HYDROLOGIC CONTROL OVER THE ORIGIN OF GYPSUM AT LAKE LUCERO, WHITE SANDS NATIONAL MONUMENT, NEW MEXICO

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by

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ABSTRACT

Lake Lucero, a modern playa, marks the southern extent of a long system of alkali flats and playa depressions lying in the western portion of the Tularosa Basin of south-central New Mexico. While many hypotheses have been proposed, very few data-supported conclusions have been formed to describe the mechanism of formation of Lake Lucero, the associated alkali flats, and the gypsum comprising the White Sands.

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 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 impressively 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 eems likely that today regional ground-water dynamics play the ost important role.

ACKNOWLEDGMENTS

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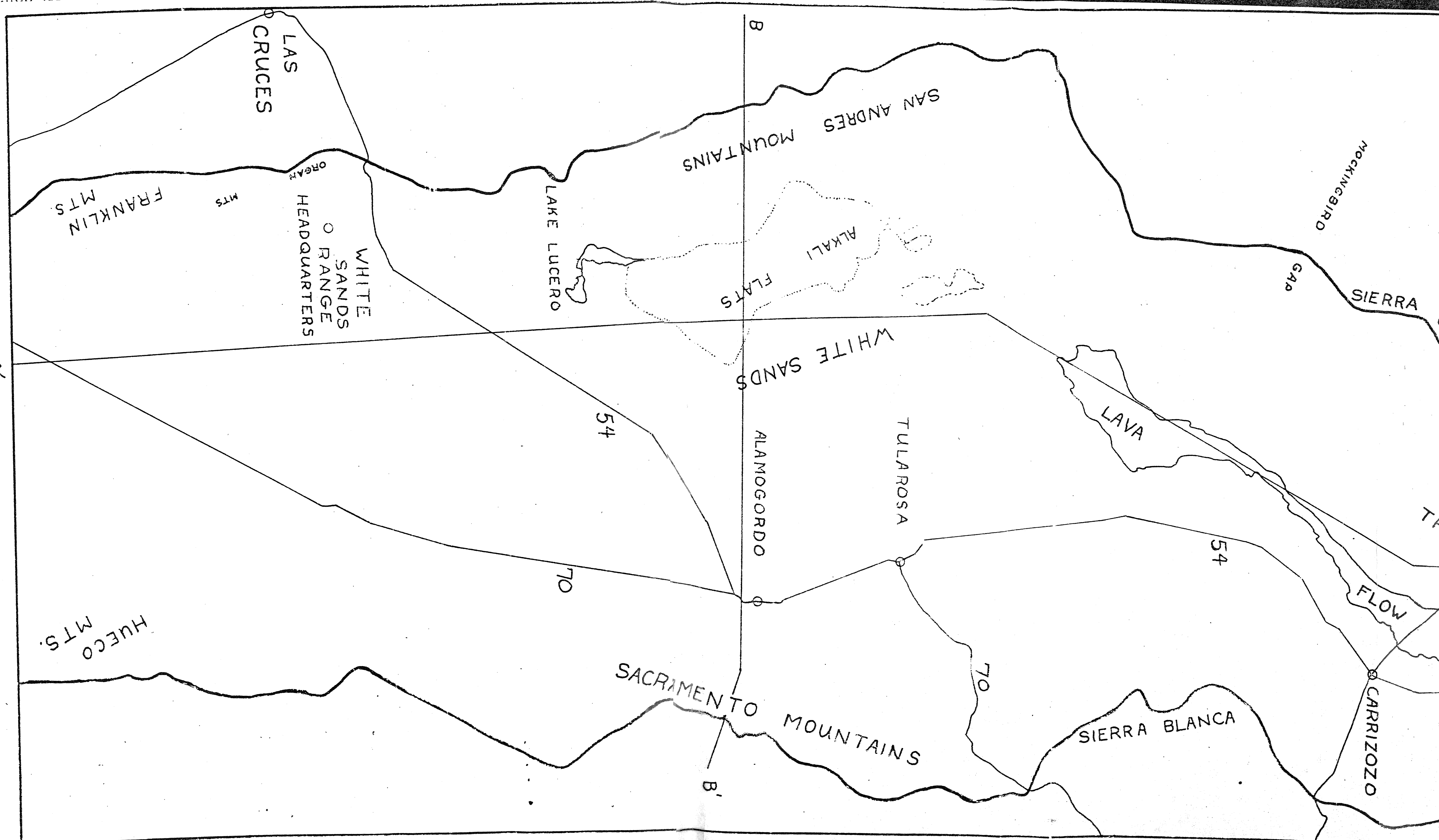
INTRODUCTION

The Tularosa Basin is an arid, intermontaine de-
sion typical of the basin and range physiographic
ince of western North America. The basin encompasses
rea of 6,500 square miles (Fig. 1). In 1909 Richardson
ded what was fromerly called the Hueco Bolson into
portions. The northern portion, which he called the
rosa Desert but is now called the Tularosa Basin, is
rated from the southern portion, or Hueco Bolson of
s, by a very slight topographic divide just north of
Texas-New Mexico border. This divide has not been
ped but is probably a very tortuous line. The complete
ctural basin extends 200 miles south from Carrizozo,
Mexico across the corner of Texas and into Mexico.
width ranges from 24 to 60 miles.

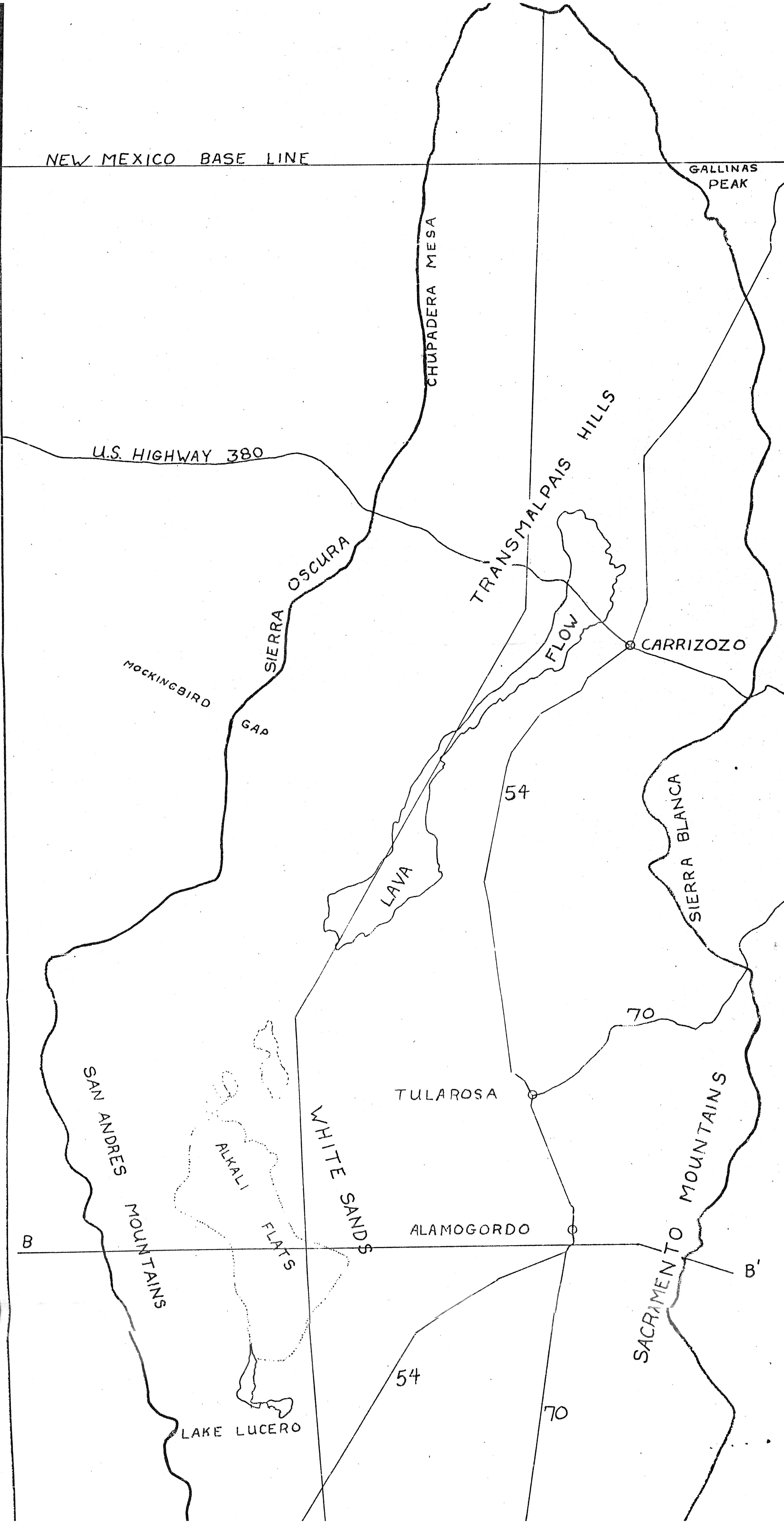
The topography varies from over 12,00 feet above sea
el at Sierra Blanca to less than 3,900 feet in the
thwestern basin region. The basin is bounded by the
nklin, Organ, and San Andres mountains and Sierra Oscura
Chupadera Mesa on the west; by a broad topographically
h region on the north; and by Gallinas, Patos, and
con Peaks, Sierra Blanca, and the Sacramento and Hueco
ntains on the east. The gentle divide on the south
uires that all drainage within the Tularosa Basin be
erior.

The climate of the study area on the valley floor is typical of arid regions of the Southwest. Rainfall varies

from 7 inches at Holloman Air Force Base and White Sands



[redacted]ur[redacted]. [redacted]ex [redacted]p o[redacted]he [redacted]ar[redacted] Ba[redacted] (a[redacted]te[redacted]om [redacted] Le[redacted] 19[redacted] Fig[redacted], 1[redacted]and [redacted]


NEW MEXICO BASE LINE
GALLINAS PEAK
CHUPADERA MESA
U.S. HIGHWAY 380
TRANSMALPAIS HILLS
SIERRA OSCURA
FLOW
CARRIZOZO
MOCKINGBIRD
GAP
54
SIERRA BLANCA
LAVA
70
TULAROSA
SAN ANDRES MOUNTAINS
ALKALI FLATS
WHITE SANDS
SACRAMENTO MOUNTAINS
B
ALAMOGORDO
B'
54
70
LAKE LUCERO

typical of arid regions of the Southwest. Rainfall varies 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). Figure 2 is a record of mean monthly maximum and minimum temperatures based on a 12-year period at White Sands Missle Range.

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).

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. mi.) lies entirely within the Co-use area of the White Sands National Monument (plate 1).

Lake Lucero is normally a dry playa whose subsurface strata consist primarily of clay and crystalline gypsum. Only rarely do summer storms furnish enough water to cover

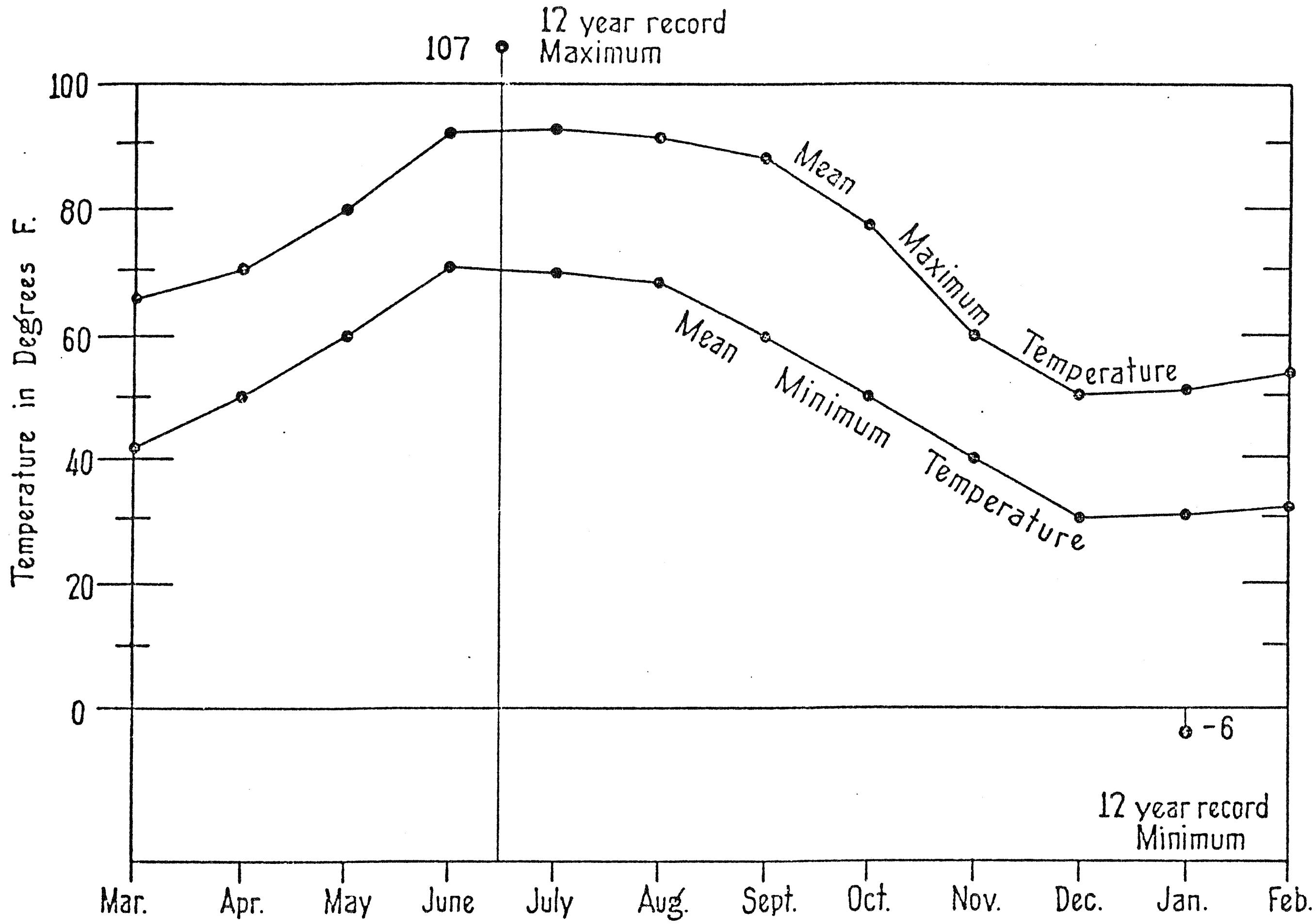


Figure 2. Temperature means and extremes at White Sands Missile Range (from Scientific Advisory Committee, 1965, Fig. 61).

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.

This paper proposes a source for the gypsum found at Lake Lucero, and possible mechanisms responsible for transporting the gypsum to its present site. A brief review of earlier theories can be found in Jicha (1954).

REGIONAL GEOLOGY

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. 3). Anticlinal deformation ceased in the late Tertiary (about 25 million years ago) 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 (Kottlowski et al., 1956, p. 73). The anticlinal axis trends nearly north-south along the western portion of the basin and extends through Mockingbird Gap, thus separating the westward dipping San Andres Mountains from the eastward dipping Sierra Oscura (Fig. 1). The eastern limb of the anticline dips very gently into the Pecos River valley 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 Mountains delineate the fracture zones which formed the graben. Total vertical movement along these fault zones has been several thousand feet.

The main fault zone of the San Andres Mountains trends slightly west of north but is offset to the east in places

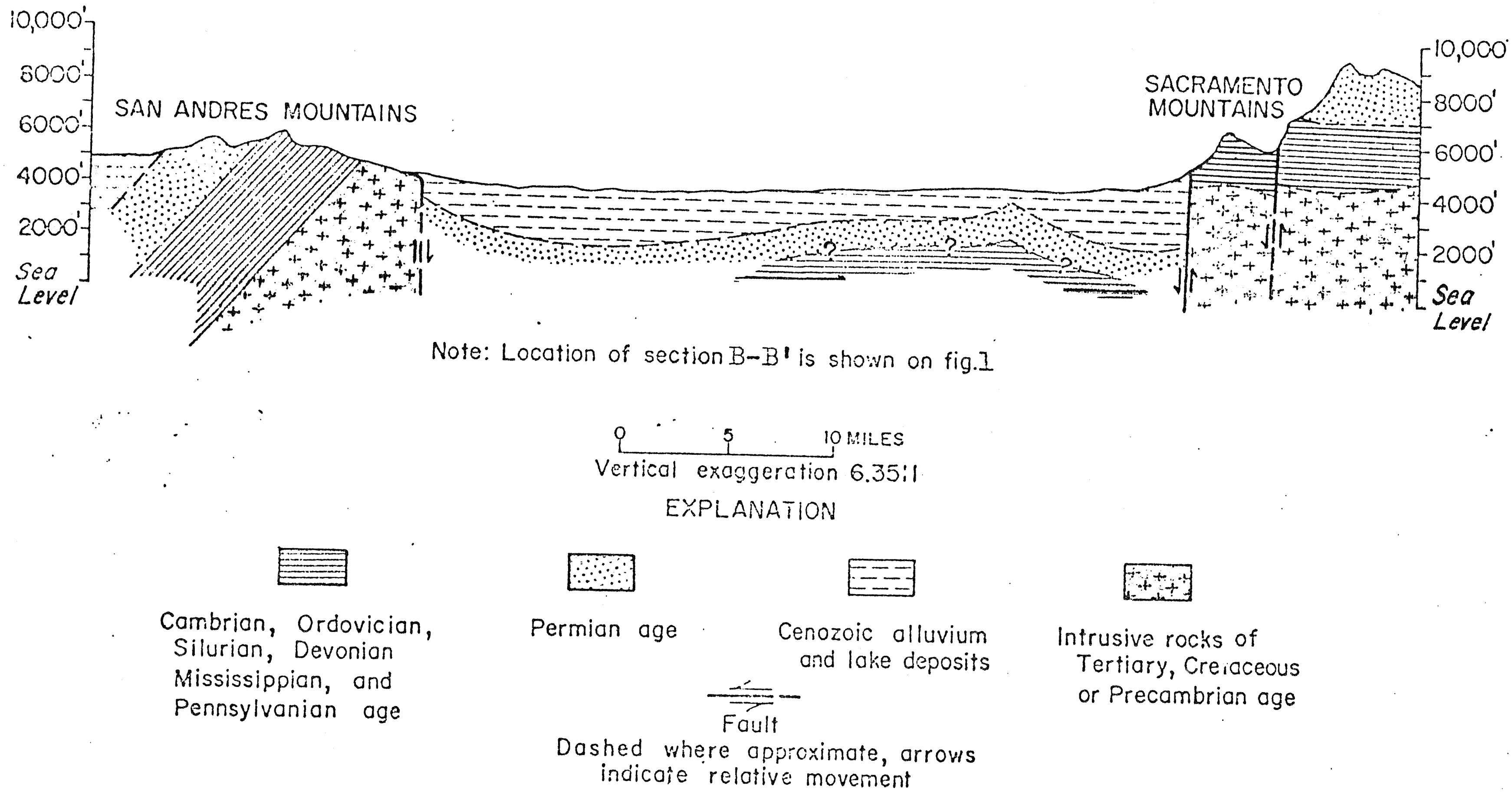


Figure 3
Geologic divisions west to east through the Tularosa Basin.
(J.S. McLean, 1970)

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 scarp of the Sacramento Mountains also trends west of north. The Sacramento Mountains rise about one mile above the valley floor in two successive steps (Fig. 3).

Weir shows that the northern portion of the Tularosa Basin is not a structural basin resulting from faulting but rather is a synclinal structure. The Transmalpais Hills east of Chupadera Mesa express this synclinal nature.

Stratigraphy of the Tularosa Basin Borderlands

The fault scarps of the bordering mountains expose thick sections of Pennsylvanian and Permian Rocks. Strata deserving the most attention in this study are the evaporites of the Yeso and San Andres Formations deposited during the Permian Leonardian and Guadalupian times. These deposits 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 lower most portion being upper Wolfcampian. Overlying the Yeso is the San Andres Formation, a massive to medium-bedded limestone of Guadalupian age. The Yeso and San Andres formations may be separated by the Glorieta Sandstone which is possibly a beach sand of Guadalupian age. The Glorieta sandstone may correlate with the Hondo Member of the San Andres Formation as it is mapped in the Sacramento Mountains.

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

Kottlowski et al. (1956, p. 53) have described the Yeso as it crops out in the San Andres Mountains (Figs. 4 and 5). 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) report a maximum 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. Figure 6 is an isopach map of the Yeso Formation showing the Carrizozo structural basin and outcrop and oil test section thicknesses.

Pray (1961) described the Yeso Formation in the northern (Tularosa Canyon) and southern (Orendorf Peak) parts of the Sacramento Escarpment and noted a decrease in thickness from 1,800 feet in the south to about 1,350 feet in the north. Table 1 expresses the lateral lithologic variations from north to south in this region.

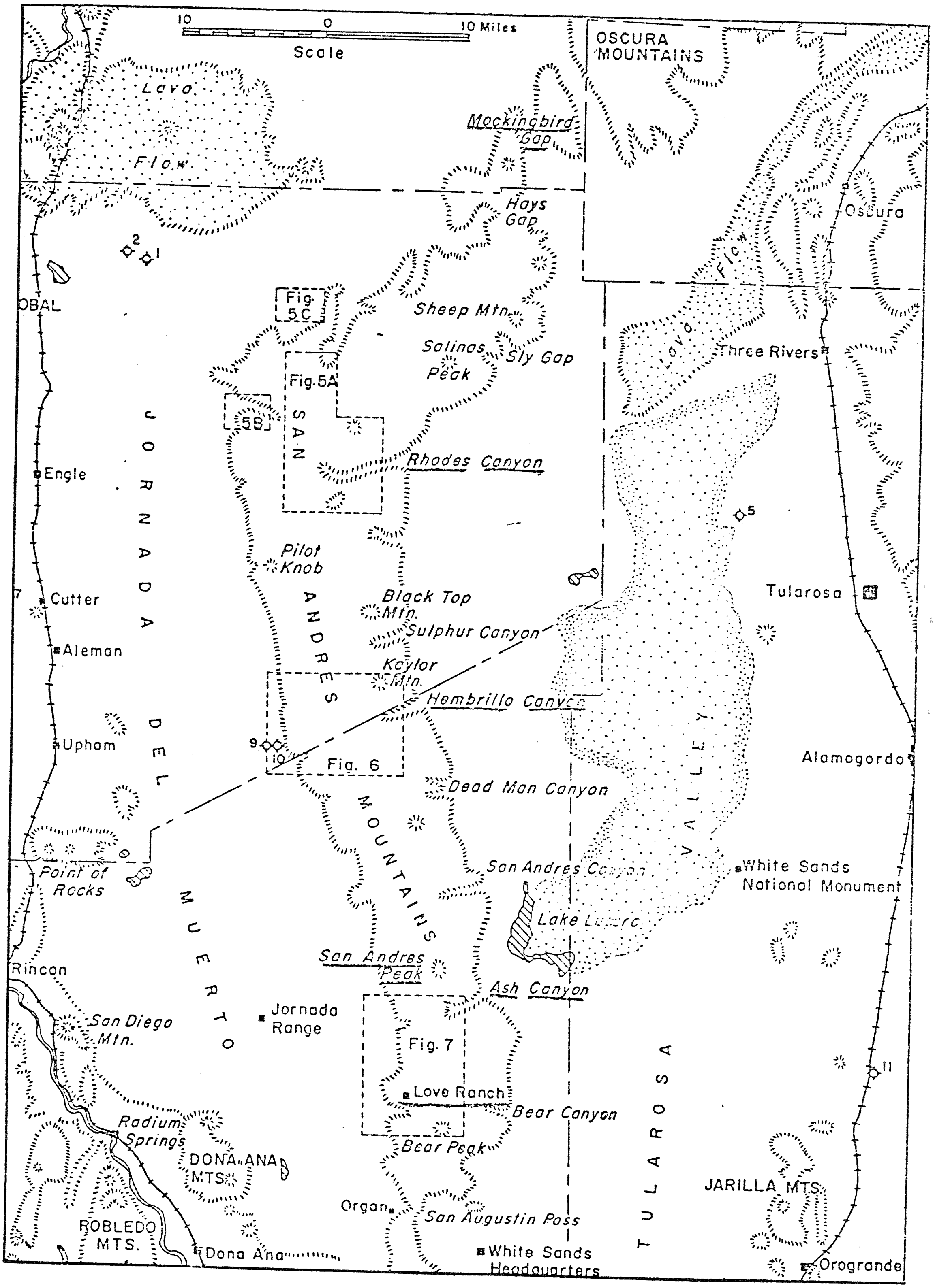


Figure 4. Index map of the San Andres Mountains (modified from Kottlowski et al., 1956, Fig. 1).

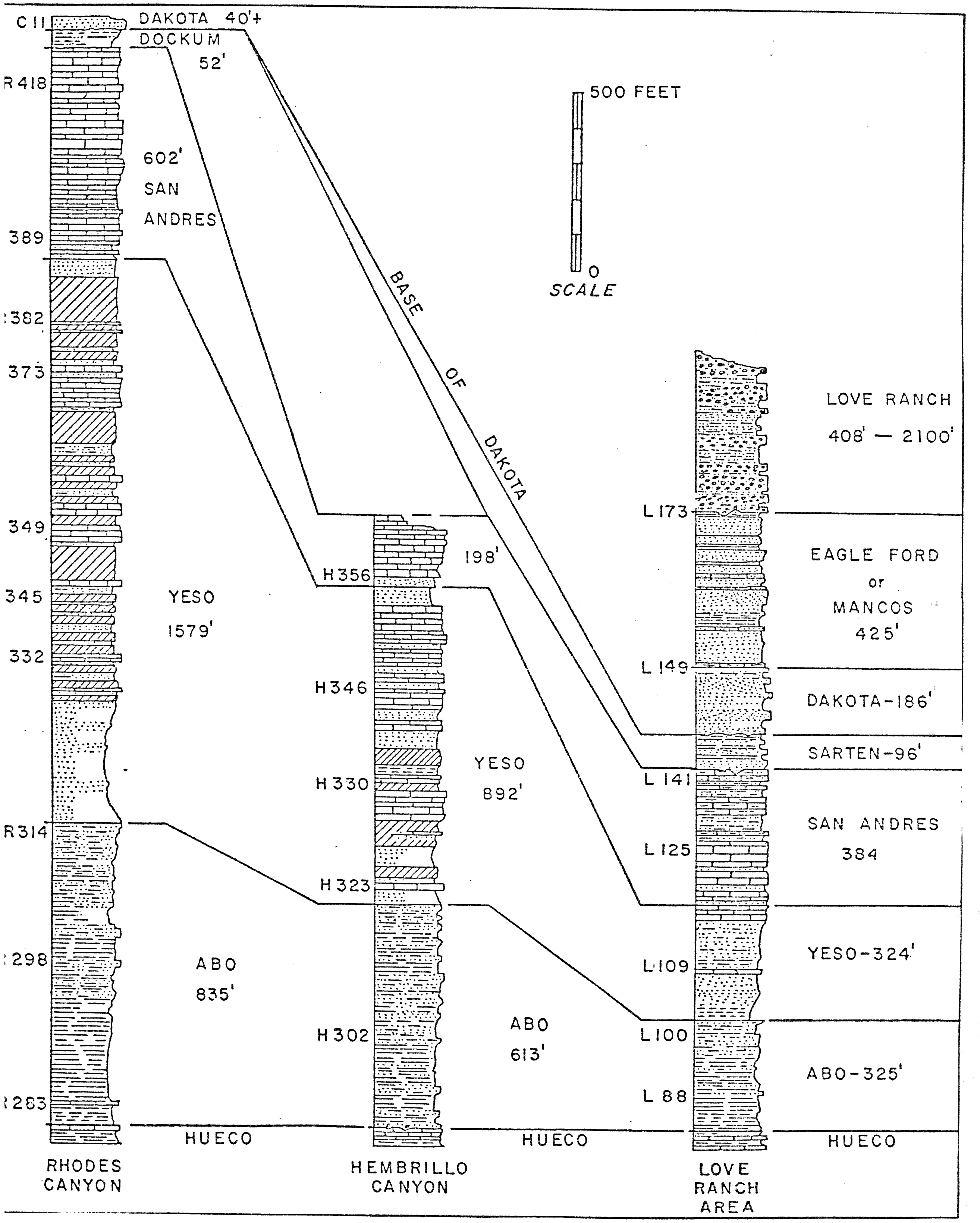


Figure 5. Generalized columnar sections Abo redbeds through Love Ranch Formation (from Kottlowski et al., 1956, Fig. 4).

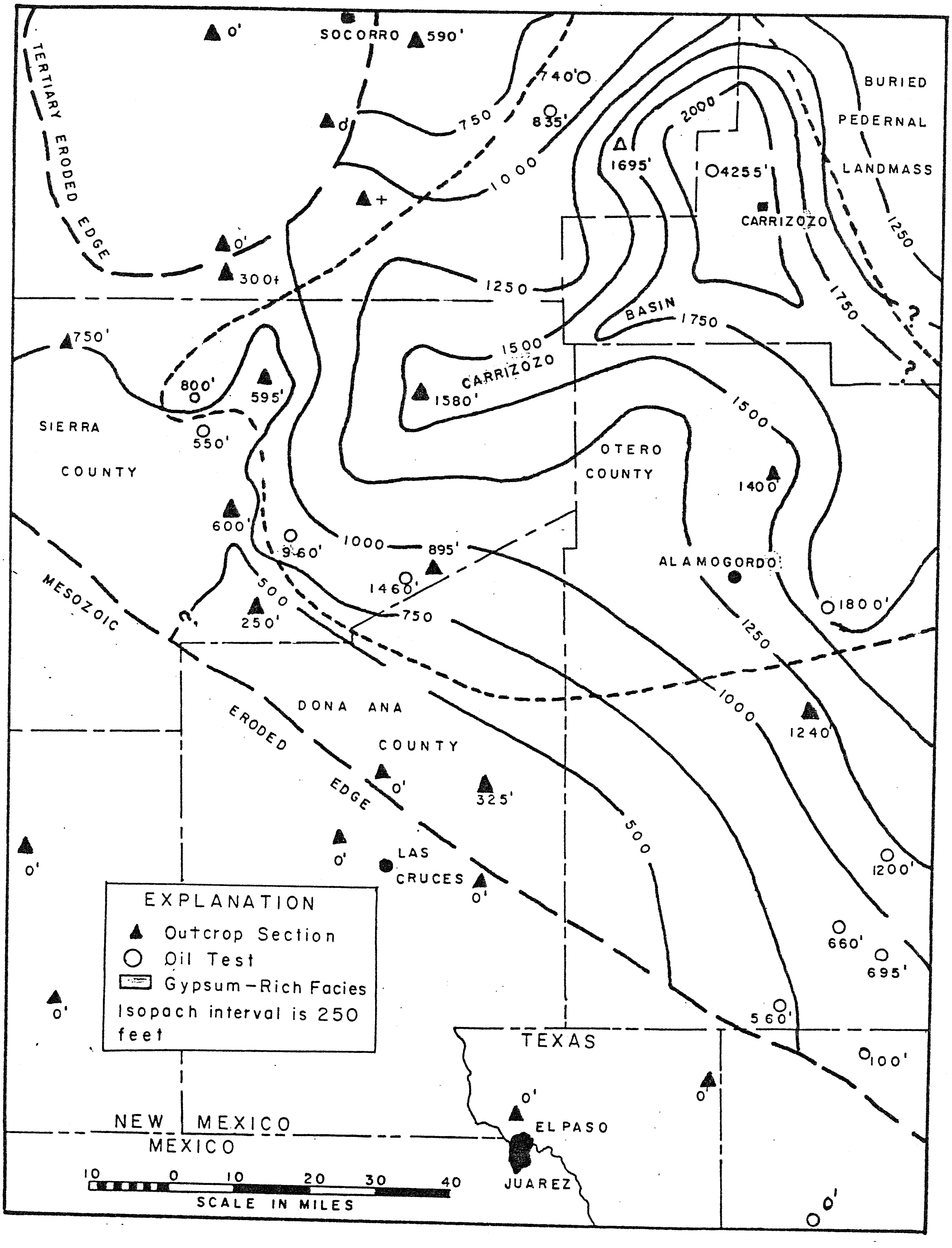


Figure 6. Isopach map of the Yeso Formation in south-central New Mexico (modified from Kottlowski, 1963, Fig. 15).

Table 1

	Tularosa Canyon (Northern section)	Orendorf Peak (Southern section)
Limestone	25 %	45%
Dolomite	0.1%	2%
Sandstone	1 %	5%
Siltstone	1 %	4%
Shale, and silty shale, gray and buff	13 %	20%
Shale (mudstone), pink and reddish	13 %	10%
Mixed gypsum and shale	28 %	2%
Gypsum	19 %	7%

Lithologic variations in the Yeso Formation from north to south in the Sacramento Mountains (from Pray, 1961, p. 112)

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.

Griswold (1959, p. 110) appended a log of the Standard of Texas No. 1 Heard Well by Roy W. Foster, in his report on the mineral deposits of Lincoln County, New Mexico. This well, located in Section 33, T.6S., R.9E., totals 8,049 feet and penetrates 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. Weber attributes this unusual thickness of Yeso to close folding which might be associated with plastic flow of the halite beds. Very little structural and areal data can be obtained since the Heard test is the only well to penetrate this particular feature.

To the northeast in the Gallinas Mountains, Perhac (1970, p. 10) reports that the Yeso Formation may be anywhere from 1,000 to 2,300 feet thick. Perhac assumed fifteen hundred feet to be a reasonable estimate. An interesting feature of the Yeso in this region is the near-lack of gypsum. Fine-grained, feldspathic sandstone constitutes 90 percent of the formation with the remaining 10 percent consisting primarily of dolomitic limestones, shales, and siltstones. Only one bed of gypsum is reported to crop out, this being at the southern end of the mountains. Since the Glorieta Sandstone (quartz sandstone deposited between Yeso and San Andres) is the youngest stratum found in this area, the San Andres does not exist.

Evidence for solution of evaporites

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

Weir (1965, p. 19) identifies 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) presents the most complete description of solutioning in the Yeso in his paper on the geology of the Carrizozo Quadrangle, New Mexico. As reported by Weber, surface water drains into solution cavities in gypsum and limestone on the west side of the Malpais lava flow. These waters may 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 basalt 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. Weber has recorded dips as steep as 65 degrees, but they generally vary between 5 and 10 degrees. One section of the basalt flow collapsed into a solution cavity 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 accelerate the solution of the underlying Quaternary, lacustrine, saline deposits by damming storm waters which flow westward from the Sacramento Mountains. Herrick reported many sinkholes and caverns where arroyos from the east encountered these dunes.

Basin fill

Basin fill, as discussed here, refers to the unconsolidated rocks of the basin interior which were deposited by alluvial, lacustrine, and eolian agents. Strain (1969, p. 122) suggests 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 scarce. Most data refer to the eastern and northern portions of the basin owing to the population distribution and the corresponding demand for water wells.

McLean (1970, p. 17) reports possible thicknesses of alluvium as 8,000 feet at the southern end of the basin, 3,000 feet south of Alamogordo, and 5,000 feet southeast of

Rhodes Canyon. In several of his maps of the Tularosa Basin, McLean (Figs. 2, 5, 23) shows the elevation of the bedrock, to be 2,000 feet above sea level in the area of Lake Lucero. The valley fill here must be about 1,900 feet, since the elevation of the playa is 3,900 feet. Hood (1959, p. 247) attributes much of the variation in thickness to the fact that deposition took place in a structural trough with an irregular surface.

Davis and Busch (1965) report data from three test wells drilled in sections 17, 21, and 28 of T.19S., R.5E. The log of the well drilled in section 17 (MAR test well 1) is representative of all three wells and is shown in Table 2. The rocks obtained from this well, totalling 1,000 feet give no indication of approaching the basement.

Data reported from test wells, and information contained in McLean's report indicate a thickness of unconsolidated basin fill in the Lake Lucero vicinity on the order of 2,000 feet with, basins to the north and south having up to 5,000 and 6,000 feet of fill respectively.

Table 2

Log of MAR 1 Test Well
(from Davis and Busch, 1965, Table 17)

Material	Thickness (ft)	Depth (ft)
Gravel, granule to pebble and some course sand. Particles are subangular to rounded and consist of limestone, dolomite, chert, vein quartz and igneous rock. Some caliche cement	0	112
Clay, tan, gravel, and coarse sand	18	130
Clay, tan, some fine to very fine sand	15	145
Clay, tan	10	155
Clay, tan and large gravel	5	160
Gravel, little clay	5	165
Clay, tan, with imbedded pebbles	5	170
Clay, tan, and granule to pebble gravel	30	200
Gravel, pebble, and some clay	10	210
Clay, tan, and some gravel	5	215
Clay, tan	10	225
Clay, tan, and pebble gravel, some sand	30	255
Gravel, pebble, tan clay and some coarse sand	15	270
Clay, tan and pebbles	10	280
Clay, tan	5	285
Gravel and some clay	5	290
Gravel, pebble	10	300

Table 2 (continued)

Material	Thickness (ft)	Depth (ft)
Clay, tan, and some pebbles	5	305
Clay, tan and pebble gravel	15	320
Gravel and clay	10	330
Clay and gravel	25	355
Gravel, and tan and white clay	10	365
Clay, tan, granules and some coarse sand	20	385
Gravel and clay	10	395
Clay, tan and some granule to pebble gravel	55	450
Gravel and white, green and tan clay	10	460
Clay and some granules to pebble gravel	75	535
Gravel, granule to pebble, and clay	10	545
Clay, tan, and a few granules	45	590
Gravel and clay in beds 4 to 5 inches thick	10	600
Clay, tan, and a few granules	20	620
Gravel, granule to pebble, and clay	10	630
Clay and a few granules	40	670
Clay, tan, with streaks of white sandy, silty clay	5	675
Clay, tan, and a few granules	45	720
Clay	30	750
Clay and gravel	35	785

Table 2 (continued)

Material	Thickness (ft)	Depth (ft)
Clay	20	805
Clay and some gravel	35	840
Clay	20	860
Clay and fine sand	55	915
Clay	30	945
Clay and very fine sand, and few granules of limestone	5	950
Clay	10	960
Clay, hard	20	980
Clay	10	990
Clay and gravel	10	1000

GEOLOGY OF LAKE LUCERO AND THE ADJACENT WHITE SANDS AREA

Areal geology and geomorphology

The geologic map accompanying this report (Plate 1) is based on field investigation, 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 construction of the map considerably. The following map units are discussed in their approximate order of formation.

Alluvium The areas mapped as alluvium are primarily alluvial fan deposits. These deposits contain unconsolidated, cobble- to clay-sized, heterolithic rocks derived from the San Andres Mountains. The material west of Section 2, T.18S., R.5E. 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. 2) have mapped some dune lands in the area I have termed alluvium. They describe the dunes as consisting of 75 to 95 percent silica sand, averaging 3 to 10 feet in height and being reddish-brown in color (Neher et al., p. 63). The sand forming these dunes is derived from the alluvial fans and stream channels.

I believe that the primary mode of transport for these sands is alluvial, however eolian processes undoubtably played a role in the formation of these mesquite capped mounds (Fig. 7). Since this is an open area the sand size particals in the alluvium are subject to eolian transport. When the wind encounters a mesquite bush, its force is diminished and the sand is deposited. Thus the sand builds up around the mesquite bushes as they grow, until some have attained heights of over 10 feet.

Lacustrine Deposits Herrick (1904, p. 179) identified several stratigraphic units in the Lake Lucero area, one of which is the "Otero marls". He describes 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 Yeso and San Andres marine evaporites. These "Otero marls" are therefore equivalent to my lacustrine deposits.

Herrick estimated that Lake Otero covered 1,600 to 1,800 square miles at its greatest extent. Weber and

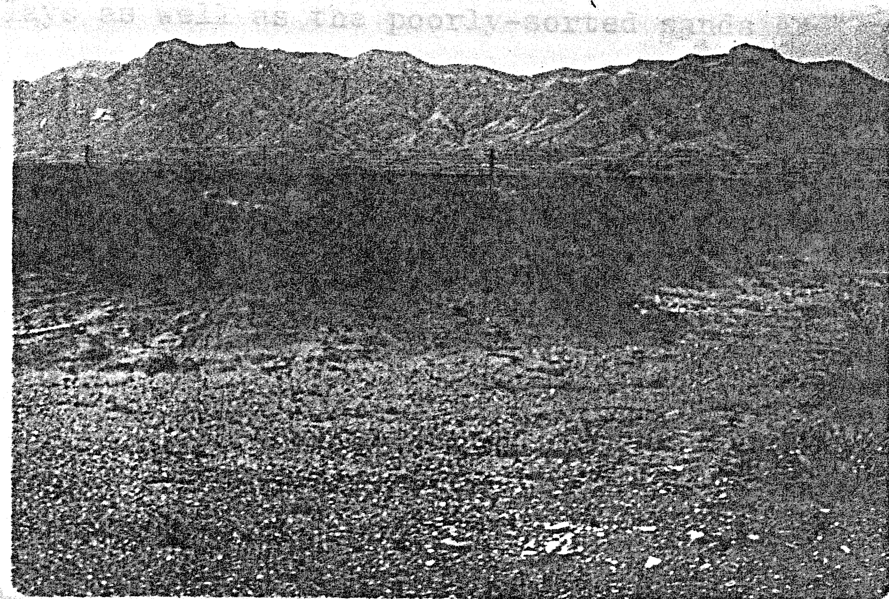


Figure 7. Mesquite-capped mounds as they occur west of Lake Lucero.

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. It is my interpretation that this sequence (similar to that found in the log of MAR test 1) 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.

Lateral variation found in this sequence also supports this hypothesis. The average grain size decreases from west to east, and bedding becomes well defined (Fig. 8). 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-grey 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.

acustrine and Eolian Deposits These deposits found n the north and central sections of the thesis area are issected lacustrine deposits, similar to those just escribed, capped by eolian dune deposits of primarily ypsiferous content. These dunes may correlate with the ld dune field located in the southeast of the study area. eflation has carved a relief in this region great enough) expose many lacustrine deposits which underlie in places ; to 20 feet of eolian deposits (Fig. 9). These eolian eposits were once probably actively migrating dunes imilar to those now found to the east. At the present he strong southwest winds are gradually reducing them to he level of the surrounding alkali flats. Cross-bedding s very obvious in these deposits of light, reddish-brown ypsum sands, and small blowouts are common.

Figure 8. Well-defined, horizontal bedding as exposed in an impact crater on the playa.

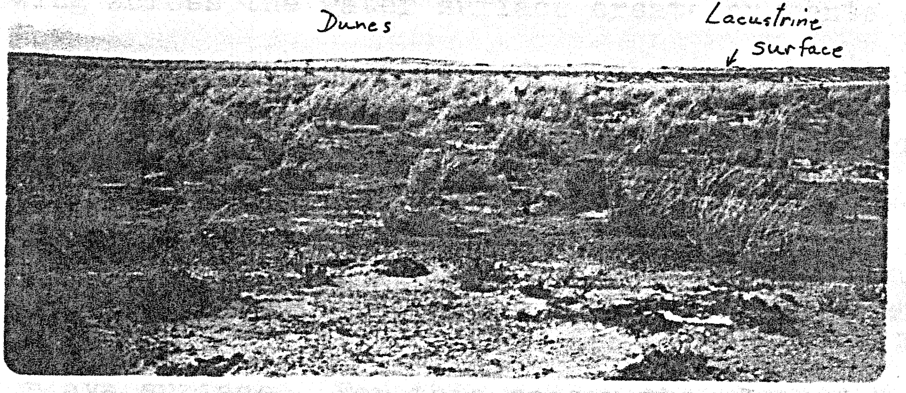


Figure 9. Dunes on old lacustrine surface.

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

The surface water which does reach the playa brings n 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 below. 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. A more detailed description of the processes which take place at the playa surface follows in the section on surface hydrology.

During most of the year, when the playa is not flooded, it becomes a surface of deflation. This is evidenced by the occurrance of 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.

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 lacustrine deposits of

Lake Otero, both have very low gradients and both are subject to the processes imposed on them by saline 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. Occasional playa depressions occur in the flats to the north, however none are as large as Lake Lucero.

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. 10).

Selenite Crystals The selenite crystal horizon closely follows the marginal zone between lacustrine and alluvial deposits. This occurrance undoubtedly 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

Figure 10. Aerial photograph of large blowout. Note well-developed blowout dunes.

they are light-grey 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) describe 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 about 25 miles northeast of Brownsville, Texas, from the Gulf of Mexico. The presence of this long island, low precipitation and runnoff, and high evaporation-potential combine to isolate the lagoon from any significant source of non-saline water and to concentrate the already saline sea water.

Nearly half of the over 600 square miles of this lagoon is exposed during low water. Strong winds create water level variations of 3 to 4 feet, often flooding much of these mud flats. Fine terrigenous material, marine clays, and eolian, fine sands and silts from Padre Island make up the bulk of these mud flats.

Within the deposits of these mud flats occur several types of gypsum which Kerr and Thomson classified as bladed crystals, rosettes and thin beds. Bladed crystals and rosettes increase in size downward from less than 0.5 mm near the surface, to 3 to 4 inches at a depth of a few feet for the bladed crystals and up to 20 inches for a rosette collected at a depth of 15 feet.

Kerr and Thomson (p. 1729) attribute this occurrence of selenite to direct precipitation from subsurface waters having a high salinity. Wind-driven waters, already high in dissolved solids, flow in thin sheets across the flats. The high evaporation increases the concentrations of these waters to salinities averaging 140°/oo (parts per thousand) before infiltration. This water then infiltrates and mixes with ground water which is also highly charged with dissolved solids. Kerr and Thomson believe the selenite precipitates from this mixture of subsurface waters which average 200°/oo salinity. This is a reasonable assumption since gypsum precipitates when salinities increase beyond normal sea water (about 35°/oo) by about 3½ times. The existance of crystals only in the subsurface also supports this hypothesis.

I believe that the present environment at Laguna Madre is very similar to the environment in which the Lake Lucero selenite formed. At Laguna Madre the crystals which form in clay and mud grow by pushing aside the matrix while incorporating very little clastic material. Thus these crystals are relatively clear and transparent. The crystals growing in sand, however, grow by incorporation of the clastics, creating "sand crystals."

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. 11 and 12)

The environment which I have envisioned for the formation of these crystals at Lake Lucero is depicted in Figure 13. 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 formed in a marginal terrestial and saline water environments; both developed into large crystals and rosettes, and both incorporated sand-size particles while pushing aside finer matter. For these reasons I believe that the Laguna Madre deposits may be a modern day illustration of the selenite beds at Lake Lucero.

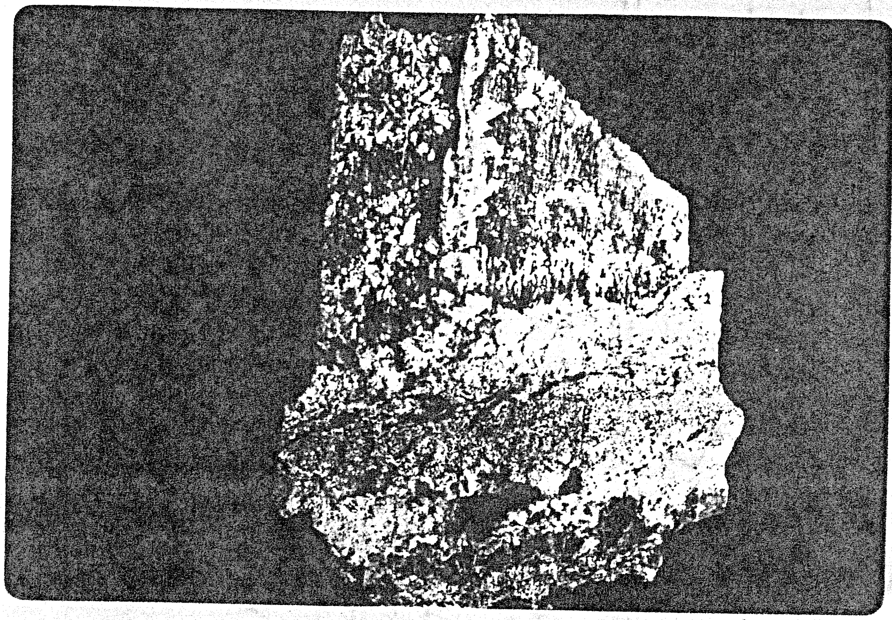


Figure 11. Gypsum crystal showing sand inclusions.

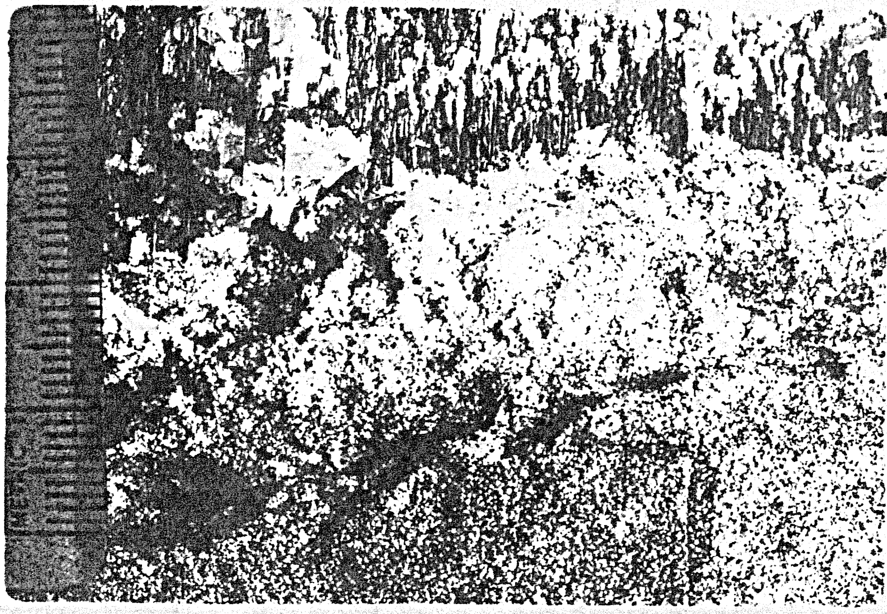


Figure 12. Close up of above crystals.

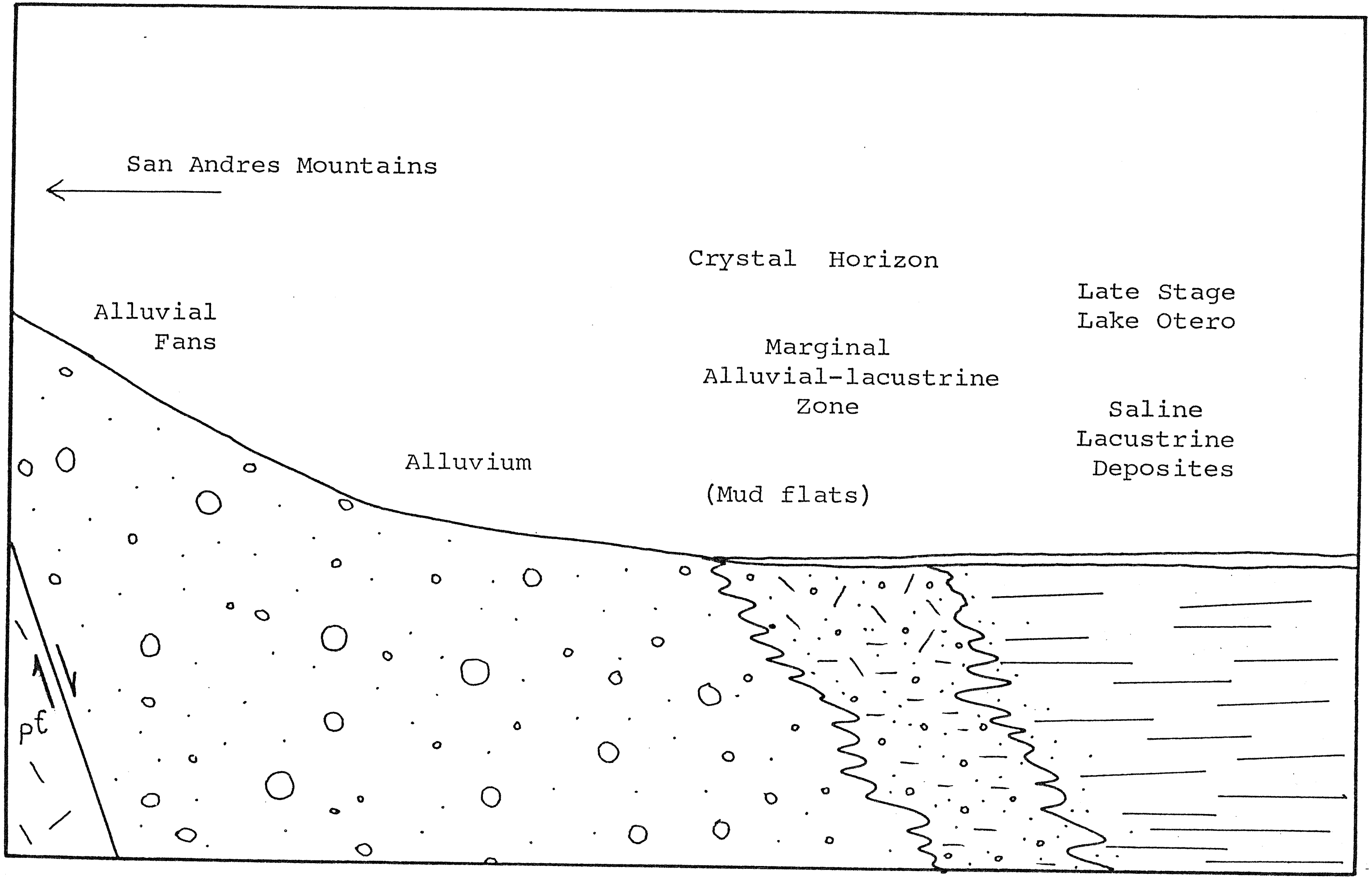


Figure 13. Environment of formation of large selenite crystals.

Sand Dunes and Interdunal Plains I used aerial photographs exclusively in mapping the sand dunes and interdunal plains. The strong contrast afforded by the White Sands simplified this procedure greatly. Little work has been done with respect to these dunes because McKee did such a definitive study of them in his paper on the dune structures of the White Sands (McKee, 1966). The interdunal plains are areas that, at present, are devoid of any significant 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

In the spring of 1969, 51, four-inch test holes were drilled by truck mounted, continuous-flight auger around the periphery of Lake Lucero (Fig. 14). These holes, drilled for hydrologic purposes, supplied stratigraphic data in the form of grab samples taken at five-foot intervals.

Most samples show gypsum 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

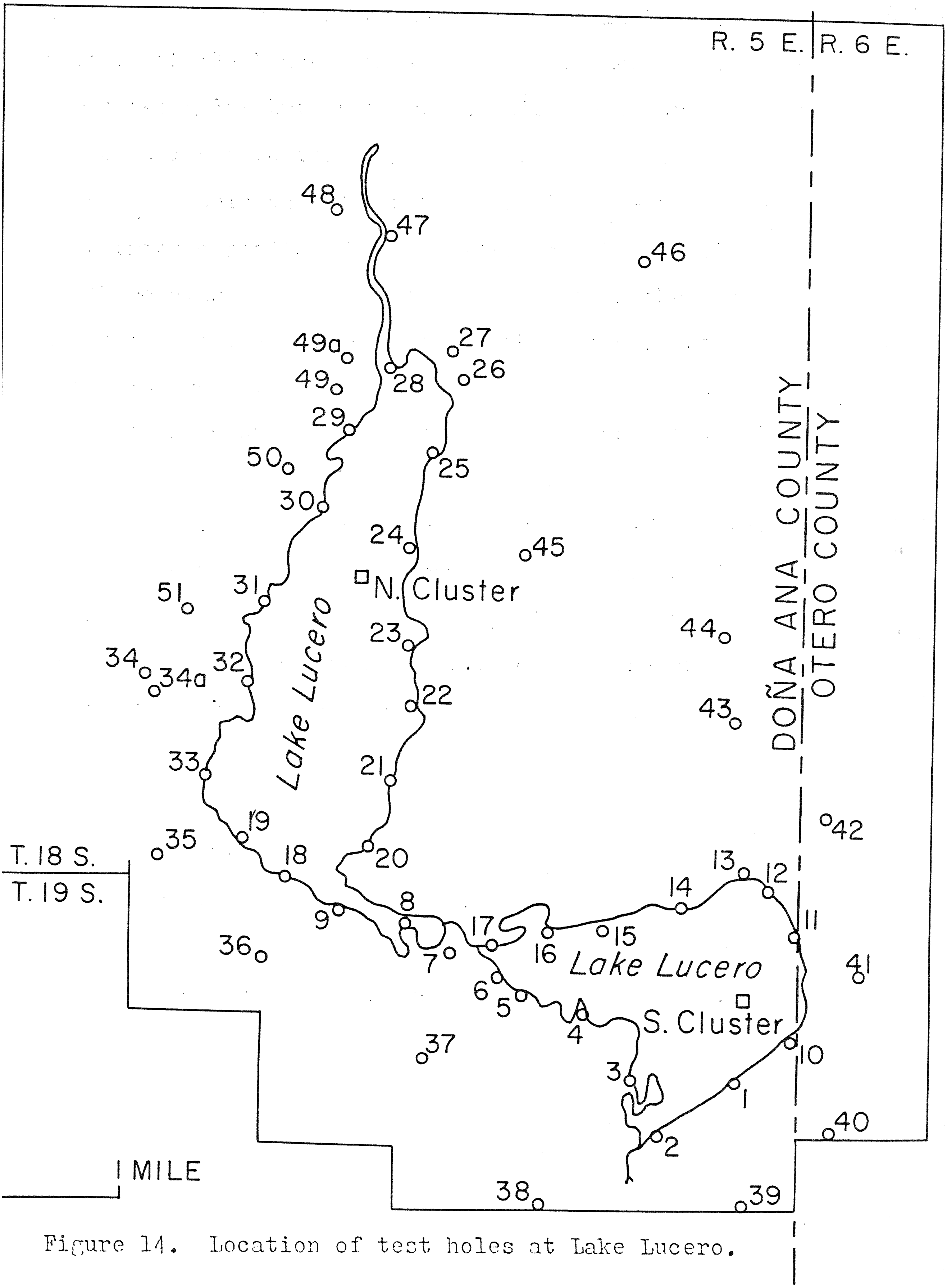


Figure 14. Location of test holes at Lake Lucero.

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 the Lake Otero saline deposits discussed earlier (Fig. 8).

Below this unit lie more typical (non-evaporite) 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 or 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 comprizing the White Sands. Observations of some of the lacustrine deposits surrounding the playa show that this type of gypsum is indeed very abundant (Figs. 15 and 16).

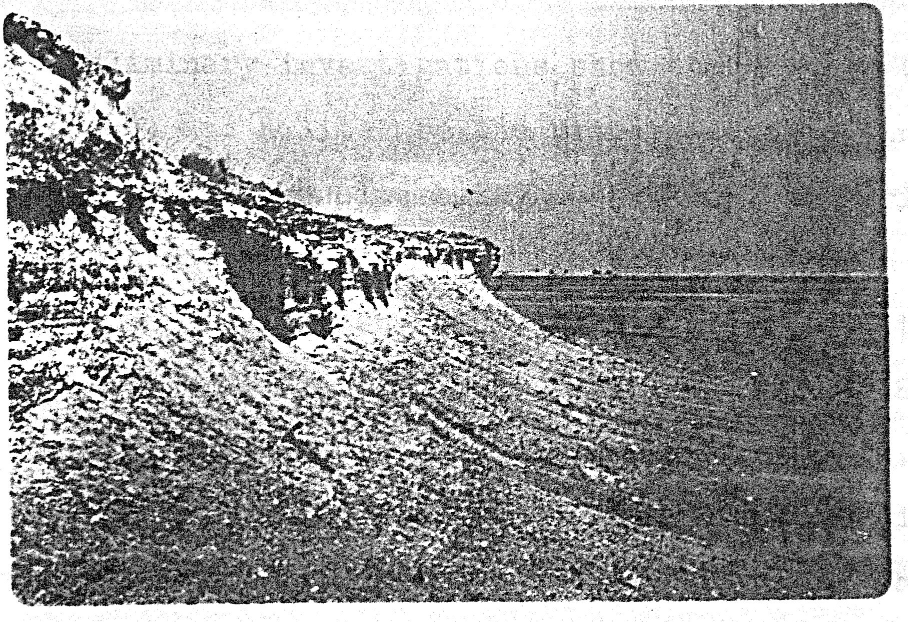


Figure 15. Outcrop of crystalline lacustrine deposits on western margin of playa.

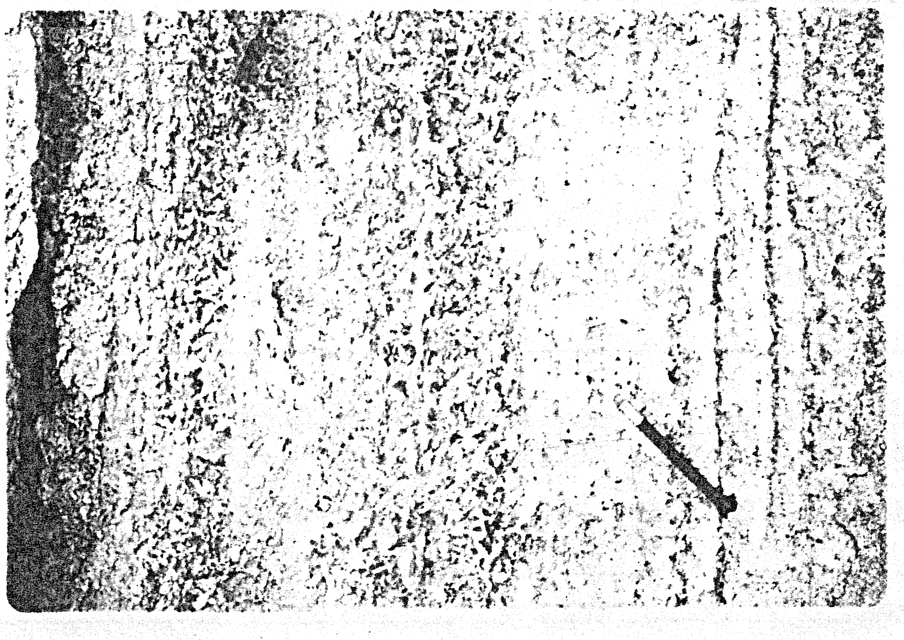


Figure 16. Close up of crystalline lacustrine deposits.

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) note 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.

The x-ray fluorescence data show that calcium and sodium are the major cations as would be expected (Table 3). Although the absolute numbers in Table 3 are questionable, the relative values are meaningful.

Sample Number	Na_2O %	CaO %	K ppm	MgO %	Fe_2O_3 ppm	S %	SiO_2 ppm	Zn ppm	Sr ppm	Ti ppm
20	2.33	5	450	3.95	1,705	19.55	16,000	515	2,140	5
25	-	38.15	335	0.30	414	20.3	11,000	448	1,300	268
27	-	38.62	190	-	95	21.3	195	450	120	268
28	-	35.02	350	2.50	385	19.6	19,000	438	2,100	350
29	0.06	7.0	high	5.45	13,000	14.0	128,000	450	890	1,360
30	C.22.0 (high)	1	-	-	193	19.5	-	490	390	-
31	-	34.66	high	-	485	19.2	9,500	447	1,040	-
32	-	1	425	2.48	18,700	?low	396,000	449	430	high
33	?	32.73	?	0.09	$+Al_2O_3$ 0.23	SO_3 46.62	insoluble 0.37	?	?	?

20 Hole #25 depth 10-15' (bulk sample)
25 From old sand dunes (yellow-brown)
27 Yellow-brown selenite crystal, SW lake shore
28 Lacustrine gyp - 4-6" below south playa surface
29 Puffy crust near hole #28
30 Hard, white crust between holes #25 and 26
31 White sand dunes
32 Quartz sand from hole #C-100, depth 80-85'
33 Sample 16, Table 1 - Weber and Kottlowski, 1959 (from White Sands Dune Field).

Table 3. X-ray fluorescence data.

HYDROLOGY OF THE TULAROSA BASIN

Theory of regional ground-water motion

Darcy's Law governs the most basic motion of ground-water flow. It states that ground water, like everything else in nature, tends to move towards areas of lower energy. Potential energy, related to differences in hydraulic pressure between two points, constitutes the vast majority of energy involved with ground-water motion. This potential energy can be measured by hydraulic head (h).

Ground-water moves from areas of higher hydraulic head to areas of lower hydraulic head. This outwardly simple statement contains the basis for all ground-water motion. The equation

$$\phi = gz + \int_{Po}^{p} dp/\rho$$

where p = gage pressure, Po = atmospheric pressure, z = elevation of p above arbitrary datum, ρ = density of water, g = gravitational constant, and ϕ = fluid potential, represents the force of energy involved in this motion.

Equipotential lines represent surfaces of equal potential in two dimensions. By definition, water moves perpendicularly to lines of equal potential. Flow nets graphically depict the two-dimensional dynamics of ground water (Fig. 17).

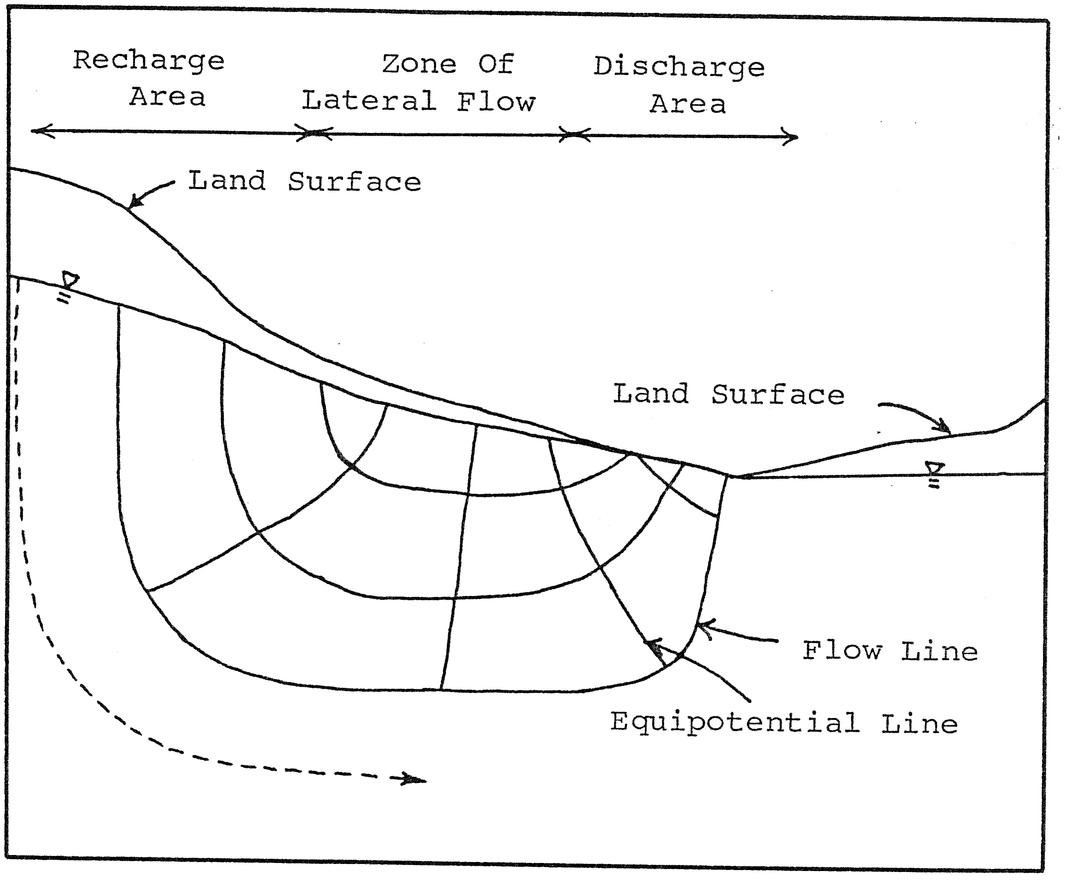


Figure 17. Idealized flow system diagram (from Maxey, 1968, Fig. 1).

The idea of ground-water divides and drainage basins is another important concept in regional ground-water motion. Topography does not always strictly define drainage basins for subsurface waters as it does for surface waters. Ground-water divides do separate subsurface drainage basins; the flow at the divide being vertical.

J. Toth (1962) discussed the following ideas on regional ground-water motion.

The drainage basins in his study area (central Alberta, Canada) are symmetrical around the divides and valley bottoms. This, plus the fact that the only source of recharge in the basins is rainfall, leads to the idea that the fluid potential in a basin is also symmetrical. This distribution of potential makes it possible to set up imaginary, impermeable, vertical boundaries at the divide and valley bottom of a basin.

Using these boundaries, Toth developed a general equation which accounts for all parameters involved in fluid motion in a permeable medium. The solution of this equation by a digital computer gives the fluid potential under varying conditions. Toth used this method to develop a potential distribution and flow net for two particular cases (Figs. 18 a and b). Figure 18a differs from Figure 18b only in the vertical distance to the horizontal, impermeable, lower boundary.

The most obvious result of this work, easily noted in Figure 18b, is the symmetrical relationship around the mid-line of the valley slope. The flow lines at this mid-point essentially parallel the water table and increase in angle upward to ninety degrees at the divide and valley bottom. The concavity of these flow lines indicates that flow concentrates near the divide and valley bottom and that this concentration decreases with depth.

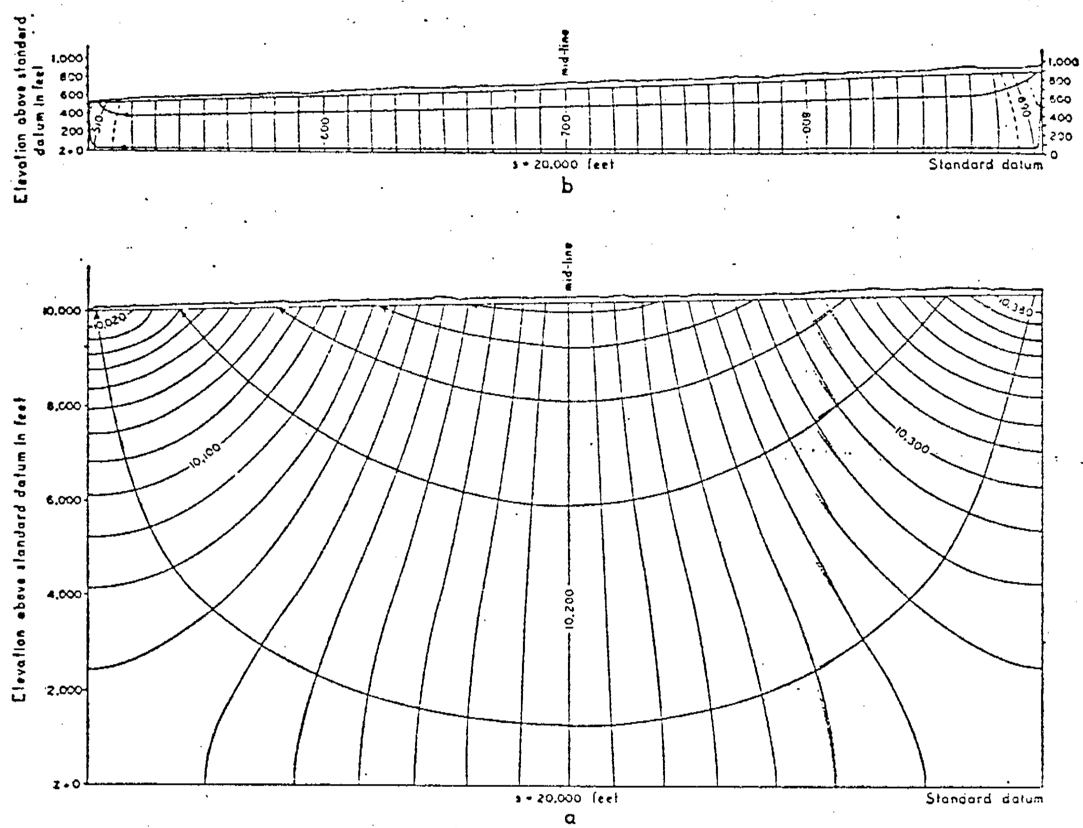
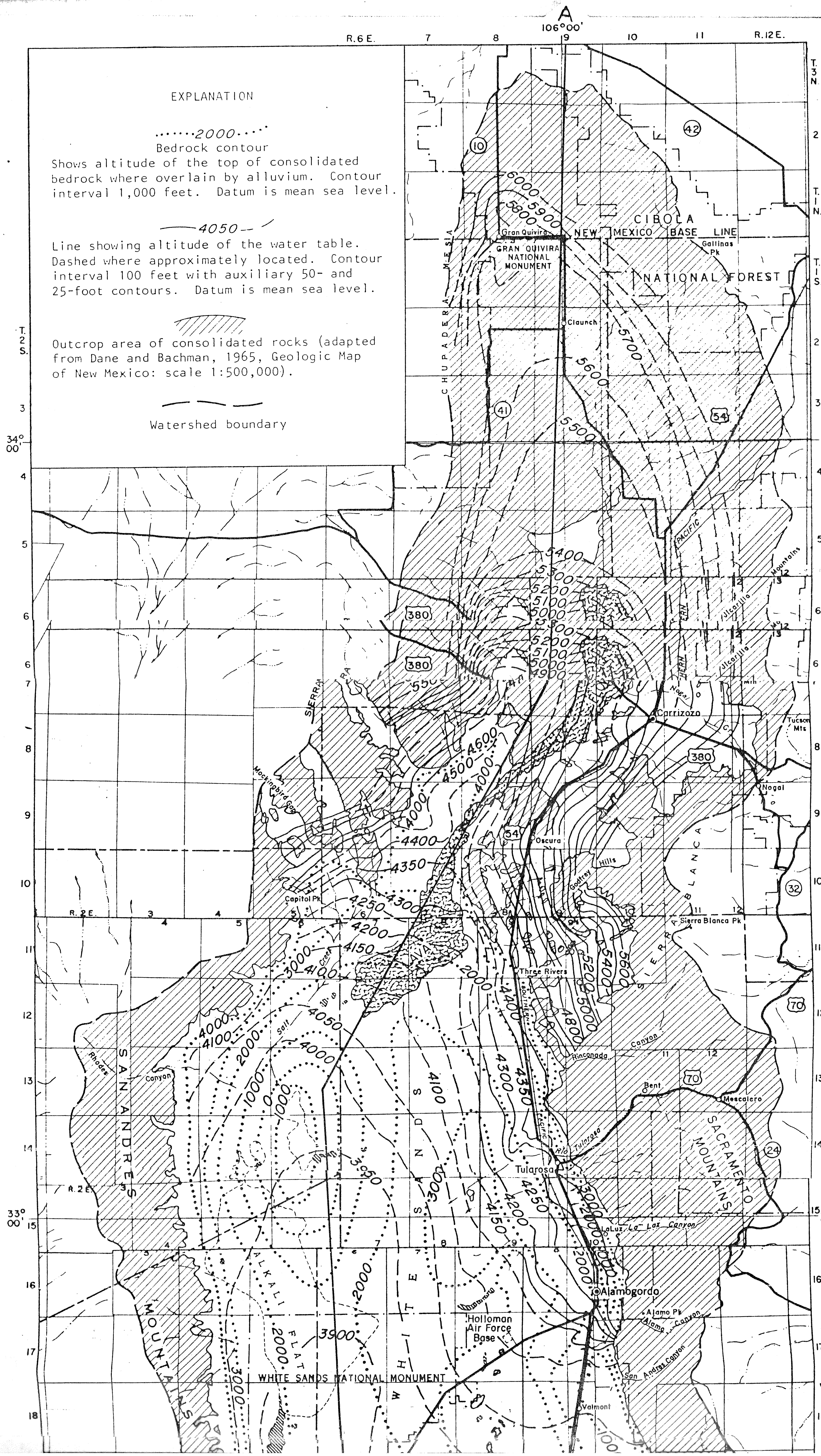


Figure 18. Two-dimensional theoretical potential distributions and flow patterns for different depths to the horizontal impermeable boundary (Toth, 1962, Fig. 3).

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

McLean has mapped the water-table configuration for the Tularosa Basin as well as the bedrock, surface topography and watershed boundaries (Fig. 19). Assuming that the watershed boundaries approximate ground-water divides I can draw a first approximation of the water-table


EXPLANATION
2000
Bedrock contour
Shows altitude of the top of consolidated bedrock where overlain by alluvium. Contour interval 1,000 feet. Datum is mean sea level.
4050
Line showing altitude of the water table. Dashed where approximately located. Contour interval 100 feet with auxiliary 50- and 25-foot contours. Datum is mean sea level.
Outcrop area of consolidated rocks (adapted from Dane and Bachman, 1965, Geologic Map of New Mexico: scale 1:500,000).
Watershed boundary
A
106°00'
R.6 E.
R.12 E.
R.2 E.
T.3 N.
T.1 N.
T.1 S.
T.2 S.
34° 00'
33° 00'
NEW MEXICO BASE LINE
CIBOLA
NATIONAL FOREST
Gran Quivira
GRAN QUIVIRA NATIONAL MONUMENT
Gallinas Pk
Claunch
CHUPADERA MESA
Carrizozo
Nogal
Tucson Mts
Jicarilla Mountains
SIERRA BLANCA
Sierra Blanca Pk
Oscura
Godfrey Hills
Three Rivers
Capitol Pk
Mockingbird Gap
Rinconada
Canyon
Bent
Mescalero
SACRAMENTO MOUNTAINS
Tularosa
La Luz
Alamogordo
Alamo Pk
Holloman Air Force Base
WHITE SANDS NATIONAL MONUMENT
ALKALI FLAT
SAN ANDRES MOUNTAINS
Rhodes Canyon
San Andres Canyon
Valmont
SOUTHERN PACIFIC

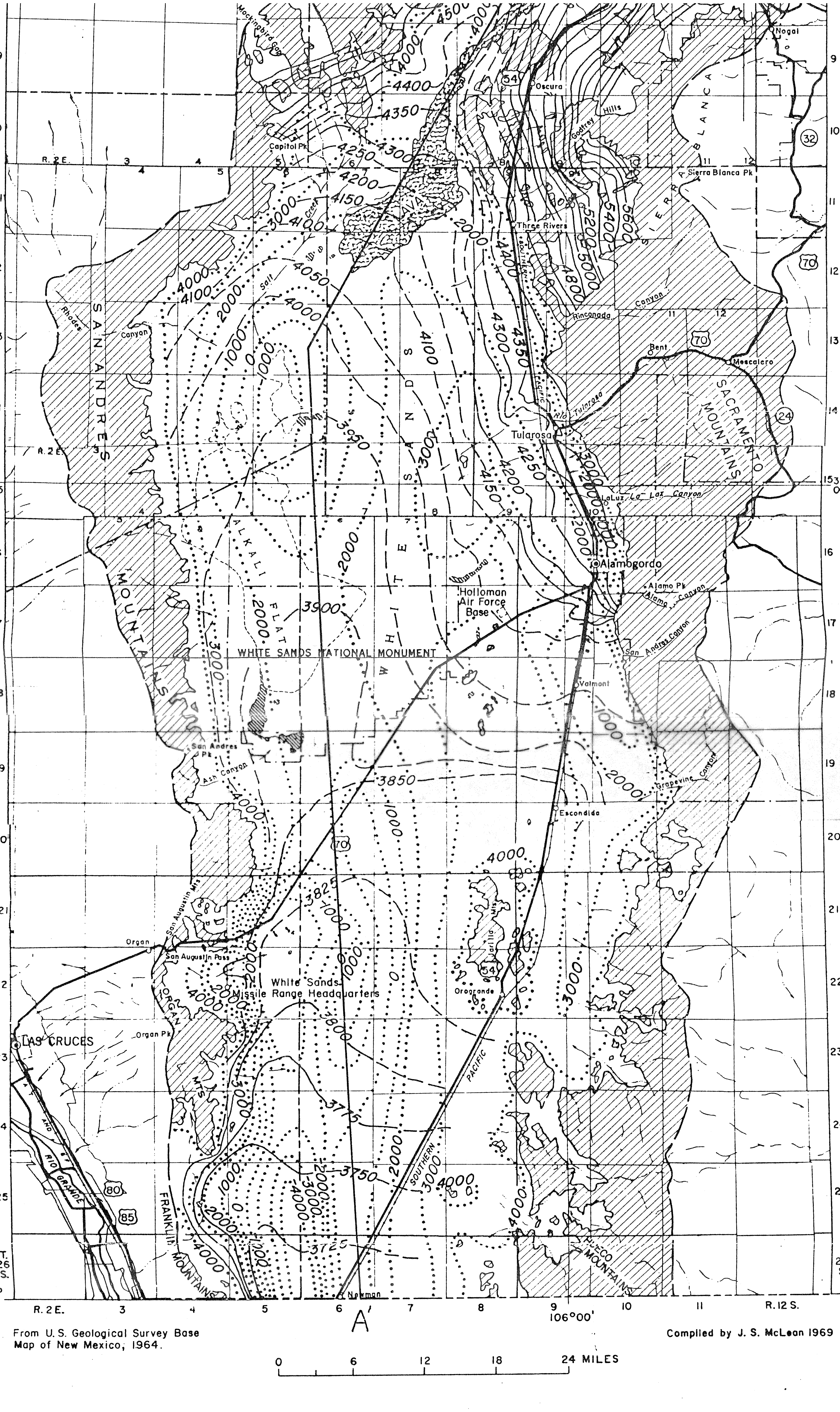


Figure 19--Altitude of the water table and altitude of the top of consolidated bedrock.

profile and accompanying flow net (Fig. 20).

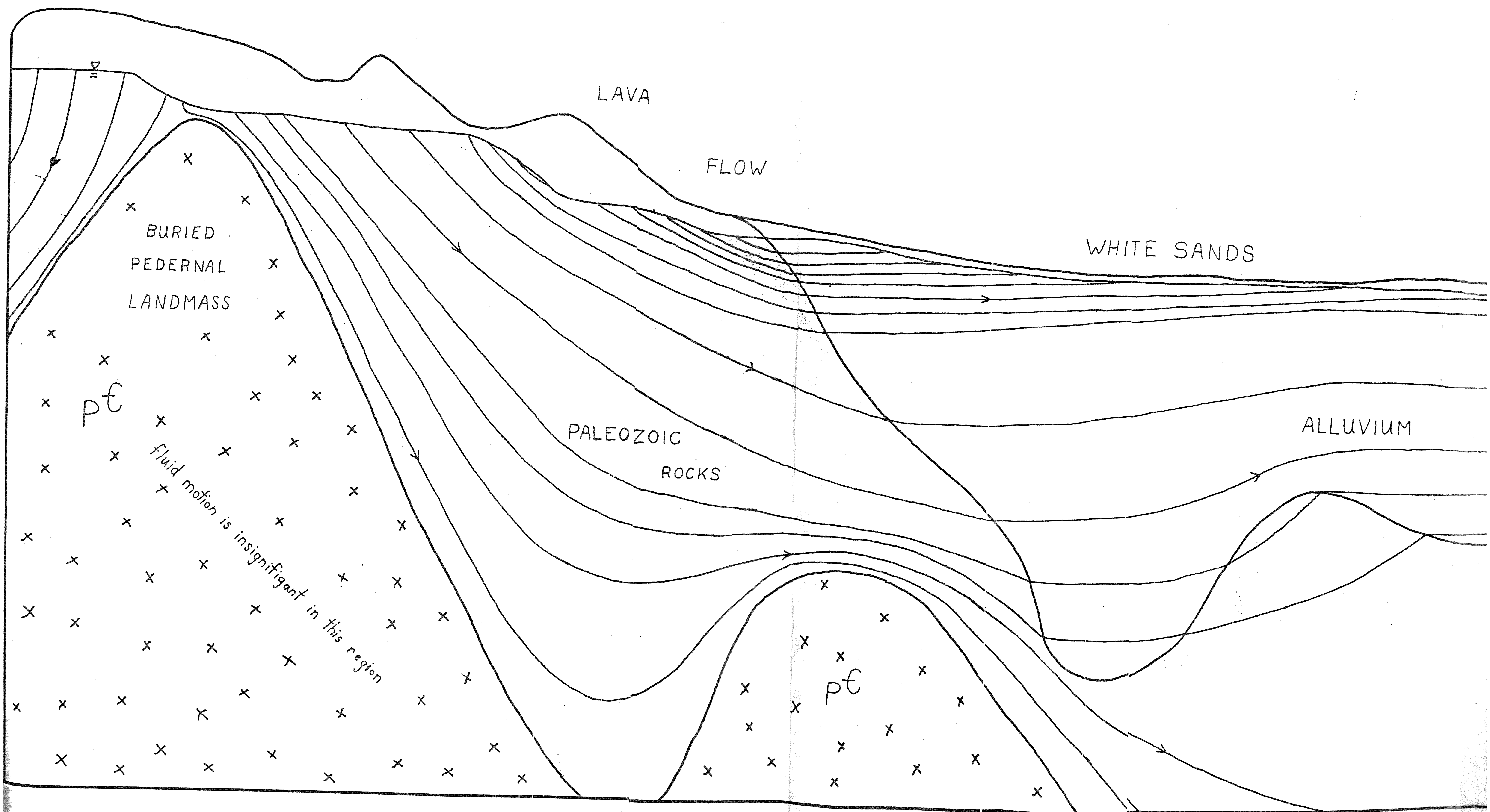
The flow net shows some interesting points. The Permian evaporites primarily lie in recharge areas and are thus susceptible to much solution. Recharging ground water is chiefly derived from meteoric water and consequently has a low initial dissolved solids content. This explains why solution cavities are common in the north and east margins of the basin where evaporites occur near the surface in recharge areas.

Figure 20 also shows the effect of the geology on the flow pattern. The buried Precambrian rocks and the Paleozoic rocks restrict flow to varying degrees. Flow lines have been omitted from the Precambrian because, although there is some fluid flow in this region, it is very insignificant when compared with the amount of flow in the alluvium and Paleozoic rocks.

There is a distinct refraction of the flow lines towards the horizontal where they cross from the less permeable paleozoic rocks to the more permeable alluvium. This refraction, when combined with the "bottle-necking" effect of the Paleozoic high below the White Sands gives the ground water an upward component of movement. This upward component is increased in the vicinity of Lake Lucero by the occurrence of the very low permeability lacustrine deposits (Fig. 21).

McLean's water-table map suggests the possibility of a water-table depression in the vicinity of Lake Lucero.

A


LAVA
FLOW
WHITE SANDS
BURIED
PEDERNAL
LANDMASS
pЄ
fluid motion is insignifigant in this region
PALEOZOIC
ROCKS
ALLUVIUM
pЄ

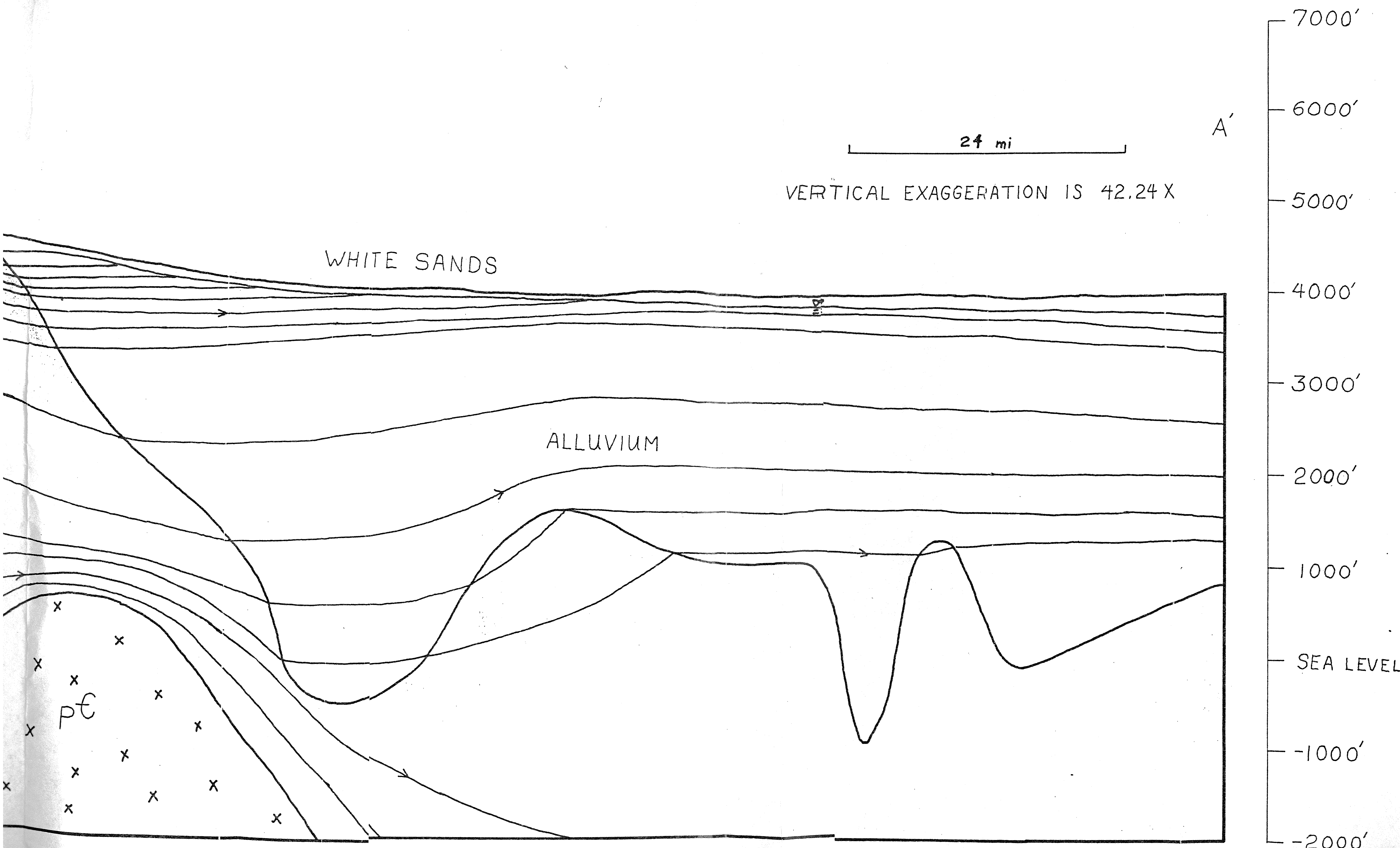


Figure 20. Cross section along line A-A' on Figure 1 showing topography, geology, water-table elevation, and probable flow lines.

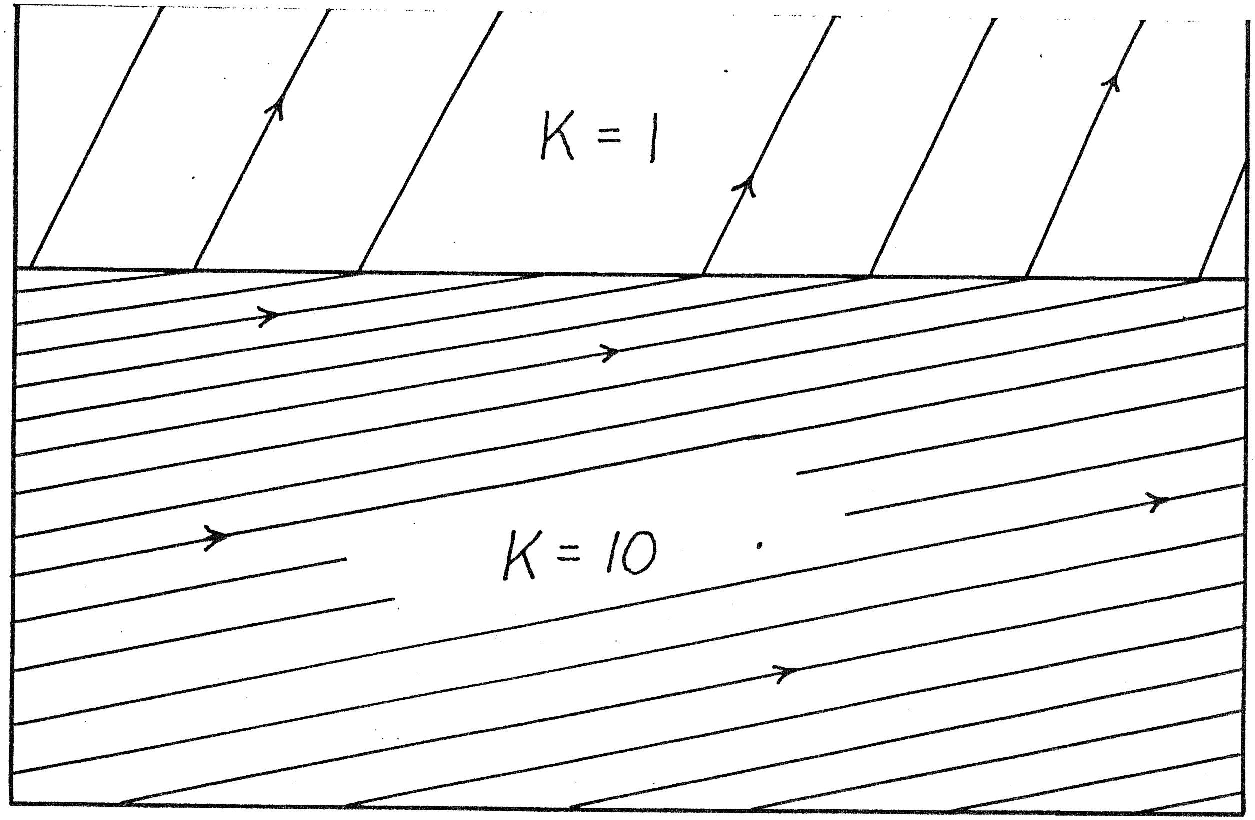


Figure 21. Detail of flow pattern below Lake Lucero showing diffraction through lacustrine deposits.

more detailed survey of water levels shows that there is deed a water-table depression. This information was tained from water levels measured in the test holes lustrated in plate 2. Plate 2 shows the elevation of nd surface at the test holes, depth to water, and ter-table elevation, as measured in the spring of 1969. is represents the lowest position of the water table nce this project began because of flooding during the mmers of '69 and '70 and a consequent raising of the er-table. Figure 22 is a contour map of the water-table owing definite water-table depressions.

A depression in the water table indicates a ground er sink, similar to a cone of depression around a nped well. This means that ground water flows radially ard towards the center of the depression and upward ards the water table. This direction of movement is agreement with that indicated in Figures 18 and 19.

Ground water must therefore be lost at the land face. The most reasonable and likely explanation for s phenomenon is capillary rise and evaporation at the face. A shallow depth to water and very fine-grained, pact nature of the strata would facilitate this process would a high evaporation potential.

The water table, as shown in Figure 22, usually lies s than ten feet below the surface of the playa, and more monly falls between two and four feet below land surface. s is within the range of capillarity for the very fine

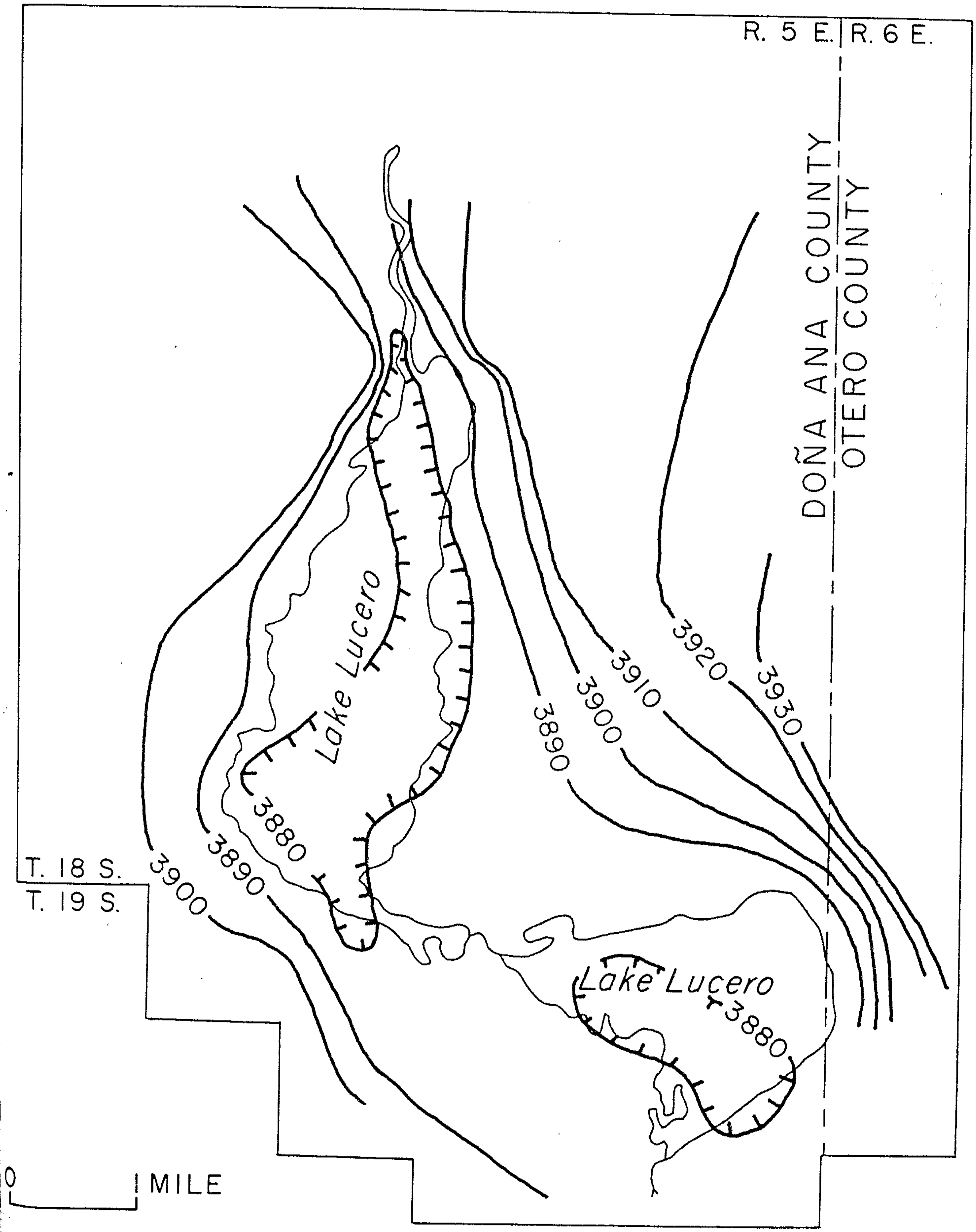


Figure 22. Contour map of the water table below the study area.

to silt size material material. Meinzer (1942) cites following correlation between sediment grain size and llary height (h_c) as reported by Atterberg (1908, p.?).

n size mm)	5-2	2-1	1-0.5	0.5-0.2	0.2-0.1	0.1-0.05	0.05-0.02
cm) er 72 ays)	2.5	6.5	13.1	24.6	42.8	105.5	200 (still rising)

grain size of the strata between the water table and land surface falls in the 0.05 to 0.02 mm range. Capillary height, or the capillary fringe, is higher e a falling water table than above a rising water e. Atterberg's data represents a rising water table e the Lake Lucero water table is usually falling een relatively short periods of recharge that occur the playa has standing water on it. Not enough data vailable to determine if a period of equilibrium lops where ground-water inflow equals discharge een periods of recharge. Regardless, the falling water e increases the likely capillary height to better than cm. The hygroscopic aspect of gypsum undoubtedly aids capillary process in producing capillary heads in ss of 200 cm. also. This more than suffices to supply to near the surface where evaporation takes place readily.

During the summer of 1970 I constructed a constant-ead lysimeter utilizing a Mariotte supply tank (Fig. 23). his apparatus was buried level with the land surface bout one-half mile northeast (downwind) of the weather tation on August 14, 1970. The lysimeter column 1.05 eters long (approx. 3.5 feet) and has a surface area of pproximately 325 square centimeters (about 50 sq. in.). he sediment in the column is a core of thinly bedded acustrine deposits taken in situ with as little disturbance s possible (Fig. 24). The Mariotte tank is constructed o as to allow adjustment of the water table in the ediment column. The water table was set at 76 cm. (2.5 t.) below land surface while the data for Figure 27 was eing collected. These data indicate that approximately 4 liters per sq. meter was lost by evaporation during the ½ winter months that the instrument was working.

The lysimeter will remain in operation through the all of 1971 in an effort to gain data for a complete ear. No correlations with the weather data have been ttempted yet.

This local region of ground-water discharge, indicated y the water-table configuration and lysimeter data, ictates that waters saturated with respect to certain ions ust precipitate the dissolved material at the time of vaporation. Precipitation may take place either above, elow, or at the water table. Many subsurface water amples collected from the test holes contain dissolved

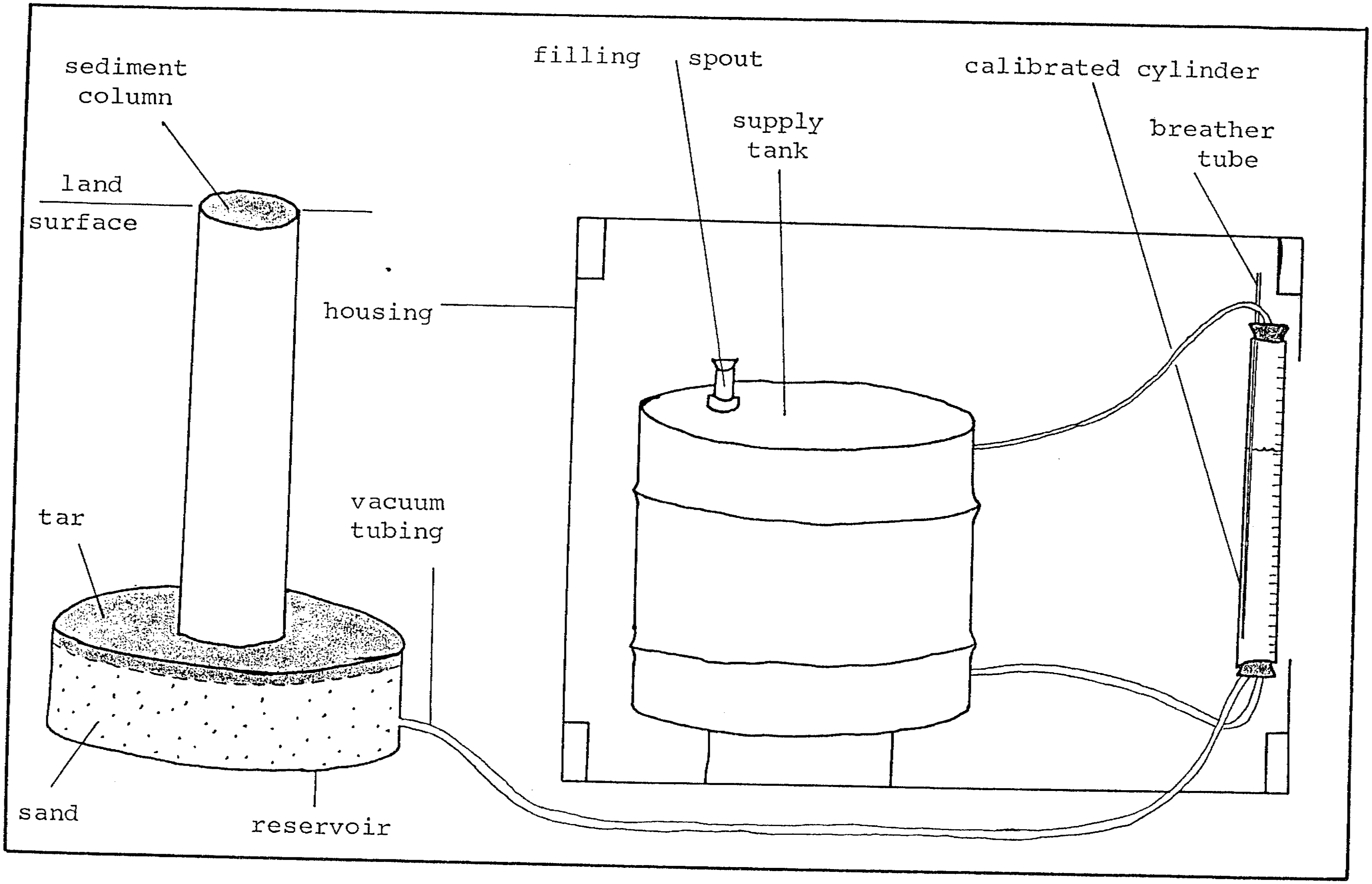


Figure 23. Sketch of constant-head lysimeter, housing, and Mariotte supply tank.

solids in excess of that required for saturation of gypsum (Table 4).

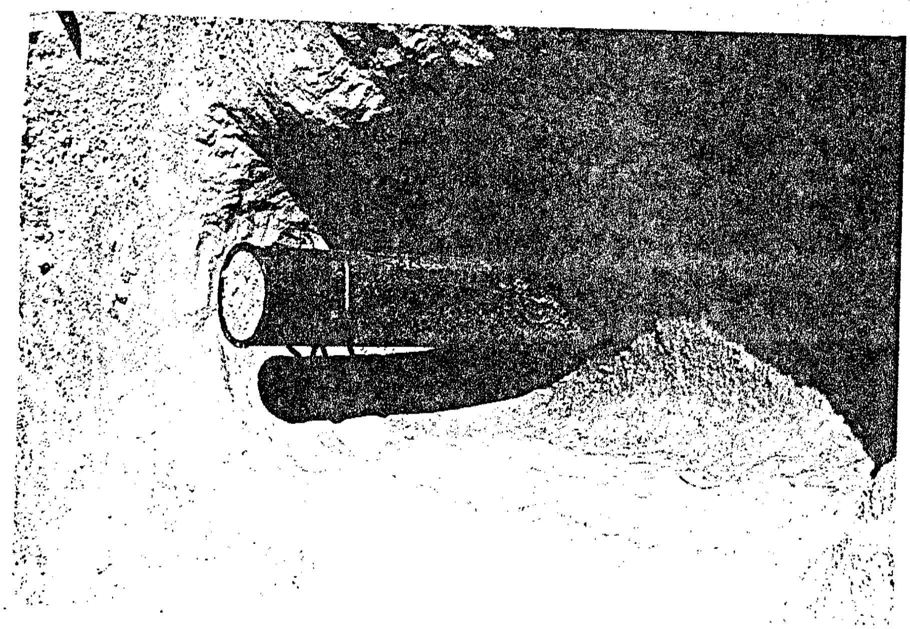
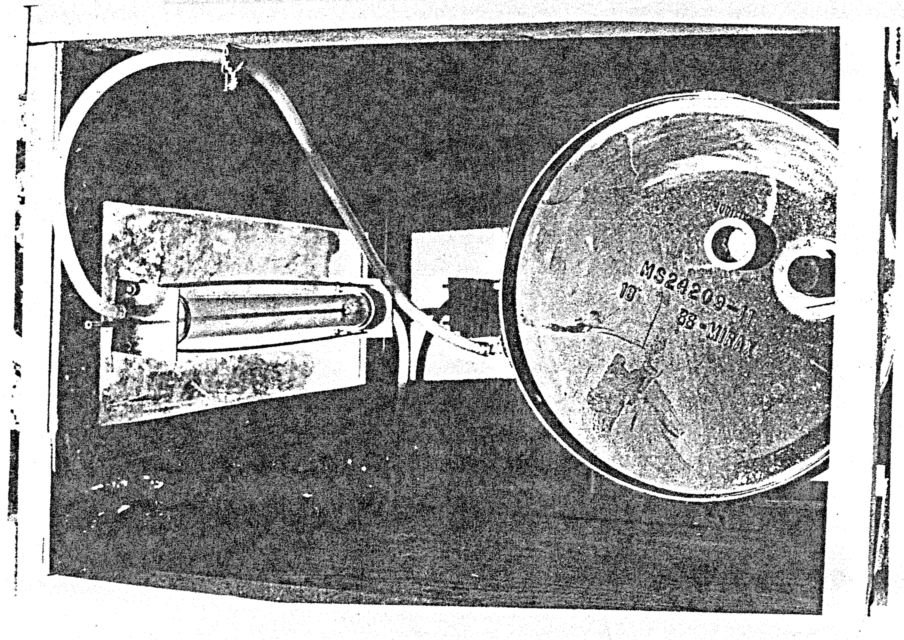


Figure 24. Photo showing sediment column for the lysimeter prior to installation of supply tank.

Because ion complexing becomes difficult or impossible to calculate at very high concentrations, the amount of free anions or cations cannot be accurately computed without considering ion complexing. It is questionable at this time whether or not saturation concentrations have been reached for minerals other than gypsum in the subsurface.



ure 25. Photograph of lysimeter after installation

ure 26. View of the top of the sediment column after installation.

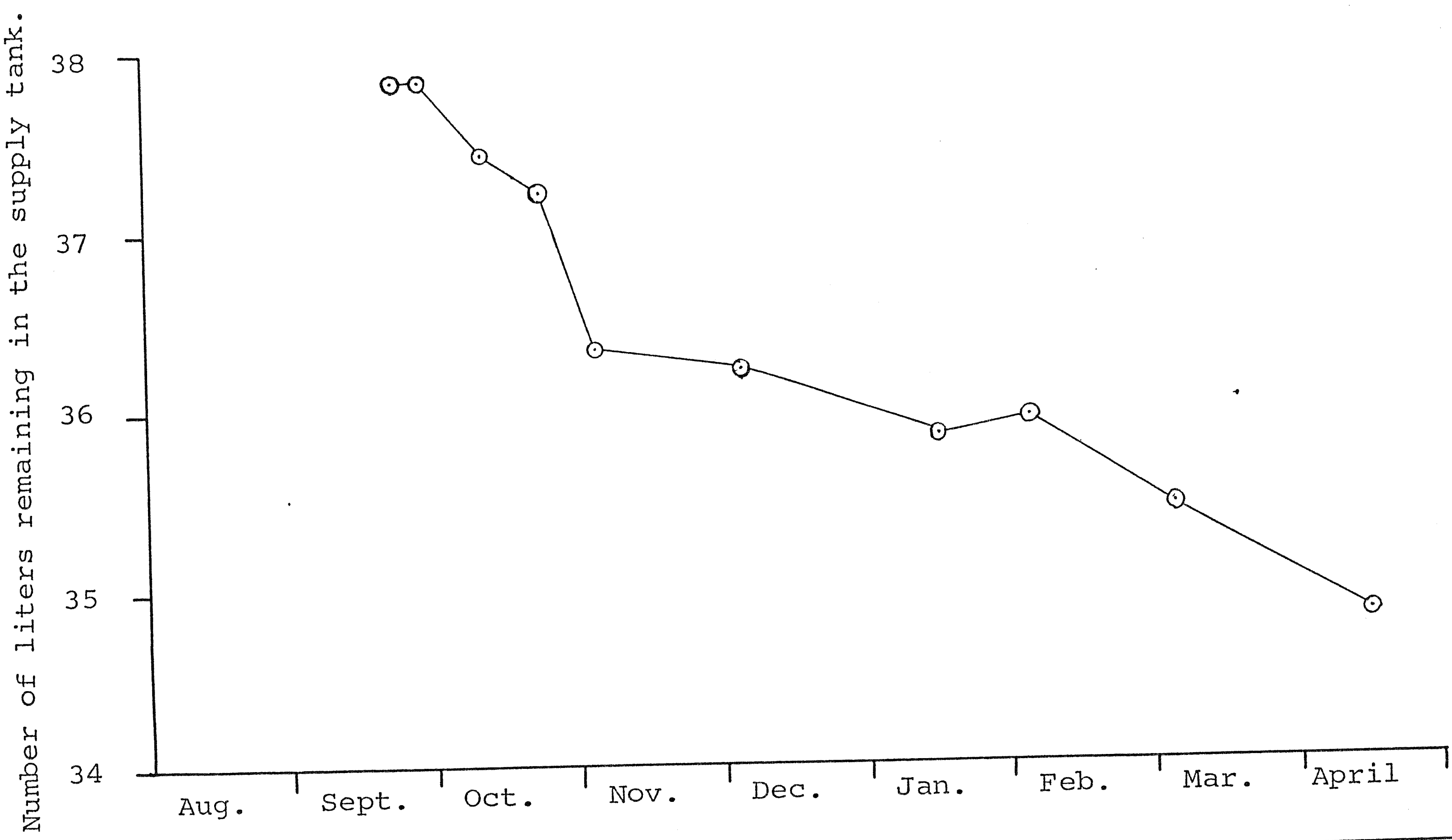


Figure 27. Lysimeter data (August, 1970- April, 1971).

	Sample Description	Na	K	Ca	Fe	Mg	SO_4
		Ion Concentration in					
A	in south portion of Lake Lucero near weather station 8/13/70	2,080	62.5	505	-	107	3,88
B	in well (dug) near weather station 8/14/70	10,000	312.0	635	-	1,530	14,56
C	in south portion of Lake Lucero near weather station 9/3/70	4,500	157.5	720	-	340	8,0
D	1 ft. below playa surface in solution channel 9/3/70	5,000	145.0	950	-	820	7,08
E	in north portion of Lake Lucero 9/14/70	5,750	125.0	102.5	-	285	7,47
F	in north portion of Lake Lucero 9/19/70	7,750	155.0	88.0	0.1	360	8,96
G	in north portion of Lake Lucero 9/26/70	11,500	220.0	91.0	0.1	560	12,69
H	in north portion of Lake Lucero 10/3/70	23,000	365.0	87.0	0.5	1,240	23,1
I	Salt Creek - stream sample	3,550	100	800	0.4	247	3,1
J	crater sample from north Lake Lucero	79,120	3,300	310	2.0	21,500	34,7
K	Well #10	3,300	230	600	0.4	1,100	8,6
L	Well #13	2,300	201	510	0.0	1,100	9,1
M	Well #30	74,000	2,030	385	1.3	7,900	88,6
N	Well #16	28,900	635	595	0.5	2,400	38,9
O	Well #20	36,500	490	585	0.3	3,260	56,8
P	south piezometer cluster center bottom	15,500	555	667	0.5	3,740	20,
Q	Well #3	21,000	610	600	0.3	3,440	30,
R	Well #7	31,500	610	595	0.4	1,880	35,
S	Well #33	41,250	1,125	667	0.7	5,040	33,

Table 4. Chemical concentrations of water samples from Lake Lucero.

grams per liter						
HCO_3	CO_3	SiO_2	F	pH	Specific Conductance (micromhos)	Total Dissolved Solids (milligrams/liter)
54	0	-	7.4	6.78	10,800	8,216
198	0	6.74	1.4	7.39	44,000	41,835
38.0	0	3.05	3.3	6.87	23,500	20,216
100.0	0	7.37	6.2	7.02	22,000	18,448
54.0	0	5.16	1.2	7.25	24,000	20,589
68.0	0	0.42	1.4	7.44	29,500	25,551
88.0	0	0.16	2.3	7.85	41,000	37,424
170.6	0	6.95	2.1	8.06	65,500	73,388
160.0	0	53.90	3.24	7.945	19,300	14,763
826.	0	5.27	0.14	7.185	177,000	395,984
201	0	33.76	1.20	7,360	20,900	19,166
332	0	33.36	2.78	7.931	16,300	17,756
350	0	16.92	0.38	7.360	163,300	295,125
279	0	33.33	2.55	7.750	88,300	93,501
331	0	5.53	7.80	7.938	96,000	123,526
107	0	3.30	0.95	7,644	54,500	60,728
294	0	11.93	1.85	7.662	80,100	82,314
294	0	15.15	1.68	7.762	88,300	94,001
120	0	4.92	0.063	7.479	124,300	144,328

The euhedral aspect of the small gypsum crystals found in the clays and silts of the lacustrine deposits suggest that they formed in place after deposition of the clastics. Any amount of transport would have destroyed the sharp crystal boundaries. Inclusions of the clastics also indicates 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, however, and I therefore believe 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 left 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 point where they too can be transported by eolian processes. It is my belief that these crystals are 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 asion encountered during transportion. This is not e of the finer grained gypsum matrix in which the crystals med. The matrix, at least below the playa surface, has initial grain size too small to compare with that in dunes and therefore must be eliminated as a possible ect source for the dune sand.

Beneath the present playa surface the crystalline ısum probably constitutes less than five percent of the .iment. In lacustrine outcrops west and east of the ıya, stratigraphically above the present surface, the ıtent of crystalline gypsum is as high as 85 to 95 percent. ; higher strata represent lacustrine material which was)osited later than the lower strata and therefore correspond a fime when the Lake Otero waters were considerably more ıcentrated. Thus the difference in gypsum content is ɔught to be the result of a depositional sequence in ə slowly evaporating lake.

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

I have estimated the amount of sand derived from the .ke Lucero area to be 286,000.000 cubic meters. This ıount of sand would require deflation of a sediment ɛquence 36 feet thick over the area of Lake Lucero and .cinity. I have probably overestimated the volume of

in the dune area and underestimated the source area.
e also assumed that the percent increase in porosity,
onsequently volume, in the dunes will cancel the
ypsum content of the lacustrine deposits.

Although I have observed sections of lacustrine
its as much as 40 feet above the playa surface their
alline gypsum content is not nearly as high as the
deposits closer to the playa. This means that
r my estimates are in error or that some other
nisms must ve called on to add gypsum to the system.

Assuming that the contribution of gypsum from ground
is concentrared in the area now covered by the playa,
ssuming that the evaporation rate has been similar to
of the present, I can estimate the amount of gypsum
has been added by ground water. Using the data from
ysimeter and information from Table 3, and assuming
face area of about 26 square kilometers, I estimate
round-water contribution of gypsum to be on the order
),000,000 cubic meters over the past 10,000 years.
is equivalent to approximately 50 percent of the
ibution from direct precipitation of Lake Otero
t 95,000,000 m^3).

The addition of the ground-water contribution brings
equired thickness of gypsum source area down to 24
. This is a much more realistic number and may be
icient to account for the White Sands.

If we assume that surface water processes in the past

esemble those presently taking place, I cannot call on
hem as a source. This will be demonstrated in the
ollowing section.

<u>The role of surface waters in the formation of the White Sands</u>

As mentioned earlier 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 approximately 6 to 10 inches of water.

Figures 28 through 35 show the chemical changes in the ponded water with time. Figure 36 displays the pH trend. The Y' axis represents a shift in collecting site from the south portion of the playa to the north portion. This became necessary when the south portion of the lake "dried up" sooner than expected. The chemical trends in either portion of the playa probably resembled the other sufficiently to justify this type of plot which suggests extrapolation across the Y' axis.

These curves show an increase in the concentration of ions with time. This increase results from two unrelated processes; the first and probably most important is dissolution of soluble salts which make up the playa floor. Evaporation also acts to concentrated the dissolved solids, however the role of evaporation is greatly overemphasized if infiltration is neglected.

With the exception of calcium, none of the ions give any indication of reaching saturation equilibrium and precipitation. The solubility products of various minerals

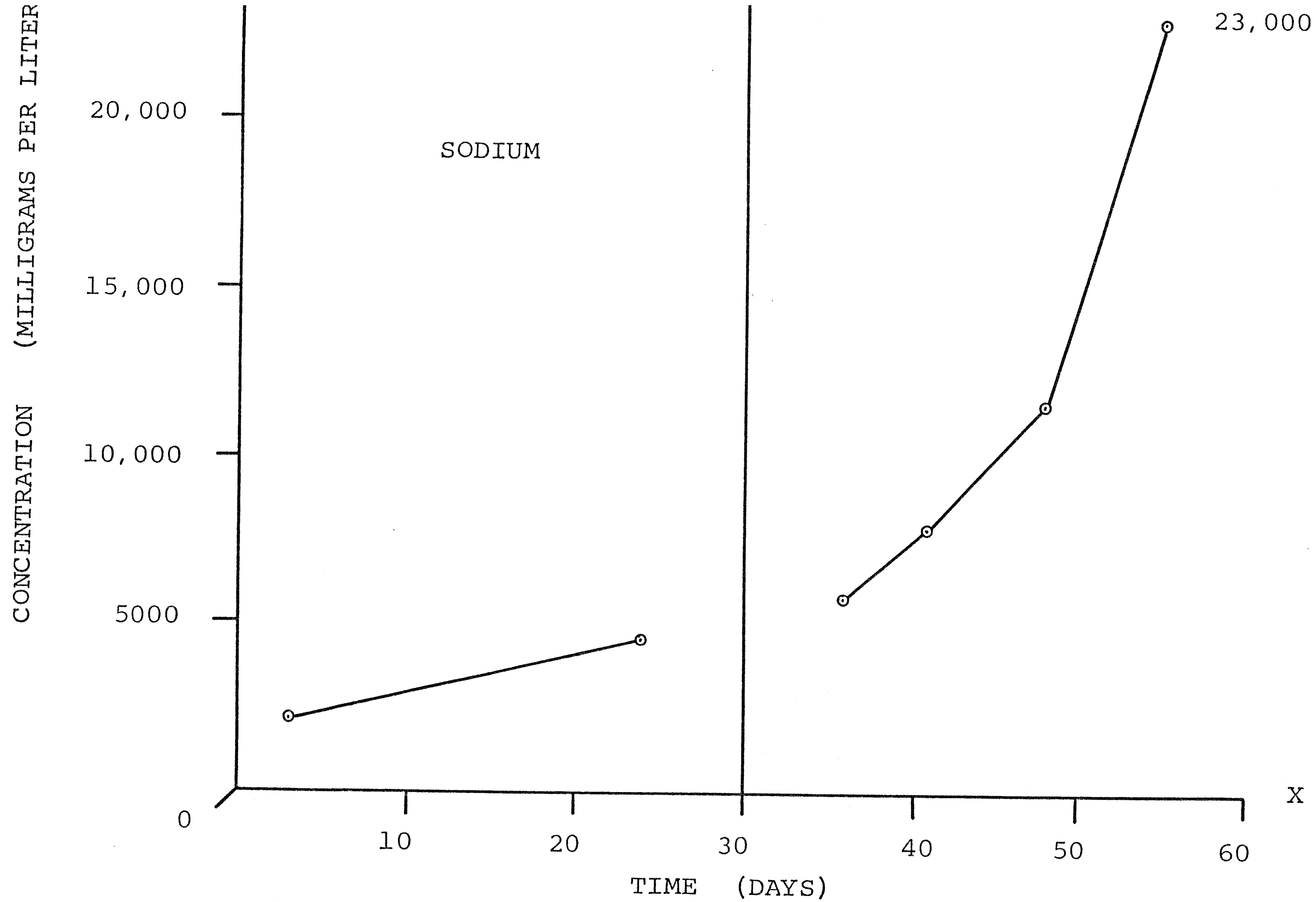


Figure 28. Change of sodium concentration in surface water with time.

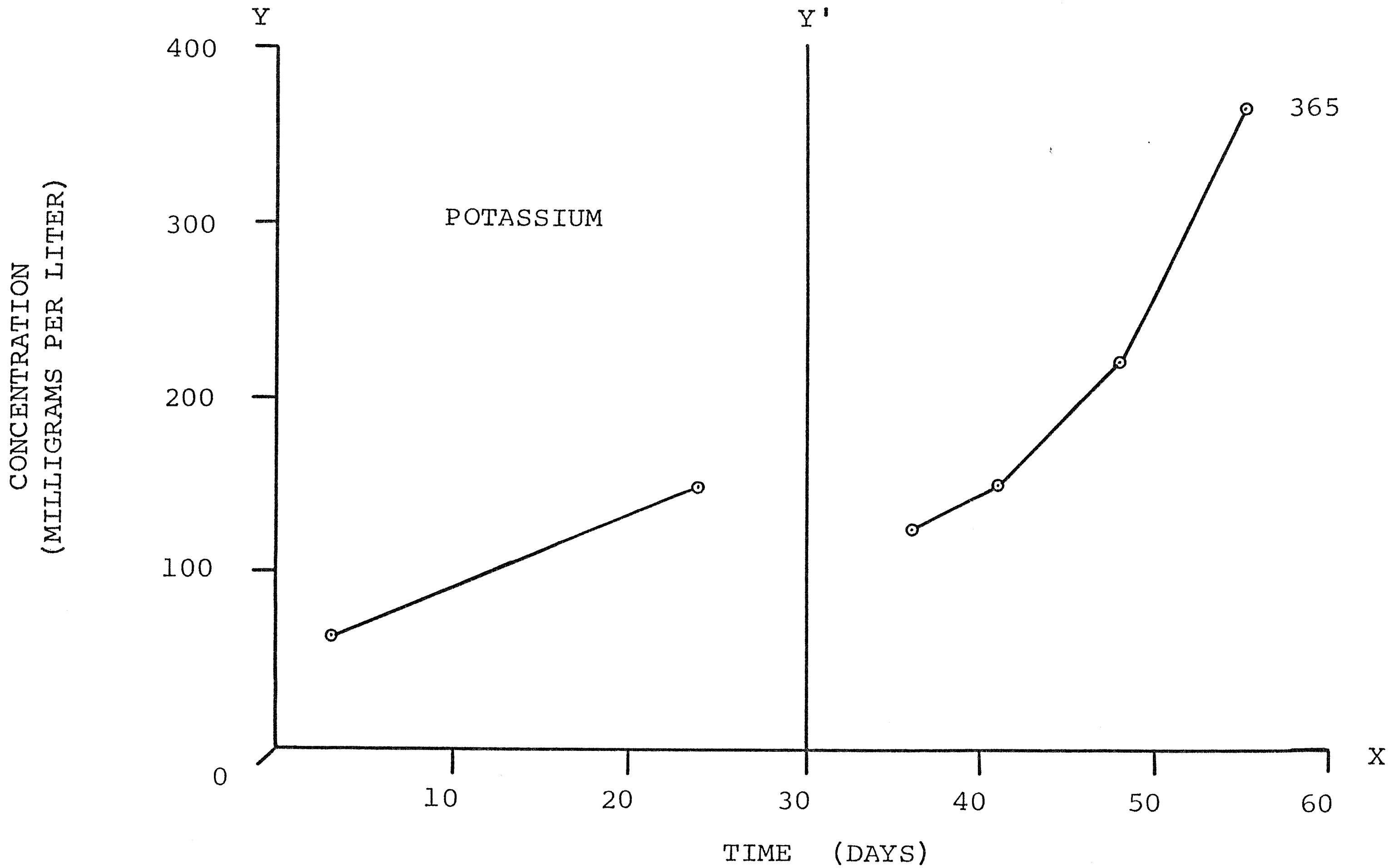


Figure 29. Change of potassium concentration in surface water with time.

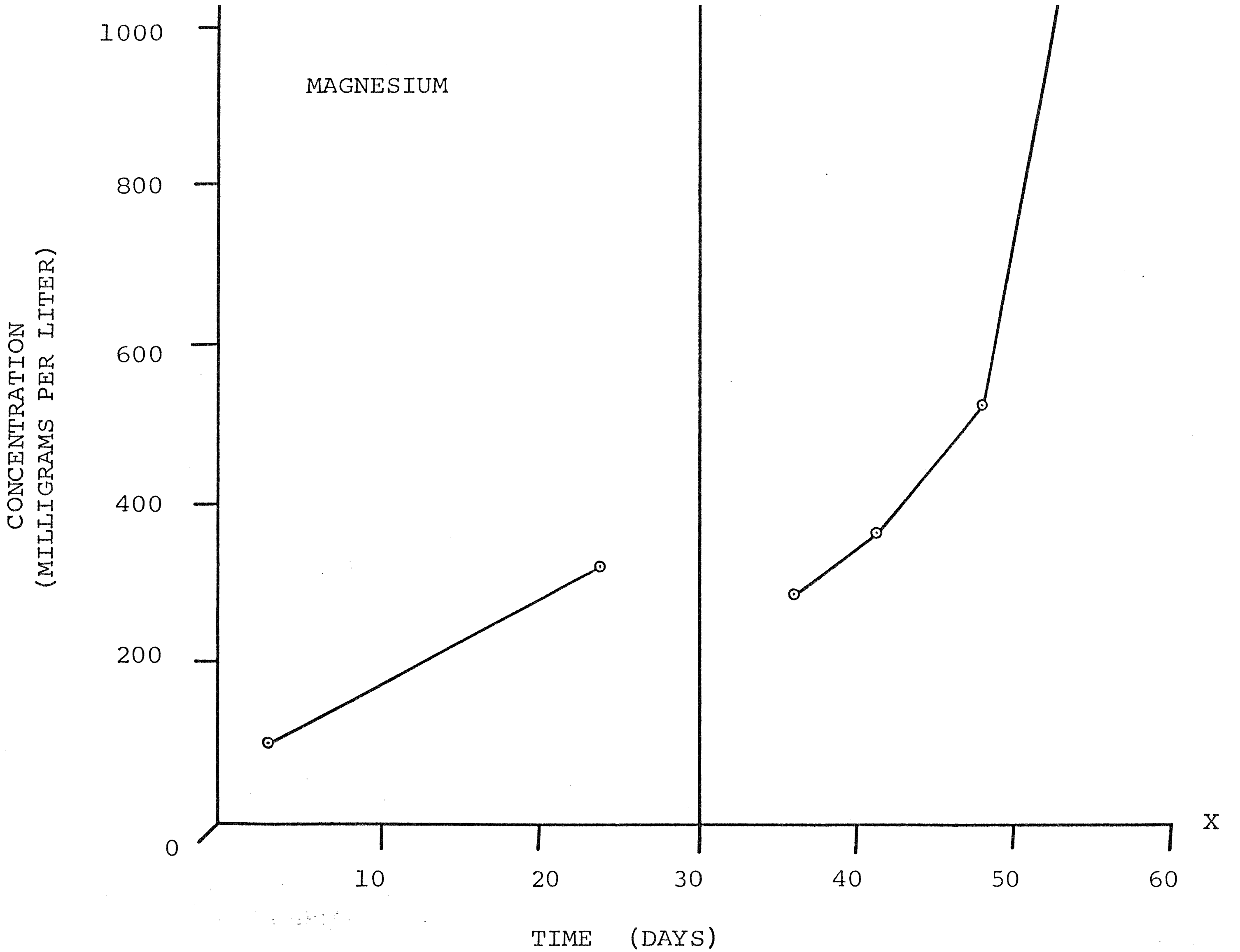


Figure 30. Change of magnesium concentration in surface water with time.

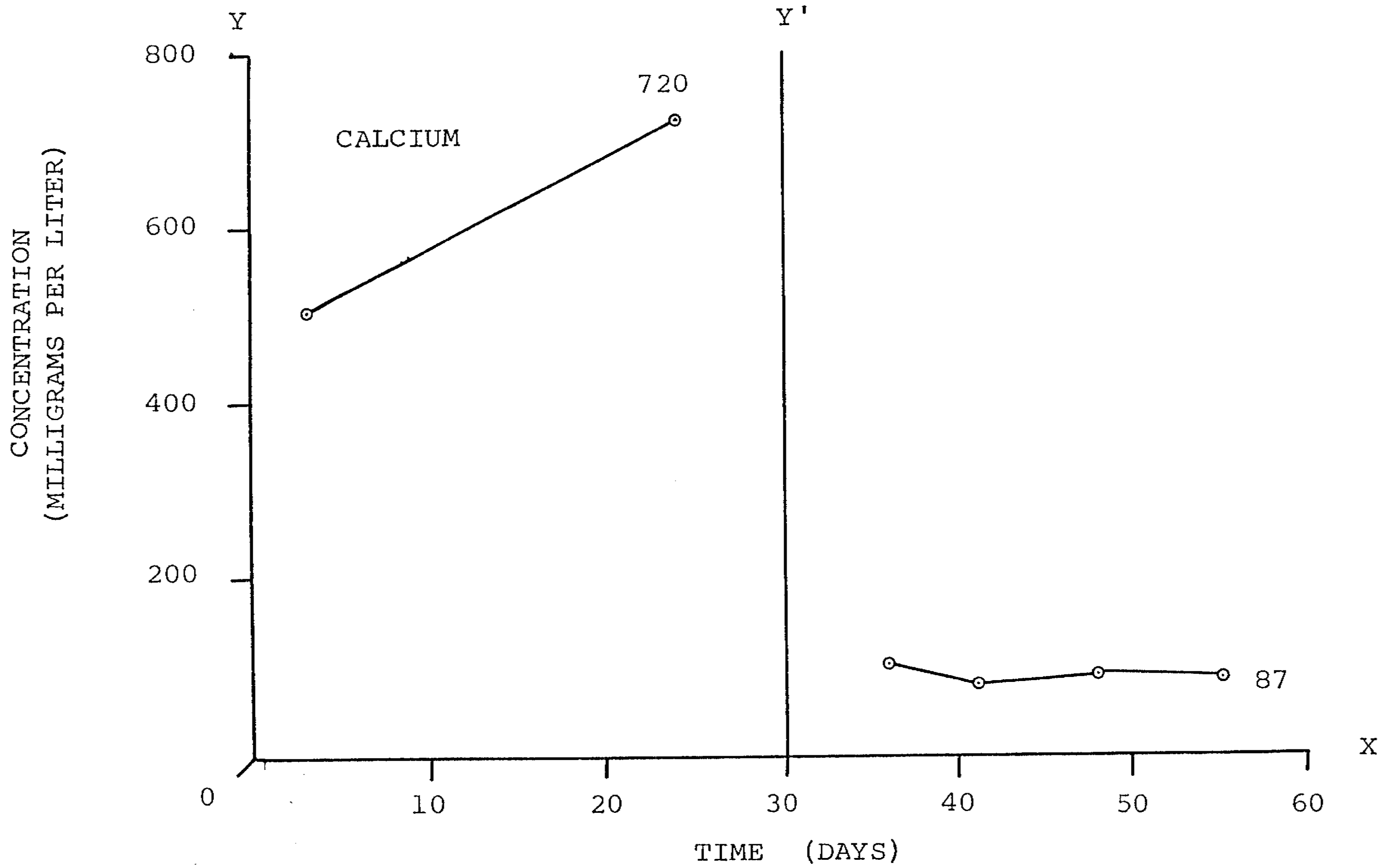


Figure 31. Change of calcium concentration in surface water with time.

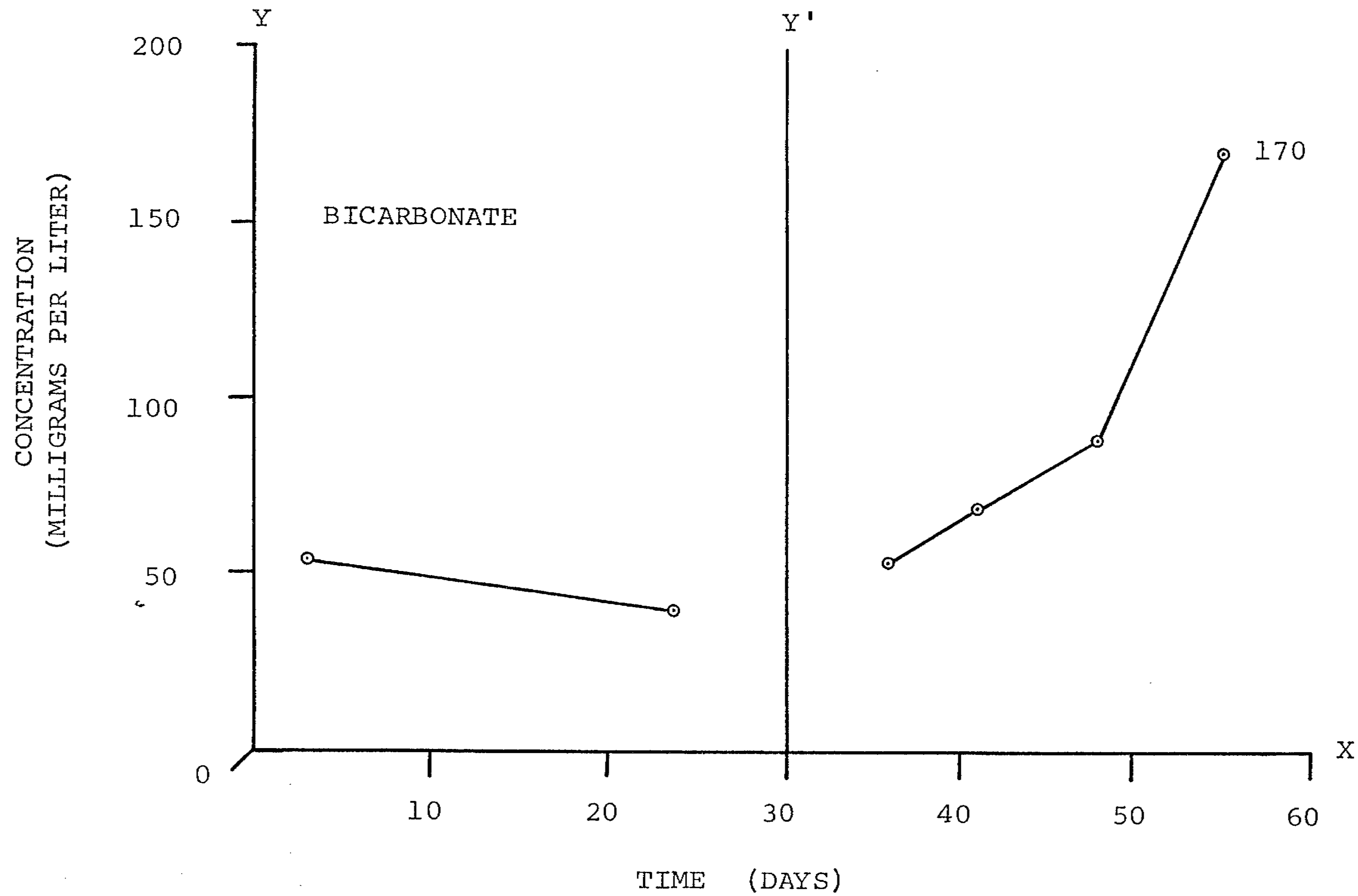


Figure 32. Change of bicarbonate concentration in surface water with time.

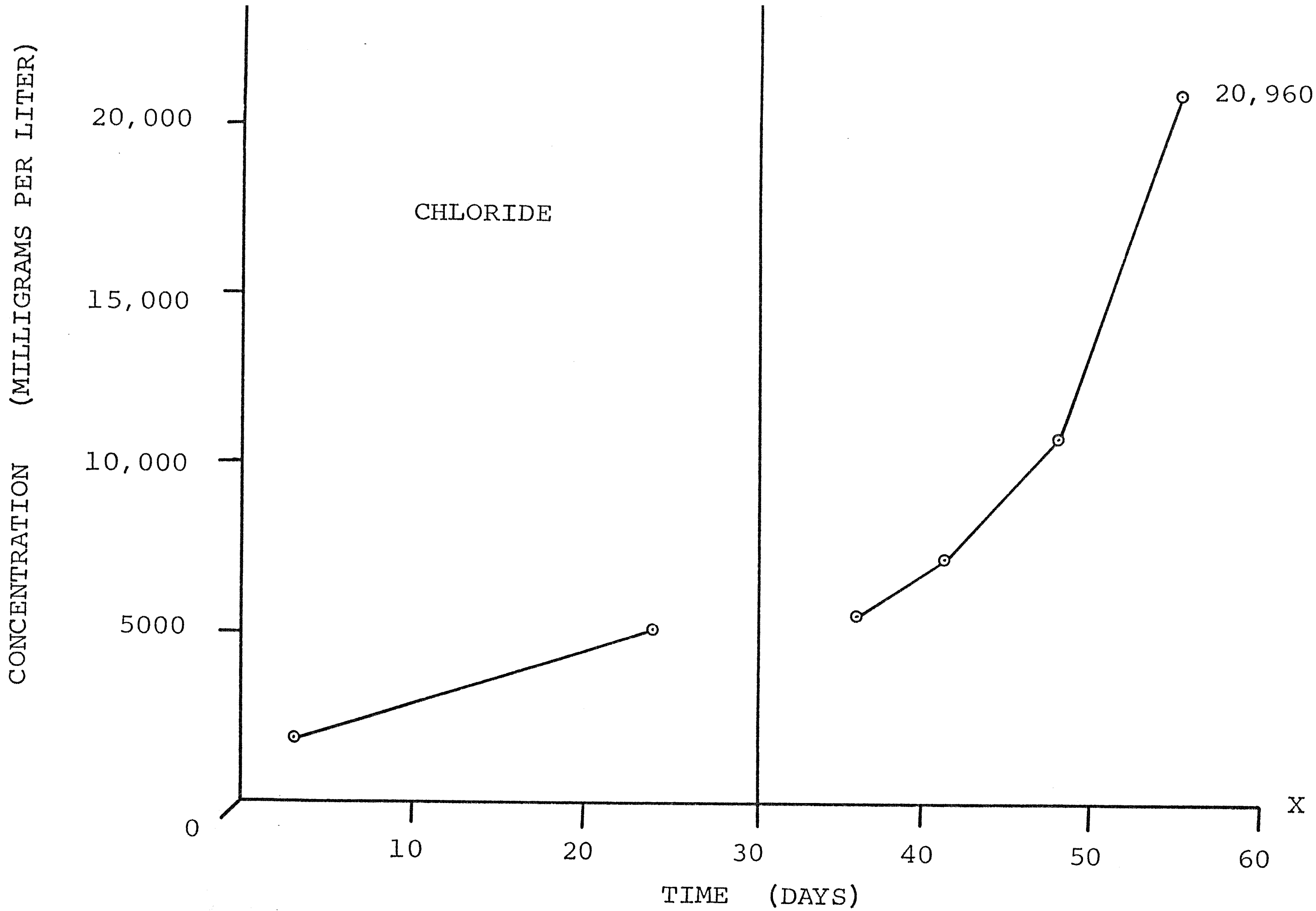


Figure 33. Change of chloride concentration in surface water with time.

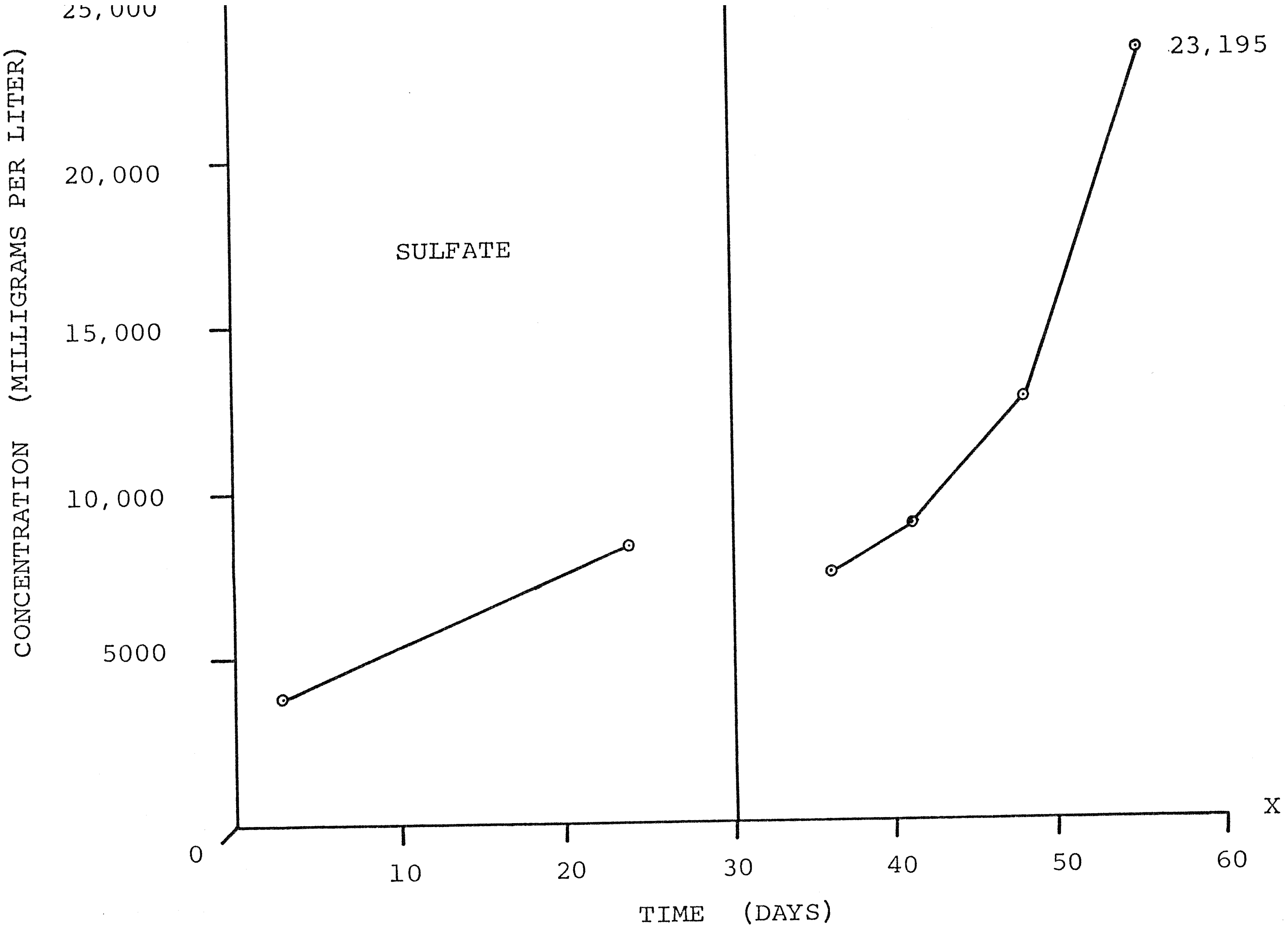


Figure 34. Change of sulfate concentration in surface water with time.

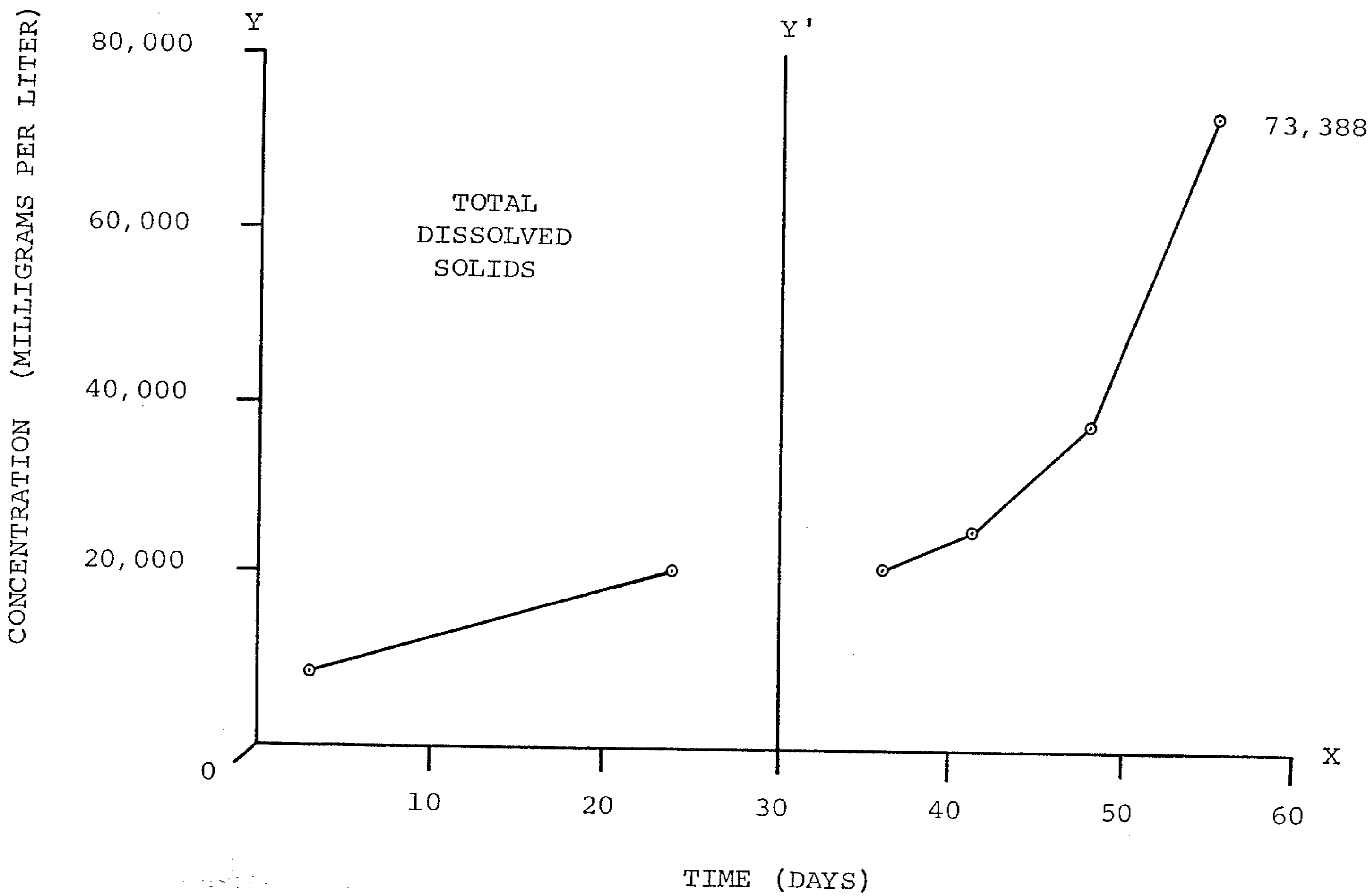


Figure 35. Change of total dissolved solids in surface water with time.

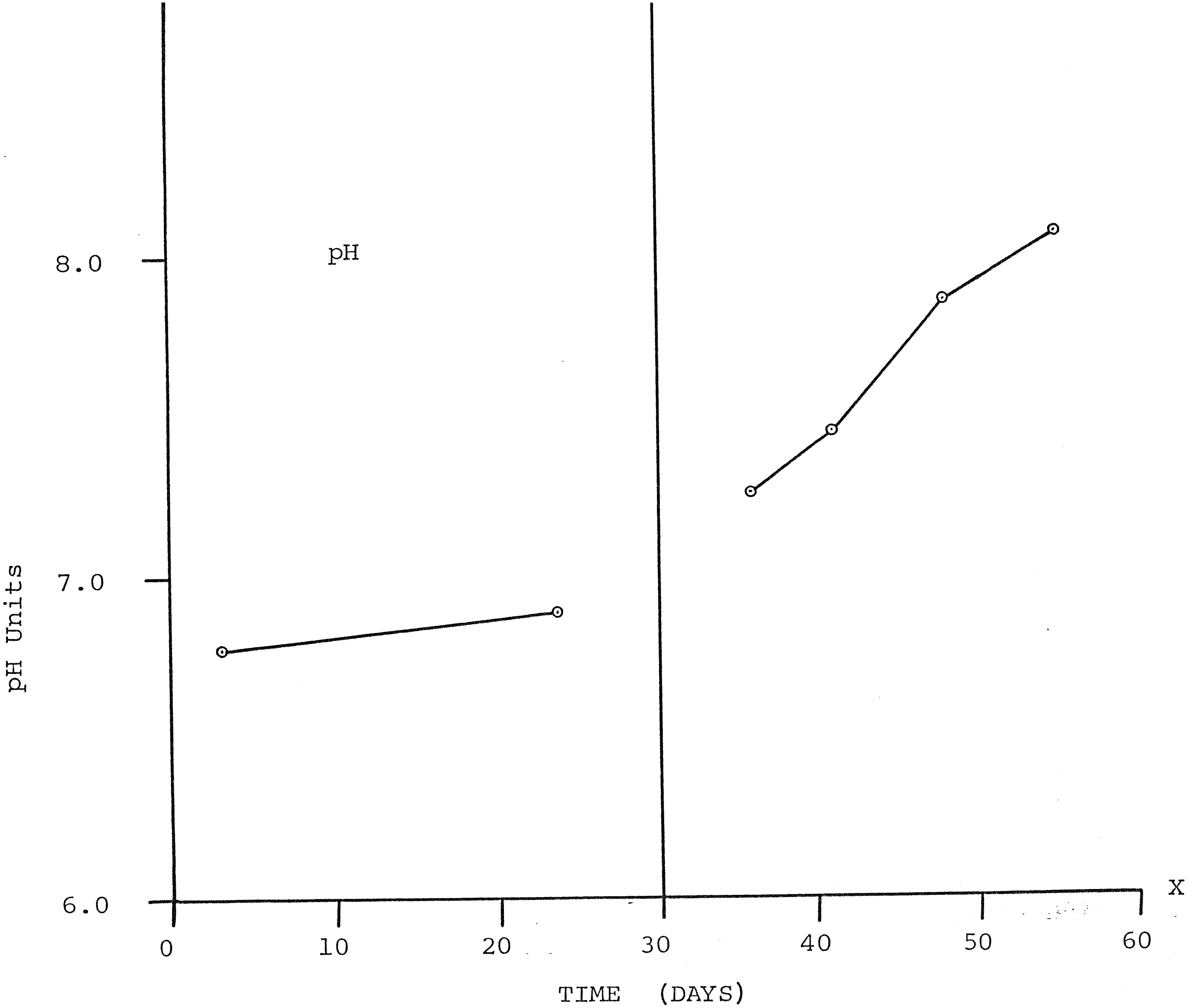


Figure 36. Trend of pH with time.

compared with the ion activity product (IAP) of
components in solution. If the IAP is less than the
lity product then saturation has not been reached.
the other hand, the IAP is equal to or larger than
lubility product then saturation or super-saturation
ken place.

n very dilute solutions the IAP is easily computed.
tivity coefficient (γ) approaches unity and therefore
ty can be substituted for activity by the equation

$$a_i = \gamma_i m_i$$

where a_i, m_i, and γ_i are the
ty, molality and activity coefficient respectively,
i th ion species.

t higher concentrations γ changes in value and must
luded in the calculations. The equation for ionic
th (I),

$$I = \frac{1}{2} \sum m_i \, z_i^2$$

where z_i is the ionic charge, must
ved first using analytical values for m_i. The value
ed for I is then used in the Debye-Huckel Equation
tivity coefficients

$$-\log \gamma_i = \frac{A \, z_i^2 \sqrt{I}}{1 + \mathring{a}_i B \sqrt{I}}$$

B are temperature dependant constants and a_i is a
ınt dependant on the particular ion. The values for
constants were taken from Garrels and Christ (1965,
. The solution to this equation represents only a
approximation to the correct γ values since it relies
ionic strength which was computed using molality
d of the more proper activity. This approximation
s used to determine an approximate activity which in
s utilized in the ionic strength equation instead of
ty, and the whole process is repeated. Several
ions (usually 3) of this type are required before
sive answers are close enough to each other to
te a correct answer.

t high ionic strengths ion complexing becomes a
icant factor and should be considered in the
ations for activity. I have a computer program
on a mathematical model used by Garrels and Thompson
which calculates, among other things, free ion
tration, ion pair concentration, and ion pair
ties. When this program becomes operative it will
ate the activity coefficients and related parameters
ore accuracy than can be obtained by hand.

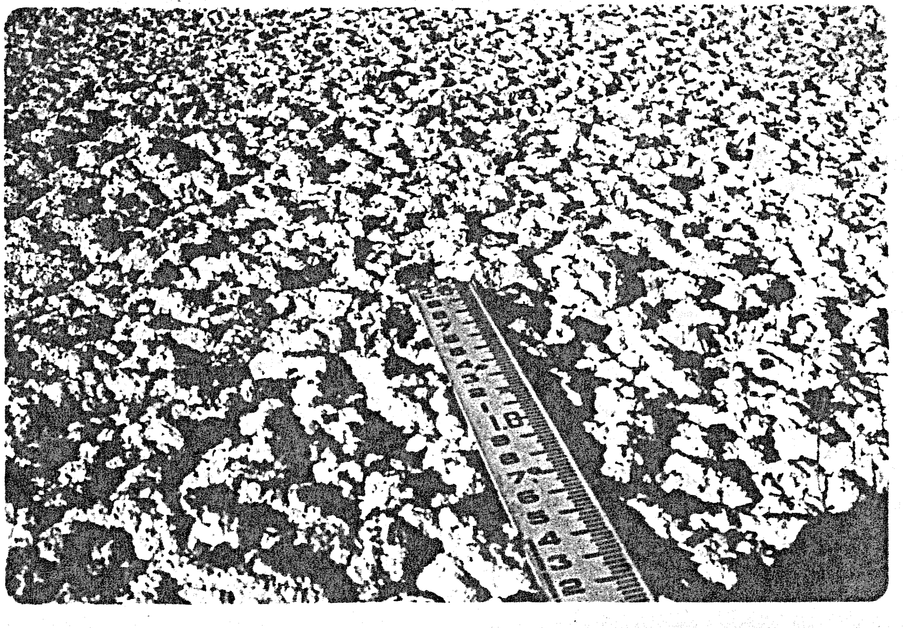
or present purposes the procedure described above is
te enough for comparison of IAP's with solubility
ts. If I can show that the IAP's of surface water do
proach saturation values without considering complexing
ne problem is solved because complexing only reduces

number of ions available for reacting and precipitating.
I have worked out the IAP of the most important ion rs in this manner and have found that, with the eption of calcium carbonate, no chemical species are r saturation. This means that no salts precipitate 'ore infiltration. I believe the last sample collected resented nearly the very last remnant water to exist 'ore infiltration was complete.

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

The crust forms fastest where the water can be drawn ward fastest, i.e. in the coarser grained sediments of gher permeability. When the crust forms very rapidly it comes extremely puffy owing to extension from ystallization (Fig. 37).

Whether or not the crust is puffy or is the more pical compact type, it soon become susceptible to the osive effects of the prevalent southwest winds. Much of is crust breaks down to a fine powder and has been served to blow thousands of feet upwards into huge white s and transported many miles from the playa. Other, r particles travel a much shorter distance to the .'s eastern side where they form small dunes and later ie incorporated into the larger dunes farther east. of the gypsum in this crust breaks down very easily er and I imagine it soon becomes winnowed out of the e dunes. Therefore the minerals directly related to ce-water phenomena do not contribute to dune formation.



ure 37. Photograph of puffy crust at Lake Lucero.

One process which may play a role, however, is the
;ual growth of the efflorescent crust. As this crust
)ws and expands it lifts with it the smaller, clear
)sum crystals described earlier as covering portions of
: playa surface in large numbers. The forces involved
the growth and expansion process may help to break up
:se crystals to a point where the wind can begin moving
:m. I have done no serious investigation into this
)cess and it is mentioned here only as a possibility
.ch may warrant further study.

SUMMARY AND CONCLUSIONS

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

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

Ground water does transport a significant amount of
um to Lake Lucero, from both the Permian evaporites
the recent lacustrine deposits throughout the basin.
ground water evaporates from the capillary fringe and
the process precipitates and recrystallizes gypsum in

lacustrine deposits in a form which does contribute
nificantly to the White Sands. Thus ground water
charging at Lake Lucero may have produced enough
stalline gypsum to make up as much as 33 percent of
White Sands.

The majority of the gypsum in the White Sands was
oubtedly derived from the primary evaporites of Lake
ro. Hydrologic processes are therefore responsible for
nsporting and depositing all of the gypsum which has
ce been deflated at Lake Lucero, and by extrapolation,
alkali flats and deposited in the White Sands dune
ld.

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This thesis is accepted on behalf of the faculty of the

Institute by the following committee:

Date 11 May 1971