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PLEISTOCENE LAKE TRINITY, AN EVAPORITE BASIN IN THE NORTHERN JORNADA DEL MUERTO, NEW MEXICO

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INTRODUCTION

Exploration for a test site in 1974-75 for a military research project led to the somewhat accidental discovery of a previously undescribed sequence of lacustrine evaporites in the northern Jornada del Muerto valley of southern New Mexico. Four boreholes provided the principal subsurface information. Gravity measurements obtained for another military project provided insight on basin shape and origin.

The basin name of Trinity is suggested because of the location immediately adjacent to the site of the world's first atomic detonation. Access to this area has been denied to most geologists for more than 30 years and may explain the basin's relative obscurity, even though shore features are visible on satellite imagery. The basin is entirely within White Sands Missile Range, operated by the U.S. Army since World War II. The results reported here are somewhat serendipitous; the data available to document the discovery were obtained for quite different purposes. Nonetheless, a picture has emerged of a small (200 km') Pleistocene lake basin with distinctive hydrochemical attributes, similar to Lake Otero in the Tularosa Basin, yet unlike any other lake in the western United States.

LOCATION AND ENVIRONMENT

The Trinity lake basin is situated in the northern Jornada del Muerto valley, in the southeast corner of Socorro County and the northeast corner of Sierra County. The approximate basin center is at coordinates 33° 35' N and 106° 35' W, 55 km southeast of Socorro, New Mexico (figs. 1).

The elevation of the basin floor averages about 1425 m and varies locally by three meters or more. Precipitation on the valley floor averages slightly less than 200 mm per year and ranges up to double this amount in adjacent mountains, the recharge source of much basin ground water.

Annual class "A" pan evaporation measured at three nearby U.S. Weather Bureau stations ranged from 216-236 cm, an amount exceeding average annual precipitation by a factor of ten. As a result of the large evaporation rate, most precipitation evaporates immediately and probably much less than ten percent is recharged as ground water. Surface water seldom stands for long on the basin floor. Several barren playas occur near the southern end of the basin; these catch and then evaporate runoff. The adjacent alluvial fan areas may recharge up to 25 percent of precipitation according to Weir (1965), but this value may be a local extreme. Geology of the region was mapped and summarized by McLean (1970) in his report on the Tularosa Basin. The mountains bordering the study area started forming during Miocene time and basin filling was concurrent.

BASIN AND SHORE FEATURES

Geomorphic Observations

Basin and shoreline features are readily seen from aircraft and on aerial and space photographs, especially along the eastern and southern borders of the basin (figs. 1, 2). The western and northern boundaries are obscured by dune deposits of probable Holocene age. Only a single, persistent strand line is evident; it occurs at 1431 m, six meters above the valley floor. A surface traverse across the basin from west to east reveals four distinct sedimentary units: dune sand, gypsum, argillaceous gypsum, and alluvial fan deposits. Boreholes have penetrated each unit and reveal indications of the vertical and horizontal extent.

The dune sand unit is widespread along the western part of the basin. Dunes are stabilized by vegetation and exhibit rolling terrain that is topographically 9 to 15 m higher than the basin floor (fig. 3). The source of this sand is probably fluvial deposits along the ancestral Rio Grande, which carried a greater sediment load during Pleistocene time. The dunes were probably derived from deflation of the channel and flood plain. Some active sand dunes exist at Sand Mountain, about 30 km northwest of the basin. The stabilized dune unit is distinctly darker than the adjacent gypsum zone and is visible even on the small-scale satellite image (fig. 1).

The gypsum unit is the most highly reflective zone and is also the most irregular as a result of ponding of water and the presence of sporadic vegetation clumps. A mottled or blotchy pattern is characteristic on aerial photographs, reflecting the distribution of barren areas and surface vegetation, which consists largely of sagebrush and grasses.

The argillaceous gypsum unit is adjacent to the basin edge, in a zone about a kilometer wide. Aerial photographs display suggestions of poorly developed polygonal patterns and subparallel lineations of very large spacing (-10 m) that are indicative of contracting clays on other playas (Neal and others, 1968). Springs and seeps occur along this zone and are manifested in areas of more luxuriant grasses and thickets; these appear darker on aerial photographs.

The alluvial fan unit consists of detritus derived from adjacent mountains, ranging from grus in the south to limestone pebble alluvium in the north. This detritus reflects the granite and limestone composition

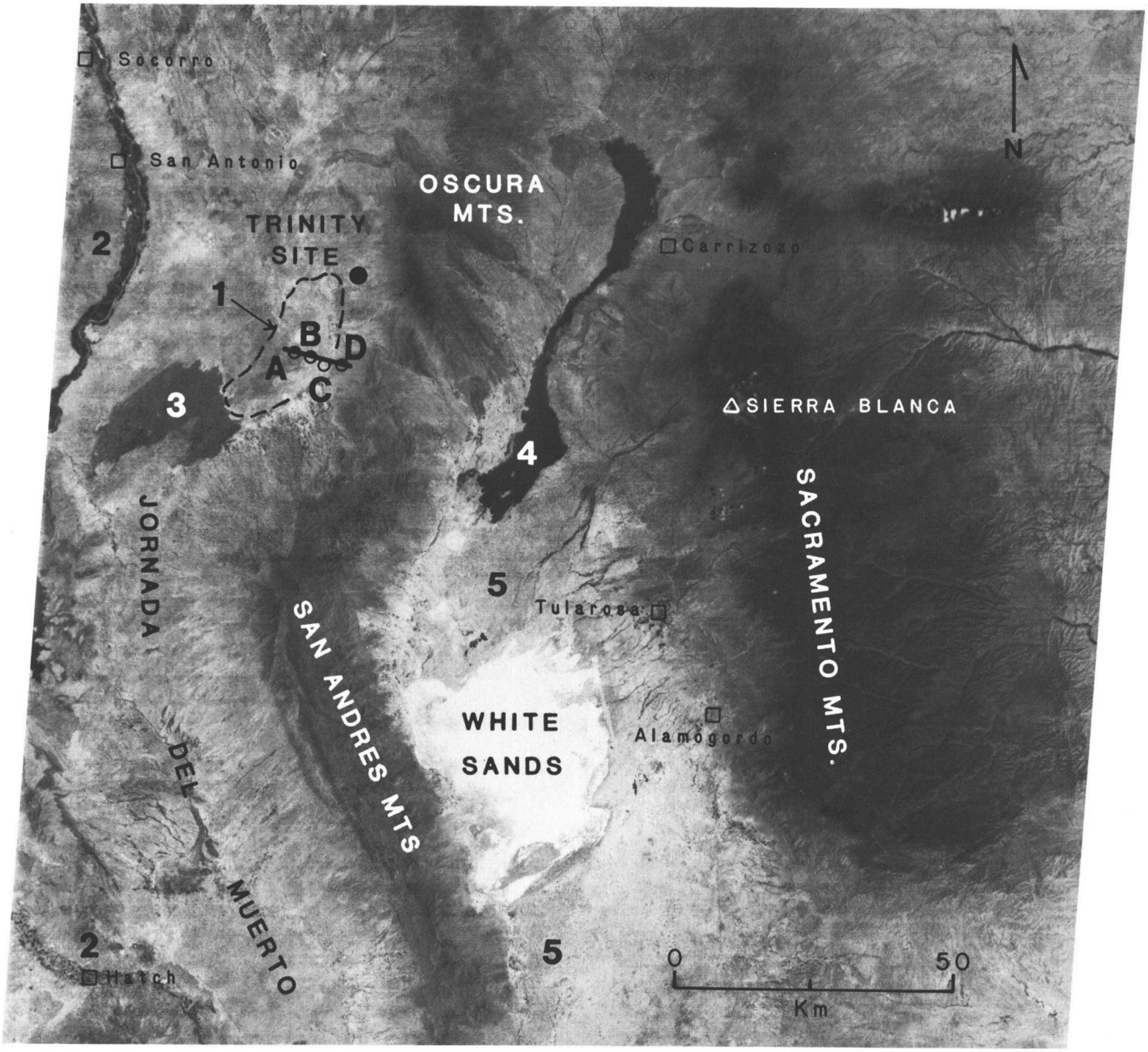

Figure 1. Space imagery (LANDSAT-A, MSS Band 5, 21 June 1973) of southern New Mexico, including Trinity Lake basin and adjacent Tularosa Basin. Principal features adjacent to Trinity basin are: (1) highest known shoreline of Pleistocene Lake Trinity, (2) Rio Grande valley, (3) Jornada malpais (lava), (4) Tularosa malpais (lava), and (5) basin of Pleistocene Lake Otero, Tularosa Basin. Boreholes A, B, C, and D are shown along east-to-west transect across central portion of Trinity basin.

of the adjacent mountains. The alluvial fans appear dark on aerial photographs and are channeled normal to the shore contours (fig. 2). The contrast between the basin and fan units is conspicuous on the satellite image (fig. 1).

Geophysical Measurements

Seismic reflection and refraction surveys, regional (basin) gravity profiling, and an aeromagnetic survey were performed in the vicinity of the Trinity lake basin; each has provided some information on basin configuration.

Gravity observations were made by Healey and others (1978) in portions of the Tularosa Basin and the Jornada del Muerto valley. The contoured gravity map and a bedrock-to-bedrock transect across the basin showed a partial coincidence of the lake basin with the gravity basin, although the latter, a major low, is centered about 20 km to the north. Gravity gradients are steepest along the eastern margins of the basin, probably indicating that major faults within the Rio Grande rift form the eastern margin of the basin. The eastern margin of the lake basin coincides with the axis of the gravity trough. A lineation on space imagery (fig. 1) may be the surface manifestation of these faults. The lineation crossing the southern portion of the basin was interpreted as a small graben by a seismic reflection profile (Neal, 1976). However, the few gravity observations allow only a broad, generalized contouring of the gravity values. The measured gravity anomalies are consistent with the thickness of Tertiary basin fill inferred from seismic reflection sounding.

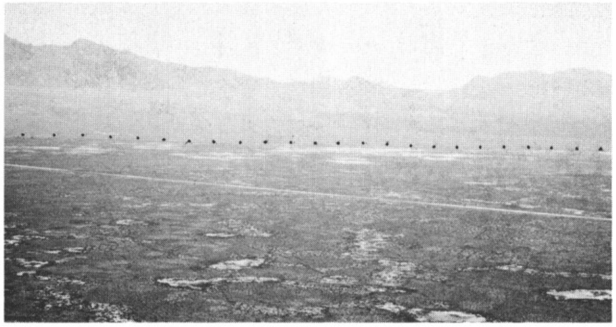

Figure 2. Looking southeastward across gypsum zone showing mottled patches in foreground. Site of borehole B is along road near center of photo. Argillaceous gypsum along eastern and southern margins of basin is marked by lighter-toned surfaces devoid of vegetation and playa-like in character. Highest recent shoreline is marked by dots. Note broad alluvial fans along eastern and southern margins.

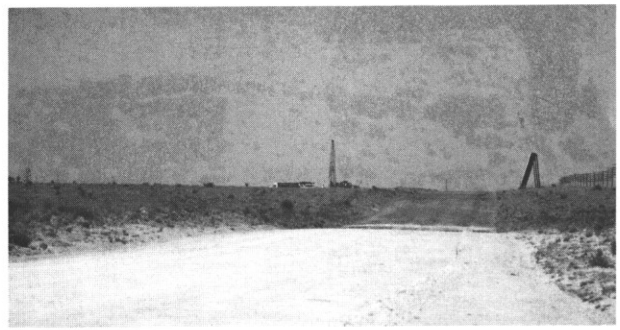

Figure 3. Looking west from gypsum zone (and site of borehole B) to dune sand and site of borehole A. Darker tone of sand is evident on aerial and space photographs (fig. 1).

STRATIGRAPHY

Borehole Data

Four exploratory borings (fig. 4) provide the subsurface data needed to plot a basin profile (fig. 5). Holes C and D were drilled first, using rotary methods; samples were collected from cuttings recovered from the drilling fluid. Attempts were made to obtain material as pure as possible from each depth sampled. Holes A and B were also drilled by rotary methods, but a Dennison tube provided undisturbed cores. Consequently these latter samples are more reliable for mineralogic studies. The stratigraphic correlation (fig. 5) is based on an evaluation of the unconsolidated sedimentary sequence penetrated in the boreholes and on geological and mineralogical data.

Sedimentary Units

The Santa Fe Group (Tertiary) underlies the younger basin deposits. The Santa Fe Group is not well defined in this area because outcrop exposures are poor and subsurface control is lacking (Weir, 1965). Even the deepest borehole (B) only reached a depth of 39.6 m in the basin center, and did not penetrate the Santa Fe Group. The upper surface of the Santa Fe Group probably grades into the Pleistocene alluvium because both units consist of silt, sand, and gravel weathered from the adjacent mountains.

Borehole data and the basin profile (figs. 4, 5) show alternating sand and clay of variable thickness; the depositional origin is uncertain but may reflect alternating fluviatile and lacustrine conditions. The sand strata of the lower portion of these deposits appears to thin eastward where it grades into, and interfingers with, alluvial-fan gravels. Borehole samples showed gradational contacts between these alternating sand and clay units.

Above the thick sand layer is a clay zone that thins toward the basin center. The clay is gypsiferous at basin center, but is less gypsiferous and more silty or sandy under the alluvial fan at borehole D. Within the massive gypsiferous clay zone in borehole A, a thin layer of pure gypsum fragments, which probably formed by precipitation in an isolated pond, occurs at 18.3 m depth. A 3-m sand bed occurs higher in the dominantly clay sequence, above the massive gypsum zone.

Fine-grained, nearly pure gypsum characterizes the most distinctive sediment zone in the basin center. This irregular sulfate body overlies and interfingers with clay at its east and west margins. A 0.5-m-thick layer of translucent hexahydrite occurs at a depth of approximately 19

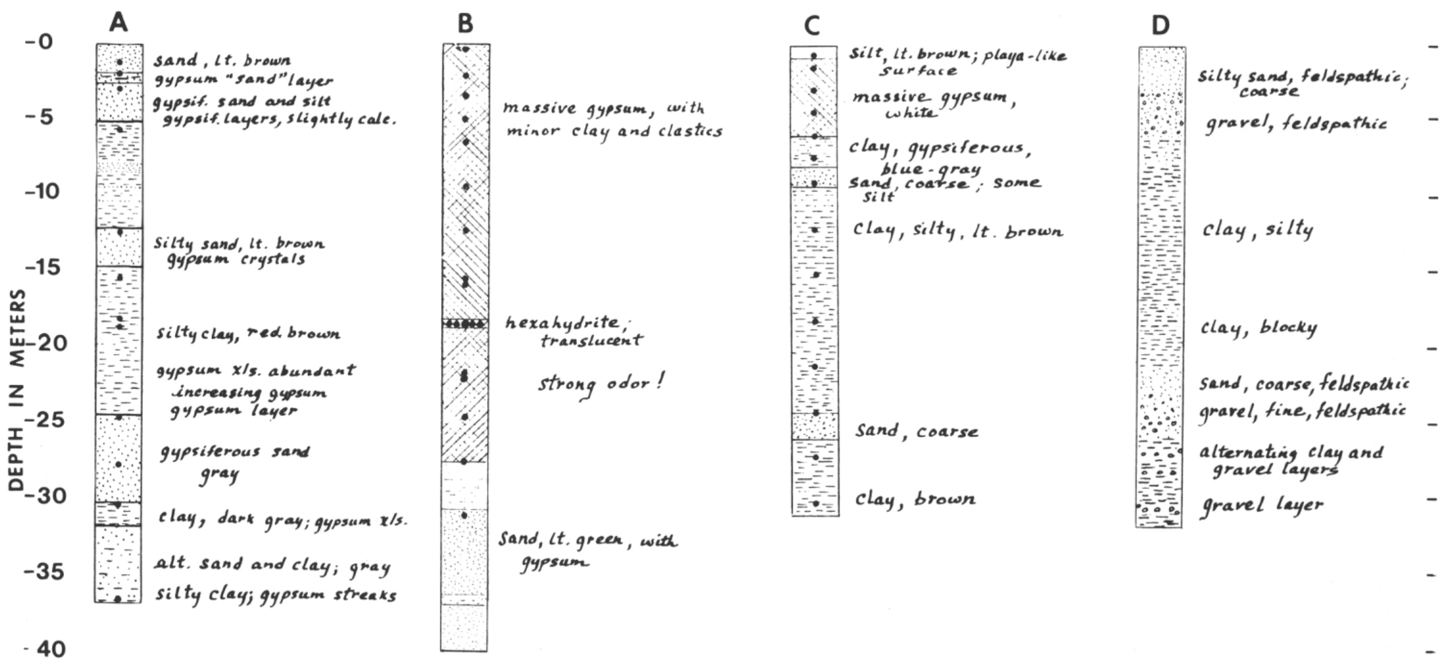

Figure 4. Field logs of boreholes A, B, C, and D. Sample locations are marked by black dots.

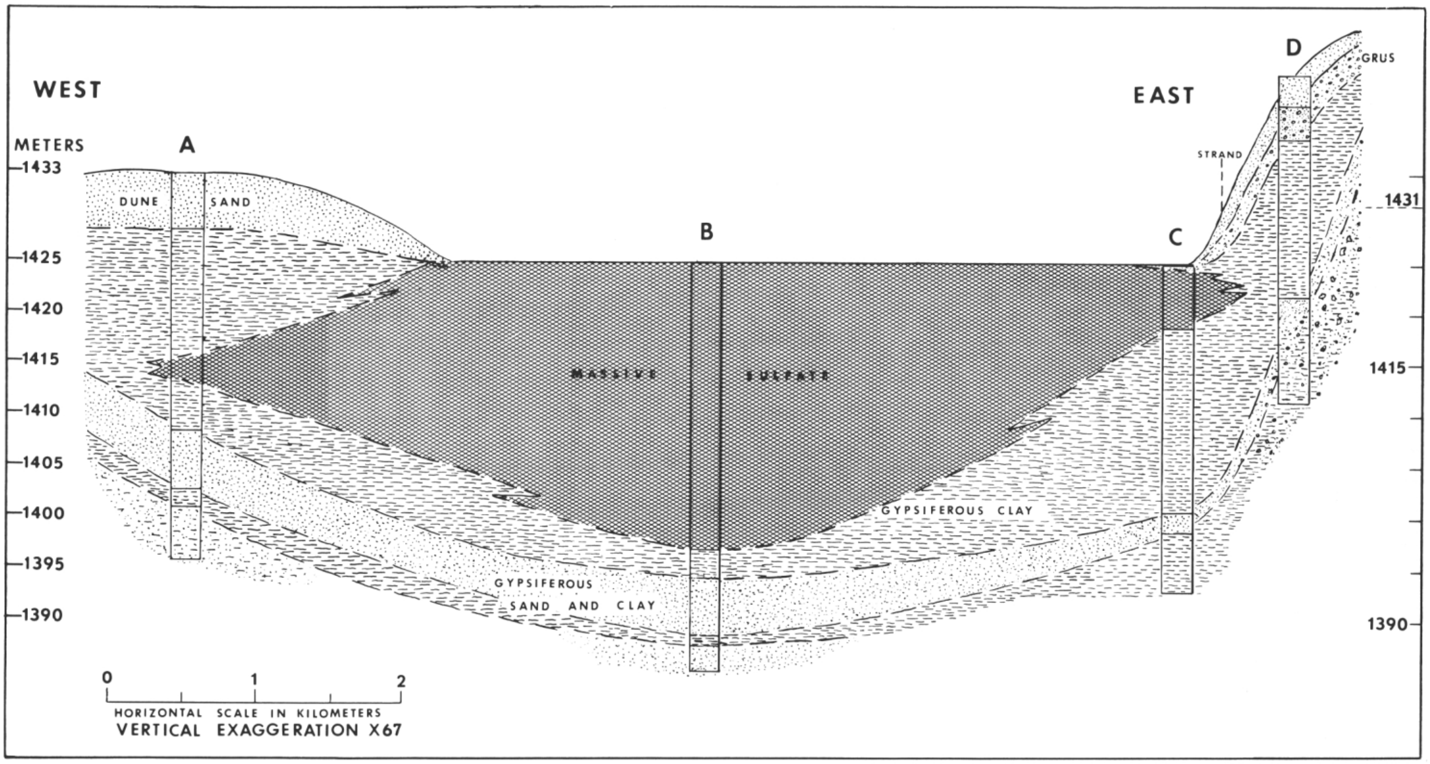

Figure 5. Generalized basin profile based on field logs (fig. 4), petrographic analysis (Table 1), and EDTA solubility (fig. 7). Location of transect is shown on Figure 1.

m within the gypsum facies in borehole B. It was probably formed by precipitation from solutions reaching saturation in magnesium sulfate. The hydrochemical implications of this sulfate zone will be discussed later.

At the western basin margin, quartz dune sands cover part of the surface of the massive gypsum zone. The contact at depth between the widespread dune sand and gypsum in borehole A is transitional with a gradual change in gypsum content. The gypsum crystals in the sand probably reflect secondary dissolution of gypsum and precipitation in place, so as to partially cement the sand. Stratigraphically, the dune sand is the youngest deposit in the basin.

The alluvial fans are the topographically highest deposits (but not necessarily the youngest). Much of this sediment is sand and gravel that thins abruptly at the contact with the sulfate body. Clast compositions reflect the granitic and limestone bedrock of the adjacent mountains.

MINERALOGY

Forty-one samples were analyzed from boreholes A, B, and C at depths ranging from 0.5 to 37.2 m (fig. 4). The first observations revealed that gypsum was dispersed in varying proportions throughout the material. Samples from borehole D on the eastern alluvial fan were not available for analysis but the field log was correlated with adjacent borehole C. Because of the highly dispersed nature of gypsum present in boreholes A, B, and C, three complementary methods were used to determine mineral composition and amount: x-ray diffraction, petrographic analysis, and chemical dissolution (for separation of solubles and insolubles).

X-ray diffraction was used to verify overall mineralogic composition of fine to coarse lake sediment and mineral distribution. Additional material from the samples was selected by sieving a <37 (— 400 mesh) fraction for clay extractions and a >37 p.m (— 400 mesh) portion for the 75-150)m6 fraction. Selected samples of these fractions were also x-rayed to determine mineral composition.

Much of the 75-1501.1m fraction (fine sand) was used for petrographic analysis to obtain a mineral distribution of the basin. The method involved mounting the material in index oils under cover glasses and making point counts (Table 1). The petrographic study was especially useful in identifying minor minerals that could not be identified by x-ray diffraction. Many of these procedures were adopted from a previous study of a playa lake by Deike and Jones (1980).

Leaching of soluble minerals by distilled water failed to produce acceptable results and gypsum peaks dominated the x-ray patterns, sometimes suppressing diffraction of important silicate minerals. It was necessary to use chemical procedures that would eliminate soluble minerals and gypsum without destroying silicates.

An effective dissolution agent for sulfates and carbonates is EDTA (ethyldinitriotetracetic acid) with the pH properly set between 10 and 12. This technique was adapted from Bodine and Fernald (1973). Results were quite satisfactory; reproducibility of a single sample analyzed six times ranged between 0.3 and 0.8 weight percent. The procedure was also helpful in delineating the sulfate zone.

The combination of all the field and laboratory investigations of Trinity basin revealed that the most abundant minerals were gypsum, quartz, clays (smectite and kaolinite), and feldspar, with lesser calcite and minor amounts of amphiboles, pyroxenes, dolomite, hexahydrite, and magnesite. Trace amounts of magnetite, hematite, highly weathered olivine, and rock fragments that appeared to be igneous detritus were noted in some samples.

Gypsum, the most abundant of two sulfates found in the basin, is primarily fine grained and massive. Satinspar (parallel, fibrous-looking fragments) was observed at 18.3 m in borehole A. Hexahydrite ($MgSO_4 \bullet 6H_20$) was identified in a 0.5-m layer at 18.7 m in borehole B only (figs. 4, 6). It is a product of epsomite ($MgSO_4 \bullet 7H_20$) dehydration in the presence of air at ordinary temperatures (Berry and Mason, 1968), but can also result from primary precipitation. This phase may have formed in situ in Lake Trinity by precipitation from highly saline, magnesium-rich solutions accumulating on the playa surface.

Table 1. Principal minerals in the 75–150 μm fraction as determined by petrographic analysis.

	Sample Depth (m)	Quartz	Gypsum	Calcite	Amphibole	Pyroxene	Feldspar	Clay
		MINERAL PERCENTAGES*						
A	1.2	40	30	7	5	10	--	6
	1.7	54	20	11	1	2	10	1
	3.1	58	21	8	--	3	8	2
	5.8	20	14	10	--	--	--	56
	12.5	54	10	6	3	1	20	5
	15.5	10	59	8	--	--	12	11
	18.3	13	62	--	4	5	4	12
	18.7	3	26	--	2	4	--	65
	24.7	20	5	10	10	--	10	45
	28.0	45	18	5	--	--	12	20
	30.5	--	--	--	--	--	--	--
	37.2	20	8	3	--	--	4	65
B	0.4	8	70	10	--	5	7	--
	1.9	2	80	--	13	3	2	--
	3.4	17	55	4	8	12	1	3
	4.9	6	69	--	15	3	6	--
	6.6	4	72	8	8	3	5	--
	9.4	6	56	--	20	3	15	--
	12.3	--	67	6	--	2	4	8
	15.6	1	75	2	8	4	8	2
	16.0	8	70	3	2	7	10	--
	18.7	--	7+	--	4	--	--	--
	21.7	--	65	30	--	1	4	--
	22.1	6	60	15	--	3	5	10
	24.8	3	70	25	--	--	--	2
	27.8	5	42	8	--	--	--	45
	31.6	57	15	--	--	3	25	--
C	0.8	10	65	2	--	--	9	14
	1.5	10	70	6	--	--	3	11
	3.0	8	70	10	--	--	9	--
	4.6	7	72	10	--	--	5	3
	6.1	6	63	10	--	--	3	18
	7.6	17	50	--	--	--	7	26
	9.1	34	44	6	4	4	10	--
	12.2	10	50	--	--	--	6	34
	15.2	24	20	++	--	--	10	38
	18.3	34	20	--	--	--	--	40
	21.3	30	10	--	--	--	2	58
	24.4	30	14	--	--	--	8	46
	27.4	43	17	10	2	2	12	12
	30.5	28	10	5	--	--	3	54

* Occasional magnetite, hematite, and highly weathered olivine were also observed.
\+ Hexahydrite accounted for 89% of sample and was observed only here.
++ Dolomite accounted for 9% of this sample, and may exist in other samples but was not verified.

Quartz is the second most abundant mineral in the basin and is the principal constituent of the clastic facies. As would be expected, the analyses show that quartz is most abundant in the dune sands on the west but is also predominant in the alluvial fans on the east, where it averages about 20 to 28 volume percent. Quartz is relatively minor in samples from the central sulfate zone, averaging about eight volume percent. The quartz is detrital in all cases.

Clay, like quartz, is abundant in the basin, commonly in aggregate particles, with the least concentration in the basin center and the highest concentration peripheral to the massive sulfate facies. Mineralogically, the clays are smectite, illite interstratifications and kaolinite.

Feldspars are also common detrital minerals in the basin; plagioclase and orthoclase occur at a ratio of about two to one. Point counts from petrographic slides showed an even distribution in the basin, but x-ray diffraction data suggested that the feldspars are more prevalent in the basin center and to the east.

In this evaporite playa, the typical solubility zoning, such as described by Hunt (1960) for the Death Valley salt pan, is not observed. One would ordinarily expect carbonates to fringe a sulfate zone which, in turn, surrounds a chloride zone, but neither carbonate nor chloride zones exist in the Trinity basin. Despite the absence of a discrete carbonate zone, 82 percent of the samples were slightly calcareous using the dilute HC1 test. Calcite, by far the most abundant carbonate, did not diffract well in all x-ray patterns but averaged 7.4 percent in point counts of samples from the center of the lake. Some calcite appears as single scalenohedral grains or crystalline aggregates. Other carbonates, such as dolomite and magnesite, were very sparse and showed no particular distribution pattern.

Figure 6. Core from borehole B, 18.3–19.0 m. Left half of core is mostly pure translucent hexahydrite, similar in appearance to ice. Aging and subsequent drying caused a change to a chalky form. Right half of core is finely banded gray gypsum, having consistency and texture similar to moist sand.

Minor minerals such as pyroxenes and amphiboles show by point count analysis a tendency to concentrate near the basin center, but the x-ray data show an irregular distribution. Pyroxenes include a green clinopyroxene (probably diopside), a brown orthopyroxene, and probably others. Amphiboles include hornblende and a colorless variety.

Clay Chemistry

Chemical analysis of the ultrafine (<0.1 11,m) clay-mineral residue from the EDTA dissolution treatment was done using the methods of Rettig and others (1983) and is presented in Table 2. These results indicate significant enrichment of magnesium in fine clays within the center of the basin and especially at the playa surface. The data suggest that this enrichment is preceded by an increase in potassium and iron. These are the same compositional trends noted by Jones and Weir (1983) in the authigenic transformation of more silicic clays in the alkaline-saline Lake Abert in south-central Oregon. Ignoring interstratification, intergrading, minor clay species, and assuming complete phase horn-

Table 2. Chemical composition of selected samples from boreholes A, B, and C; <0.1 μm EDTA dissolution residue.

	Sample Depth	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Total*
		Weight Percentage							
A	12.5	51.05	17.41	7.01	0.04	2.04	2.66	1.52	81.73
	15.5	48.15	18.28	6.88	0.03	2.21	3.03	1.45	80.03
	37.2	49.37	17.65	6.58	0.01	2.25	2.87	1.57	80.30
B	1.9	44.87	9.00	4.36	0.07	21.70	0.13	0.83	80.96
	27.8	45.59	18.11	6.31	0.06	10.13	0.19	2.53	82.92
C	1.5	44.94	8.92	4.32	0.11	20.86	0.18	0.83	80.16
	9.1	45.56	19.98	7.26	0.17	3.85	1.01	2.46	79.49
	21.3	46.94	21.87	7.69	0.01	2.09	1.23	2.33	82.16
	30.5	46.04	22.85	7.94	0.08	2.25	0.70	2.44	82.26

*Difference between total and 100% is attributed to H_2O plus volatiles

	Sample Depth	SMECTITE COMPOSITION, CATIONS PER 22 NEGATIVE CHARGES							Σ Octahedra	X^- (interlayer charge)
A	12.5	3.81	1.53	0.39	0.003	0.23	0.39	0.15	1.96	.55
	15.5	3.76	1.65	0.40	0.002	0.25	0.45	0.14	1.99	.59
	37.2	3.76	1.58	0.38	0.001	0.26	0.42	0.15	1.98	.57
B	1.9	3.44	0.81	0.25	0.006	2.48	0.02	0.08	2.98	.11
	27.8	3.41	1.59	0.36	0.005	1.13	0.03	0.24	2.49	.28
C	1.5	3.47	0.81	0.25	0.01	2.40	0.03	0.08	2.93	.13
	9.1	3.53	1.83	0.42	0.01	0.35	0.15	0.24	2.13	.41
	21.3	3.51	1.93	0.43	0.001	0.23	0.18	0.22	2.10	.401
	30.5	3.44	2.01	0.45	0.006	0.25	0.10	0.23	2.15	.35

Analysis by S. L. Rettig, U. S. Geological Survey

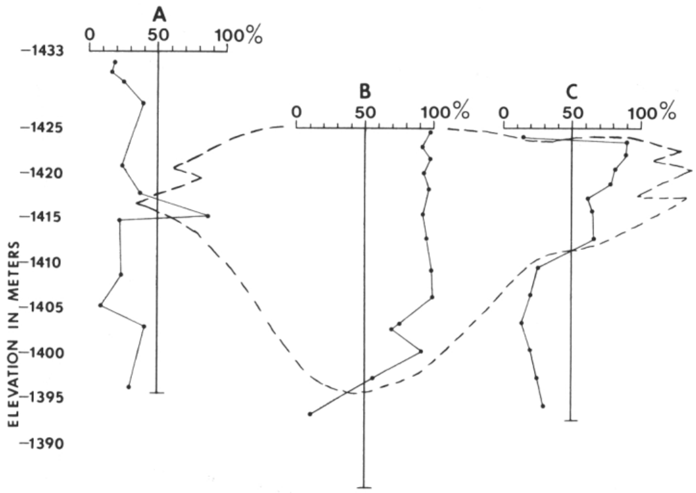

Figure 7. Weight percentage of EDTA-soluble minerals in boreholes A, B, and C, showing hypothetical boundary of massive sulfate zone (dashed line). Boundary drawn on basis of 50th percentile; sample depths marked by dots.

ogeneity in the ultrafine fraction of the Trinity basin clays, smectite formulas based on 22 negative charges were calculated and are given in Table 2. The trend in octahedral occupancy and interlayer charge in these general formulas suggest a transformation from a common detrital, dioctahedral, high-charge beidellite-type material to a low-charge, nearly completely trioctahedral saponite. This trend coicides with the magnesium enrichment in solution indicated by the occurrence of hexahydrite in the basin center, and because silicate transformations occur slowly, would suggest diagenetic reaction of the fine clays with more persistent saline playa waters than occur today.

BASIN HYDROCHEMISTRY

The general geology and hydrology of the northern Jornada del Muerto has been described by Weir (1965). Examination of Weir's data offers some immediate explanations for the character of the Trinity basin. According to Weir's geologic map (1965, Plate 1), about half of the northern and western boundary of the basin is in alluvium, which may have been derived from higher level, ancestral Rio Grande sediments prior to rift valley formation and downcutting of the trunk stream. Much of the south and east boundaries of Trinity basin are in upper Paleozoic strata of the northern San Andres Mountains, most notably the highly gypsiferous Yeso Formation. Water-table contours drawn by Weir (1965, Plate 1) slope discontinuously through alluvium of the Trinity basin area and show that it is not closed hydrologically. However, it is certainly a sump for surface waters, and ground water movement may be exceedingly slow. Hydrochemical data (Weir, 1965, Table 4) indicate that the ground water is saturated with gypsum and calcite, the latter perhaps less consistently. The small drainage area and incomplete closure can account for the lack of chloride accumulation. The high Mg content of the central basin clays, and the presence of hexahydrite at depth, suggests that dolomite was a more important soluble mineral constituent of the Paleozoic section than recognized in Weir's (1965, Table 5) lithologic descriptions for the area. The prevalence of gypsum and dolomite as solute sources for Trinity basin waters would be expected, on any amount of evaporative concentration, to lead to rapid and widespread precipitate loss of carbonate as $CaCO_3$. The lack of dolomite in the playa deposits attests to inhibition of its reprecipitation. Sulfate originally picked up from gypsum, with the calcium now lost to carbonate, becomes associated with magnesium in concentrating solutions. Weathering of the basalts to the west of the Trinity basin could be a significant source of magnesium, but infiltrating ground water would be expected to flow to the west. Also, detrital minerals assignable to a basaltic source, though more abundant in the west borehole, appear too fresh. Localization of the magnesium sulfate, in a single horizon, and the lack of both detectable sodium sulfate and chloride in the basin mineralogy, indicates the preponderance of sedimentary gypsum-dolomite solute source as opposed to silicate hydrolysis. Though pure magnesium sulfate is more soluble than NaC1, the overweening solute sulfate abundance can account for MgS0, precipitation prior to halite formation. Further, the absence of any chloride phase also suggests ground-water leakage, albeit very slowly, from the basin. In addition, the magnesium uptake by the Trinity basin clays has a significant effect in enhancing the NaC1 dominance of the chemistry of whatever ground water emerges from the basin.

AGE IMPLICATIONS

The sedimentary/evaporite sequence shown in the Trinity basin suggests semi-permanent, playa-lacustrine conditions different than currently exist, which is that of a playa that is rarely flooded. No age data were obtained during these studies and only relatively shallow subsurface sediments were examined. Nonetheless, it seems reasonable to assign a Pleistocene age to these deposits, consistent with that of the nearby Lake Otero basin and other Pleistocene lakes in New Mexico, such as Estancia, San Agustin, and Animas (Kottlowski and others, 1965).

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