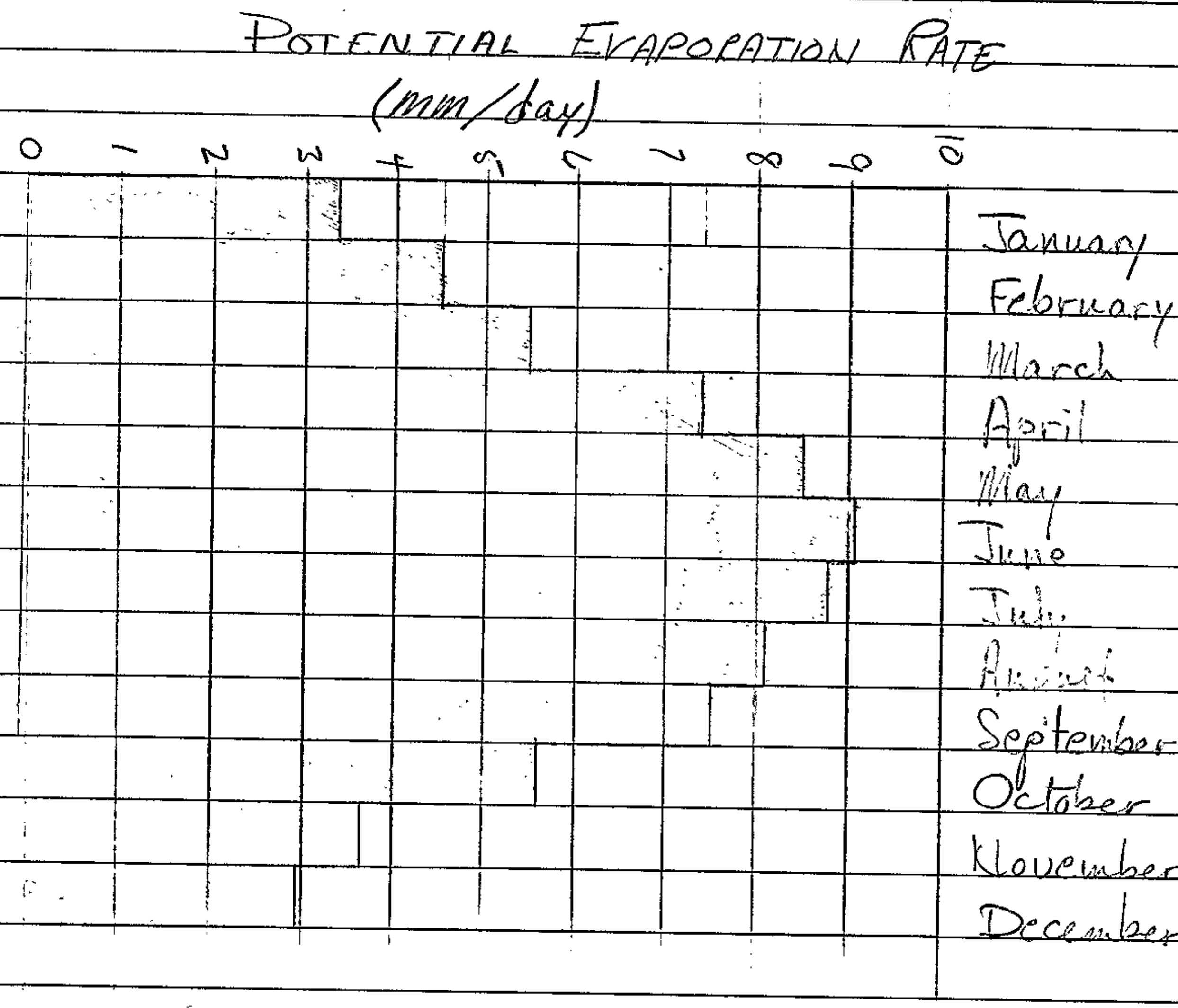

Fig 12. Monthly distribution of evaporation rates based on 2½ year period

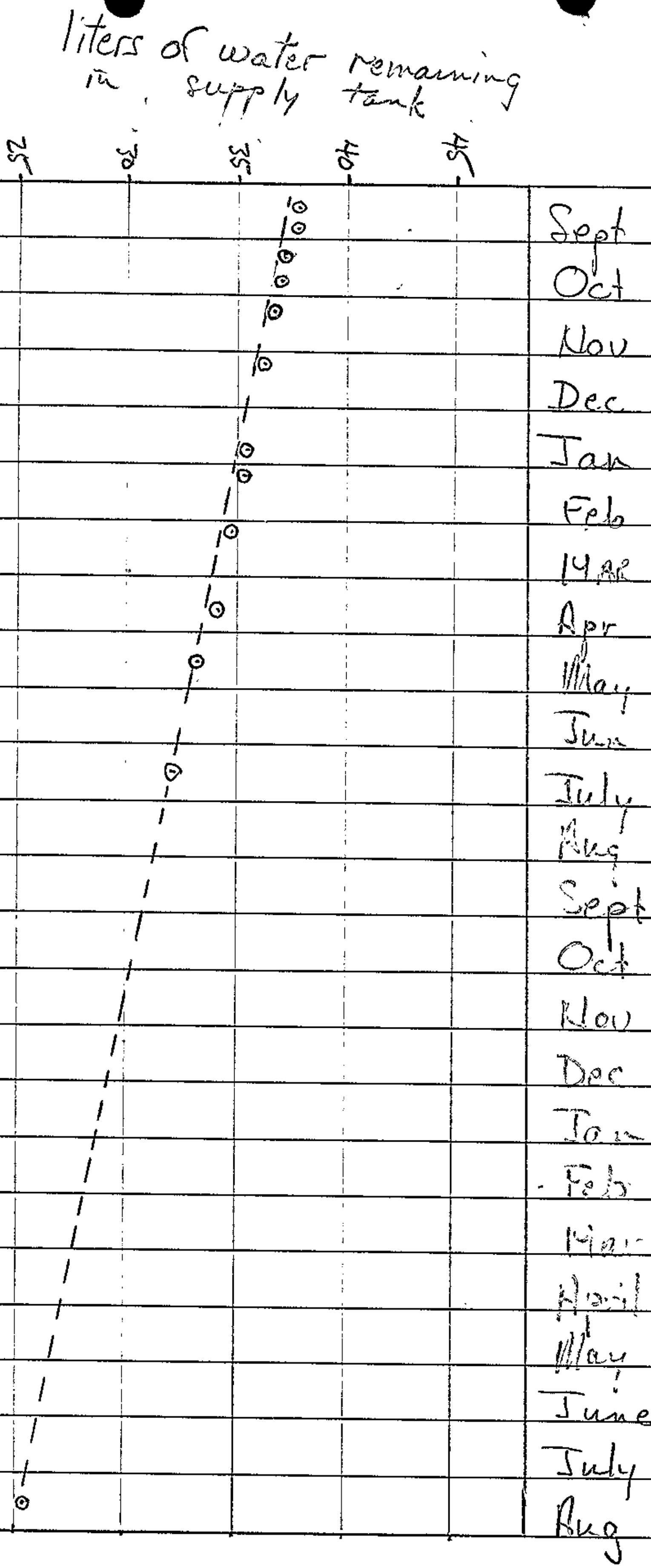

Fig 13. Lysimeter data showing measured evaporative water loss.

is based on more empirical data and therefore may be a more significant number.

Using the lower limit of precipitated gypsum and an estimated 26 square kilometers of playa surface, the total amount of gypsum added to the Lake Lucero subsurface is 6.5×10^6 kilograms per year. This is equal to about 2800 cubic meters, or assuming 30% porosity, about 4000 cubic meters of dune sand per year.

It is proposed, on the bases of the physical evidence and the above calculations, that 1) gypsum is being transported to Lake Lucero and the alkali falts as a dissolved solid, 2) high evaporation rates at the playa result in a ground-water sink, and 3) gypsum is precipitated in the subsurface as the solutions evaporate. This is an example of the mechanism of accumulation of evaporite minerals as suggested by Williams (1970).

Additional evidence in support of this mechanism is the euhedral aspect of small gypsum crystals found in the clays and silts of the lacustrine depostis. This suggests that they formed in place after deposition of the clastics because any amount of transport would have destroyed the sharp crystal boundaries of this soft mineral. Inclusions of the clastics also indicate that the crystals formed in place. The high concentration of dissolved solids suggests that the gypsum crystals may be growing at the present. If the crystals were a product of earlier processes and the present high dissolved solids content of the water is attributed to dissolution of the soluble minerals in the immediate vicinity, one would expect to see evidence of dissolution on these crystals. This is not the case, and it is therefore believed that the crystals are forming in place as a result of evaporation of ground water at the capillary fringe.

As the finer grained lacustrine deposits are deflated these small (10-20 mm.) crystals are exposed in large aggregates at the playa surface. Here diurnal temperature variations and impacting wind-blown particles work to break the crystals down to a size where they too can be transported by eolian processes. (The effectiveness of wind-blown particles, as an abrasive, is demonstrated in Figure 14.) These crystals appear to be the primary source of gypsum now active in the dunes. Their color more closely resembles the dune sand than does the color of the very large brown selenite crystals discussed earlier. Also, these small crystals are large enough to compensate for the fracture and abrasion encountered during transportation. This is not true of the finer grained gypsum matrix in which the crystals formed. The matrix, at least below the playa surface, has an initial grain size too small to compare with that in the dunes and therefore must be eliminated as a possible direct source for the dune sand.

Beneath the present playa surface the crystalline gypsum probably constitutes less than five percent of the sediment. In lacustrine outcrops west and east of the playa, stratigraphically above the present surface, the content of crystalline gypsum is as high as 85 to 95 percent. The higher strata represent lacustrine material which was deposited later than the lower strata and therefore correspond to a time when the Lake Otero waters were considerably more concentrated. Thus the difference in gypsum content is thought at least partially to be the result of a depositional sequence in the slowly evaporating lake.

The abundance of crystals in nearby strata equivalent to that which has been removed by deflation at the playa, and the resemblence of their physical properties to those of the gypsum sand in the dune fields, indicate that they are the primary source of the White Sands.

The amount of sand derived from the Lake Lucero area is estimated to be 286,000,000 cubic meters. This would require deflation of a sediment sequence 36 feet thick over the area of Lake Lucero and vicinity. It is assumed that the percent increase in porosity, and consequently volume, in the dunes will cancel the non-gypsum content of the lacustrine deposits.

Although there are sections of lacustrine deposits as much as 40 feet above the playa surface their crystalline gypsum content is not nearly as high as the lower deposits closer to the playa. This means that either the estimates are in error or that some other mechanisms must be called on to add gypsum to the system.

The addition of the ground-water contribution reduces the required thickness of the gypsum source area to 24 feet. This is a much more realistic number and may be sufficient to account for the White Sands.

The role of surface waters in the formation of the White Sands

The playa surface does occasionally become flooded with runnoff waters. Such an event occurred in the summer of 1970 when both portions of the lake were inundated with about 6-10 inches of water.

The chemical changes in the ponded water, as it evaporated showed an increase in the concentration of dissolved solids with time. This increase resulted from unrelated processes; the first and probably most important is dissolution of soluble salts which make up the playa floor. Evaporation also acted to concentrate the dissolved solids, however, the role of evaporation is greatly overemphaiszed if infiltration is neglected.

With the exception of calcium carbonate, no chemical species were near saturation. This means that no salts precipitate before infiltration. The writer believes that the last sample collected represented nearly the very last remnant water to exist before infiltration was complete.

After the surface water completely infiltrated other processes began. Probably some salts precipitated when the mud first began to dry. Capillary forces would then keep supplying the near surface with additional water which would evaporate and deposit more salts on the sediment. As this process continued a very fine-grained efflorescent salt crust formed which X-ray diffraction data determined as being gypsum and halite.

The crust forms fastest where the water can be drawn upward fastest, i.e. in the coarser grained sediments of higher permeability. When the crust forms very rapidly it becomes extremely puffy owing to extension from crystallization (Fig. 15).

Fig. 14. An old, wooden post showing the effects of the abrasive action of wind-blown particles.

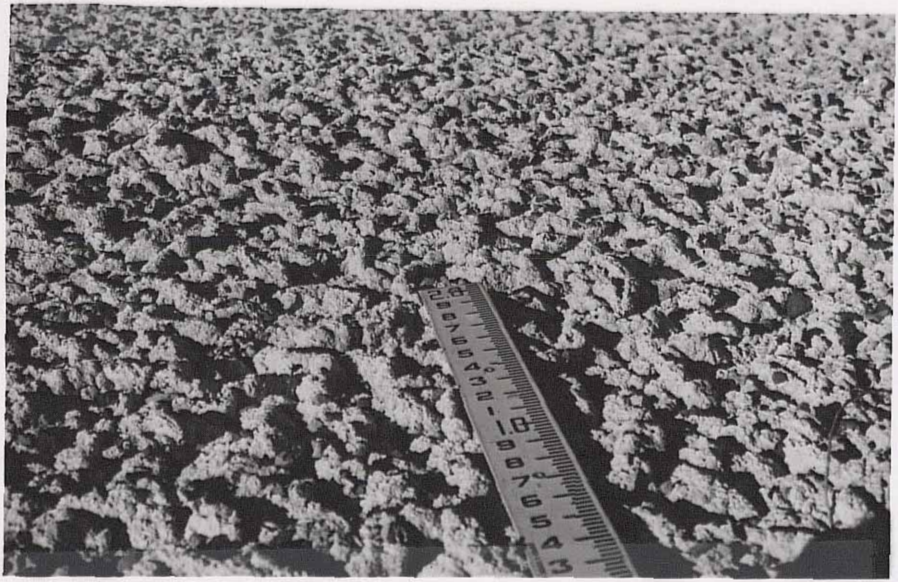

Fig. 15. Photograph of puffy crust at Lake Lucero.

Whether or not the crust is puffy or is the more typical compact type, it soon becomes susceptible to the erosive effects of the prevalent southwest winds. Much of this crust breaks down to a fine powder and has been observed to blow thousands of feet upwards into huge white clouds and transported many miles from the playa. Larger particles travel a much shorter distance to the playa's eastern side where they form small dunes and later become incorporated into the larger dunes farther east. Most of the gypsum in this crust breaks down very easily, however, and soon becomes winnowed out of the active dunes. Therefore, the minerals directly related to surface-water phenomena do not contribute significantly to dune formation.

One process which may play a role, however, is the actual growth of the efflorescent crust. As this crust grows and expands it lifts with it the smaller, clear gypsum crystals described earlier as covering portions of the playa surface in large numbers. The forces involved in the growth and expansion process may help to break up these crystals to a point where the wind can begin moving them.

SUMMARY AND CONCLUSIONS

Various aspects of the hydrologic cycle have been instrumental in the formation of the White Sands since Pleistocene times. The discharge of dissolved solids into Lake Otero was the first step. This stage probably took place 24,000 to 12,000 years ago. The second step was the eventual concentration of these dissolved solids as Lake Otero slowly diminished in size because of a changing climate, and eventually evaporated to dryness. During this time the saline lacustrine beds were deposited. The large selenite crystals formed either concurrently or shortly after the deposition of the gypsum beds. Deflation has since lowered the playa surface exposing both the crystals and gypsum beds.

The amount of gypsum brought in by surface waters is very small and contributes little to the total gypsum budget. More importantly, the gypsum which is brought in by this process precipitates in a very fine-grained form and does not become included in the sand dunes. Hence surface waters make no significant contribution to the White Sands.

Ground water does transport a significant amount of gypsum to Lake Lucero, from both the Permian evaporites and the recent lacustrine deposits throughout the basin. Ground water evaporates from the capillary fringe and in the process gypsum precipitates and crystallizes in the lacustrine deposits in a form which does contribute significantly to the White Sands. This is probably the only process currently operating which may eventually contribute gypsum to the dune field.

The majority of the gypsum in the White Sands was undoubtedly derived from the primary evaporites of Lake Otero. Hydrologic processes are therefore responsible for transporting and depositing all of the gypsum which has since been deflated at Lake Lucero, the alkali flats and deposited in the White Sands dune field.

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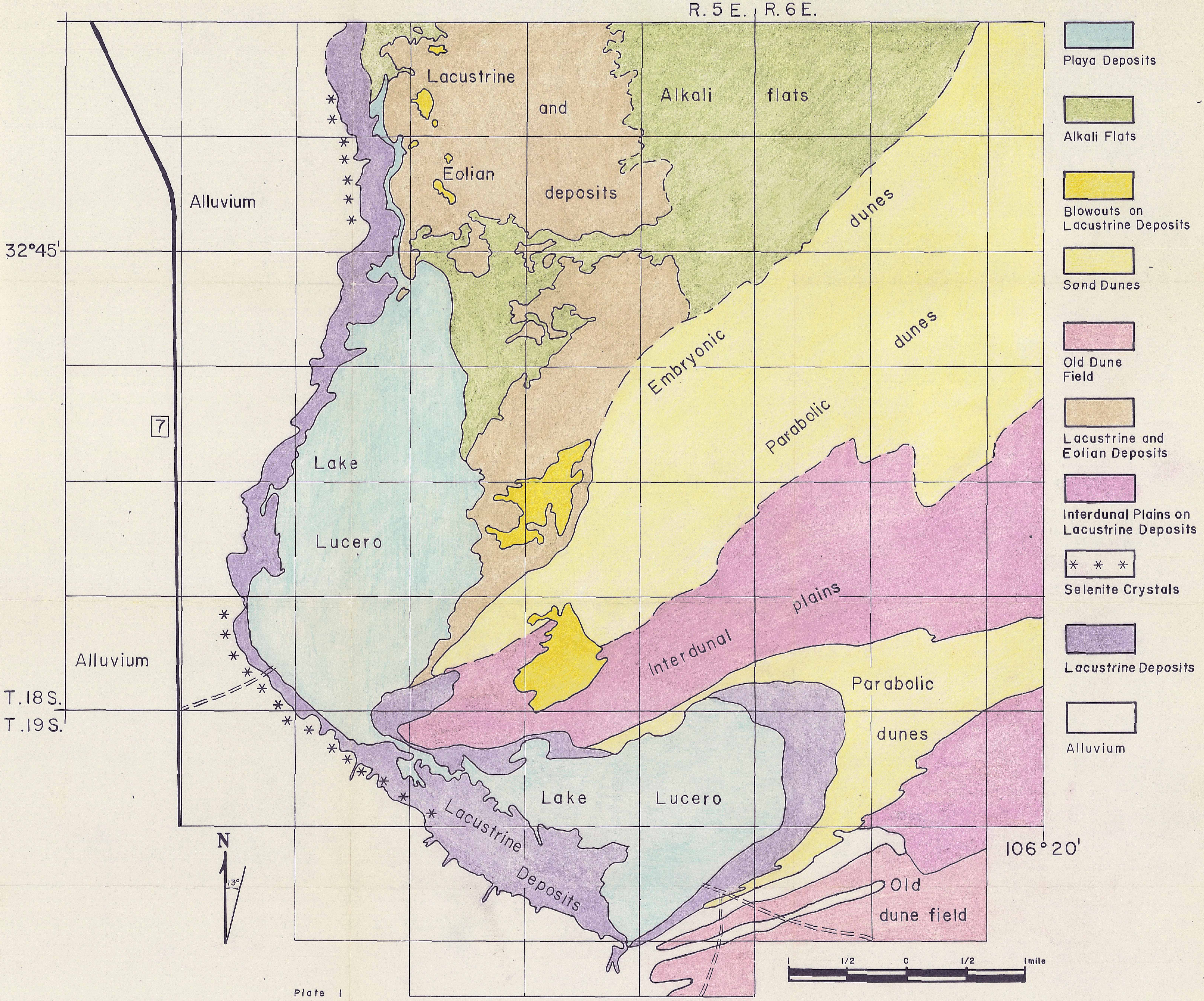

Plate I

Geology and Geomorphology of Lake Lucero and the Adjacent White Sand Area