# Core KM-3, a Surface-to-Bedrock Record of Late Cenozoic Sedimentation in Searles Valley, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1256

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*By* GEORGE I. SMITH, VIRGIL J. BARCZAK, GAIL F. MOULTON,
*and* JOSEPH C. LIDDICOAT

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*The basin sedimentation history of Searles (dry) Lake from Miocene or early Pliocene time to the present*

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# CORE KM-3, A SURFACE-TO-BEDROCK RECORD OF LATE CENOZOIC SEDIMENTATION IN SEARLES VALLEY, CALIFORNIA

By GEORGE I. SMITH, VIRGIL J. BARCZAK[1], GAIL F. MOULTON[2], and JOSEPH C. LIDDICOAT[3]


## ABSTRACT

A 930-m core designated KM-3, recovered from an area near the center of Searles Lake in Searles Valley, Calif., records a history of nearly continuous sedimentation from Miocene or early Pliocene time to the present. The earliest sedimentary deposits, 220 m of reddish-brown alluvial gravel, rest on 15+ m of quartz monzonite bedrock. Lacustrine sedimentation in ancestral Searles Lake started 3.18 million years ago (m.y. B.P.) and left 693 m of various types of lake deposits that make up the rest of the fill in that part of the valley where the core was recovered.

The lacustrine sediment is here divided into 14 informal stratigraphic units, three of which are new, on the basis of field logs, chemical and mineralogic data, and study of the preserved core and color photographs taken when the core was fresh. Quantitative reconstruction of the evaporite mineralogy, based on 254 analyses of the acid-soluble components and X-ray diffraction data, allows the details of chemical sedimentation to be documented. Ages of critical contacts are estimated from $^{14}C$ data (younger sediment), paleomagnetically established horizons (older sediment), and interpolation and extrapolation from these levels. Apparent sedimentation rates in core KM-3, overall, average 22 cm/1,000 yr; most older intervals have rates between 10 and 30 cm/1,000 yr, whereas younger, less compacted deposits average 53 cm/1,000 yr.

The upper five informal stratigraphic units beneath the surface of Searles Lake, described briefly above, extend to a depth of 69 m and represent approximately the past 0.13 m.y. The underlying lacustrine sediment, here referred to informally as the Mixed Layer, is subdivided into nine units (only seven of which can be separated in core KM-3), with the following lithologies, indicated depths, ages, and inferred depositional environments:

| Unit | Depth to base (m) | Lithology and color of mud | Age of base (m.y.) | Inferred lake character |
|---|---|---|---|---|
| A+B-------- | 114.0 | Salines and mud, olive-brown. | 0.31 | Perennial, intermediate to shallow depths, fluctuating. |
| C---------- | 166.4 | Salines---------- | .57 | Dry (salt flat), briefly perennial. |
| D+E-------- | 227.7 | Mud, olive-brown, some salines. | 1.00 | Mostly perennial, intermediate depths, occasionally desiccated. |
| F---------- | 291.1 | Mud, light- to dark-green. | 1.28 | Perennial, deep. |
| G---------- | 425.5 | Salines and mud, olive. | 2.04 | Perennial, intermediate depths, periodically desiccated. |
| H---------- | 541.6 | Mud, brown------ | 2.56 | Dry (playa), briefly perennial. |
| I---------- | 693.4 | Mud, olive------ | 3.18 | Perennial, deep. |

The most extreme change in sedimentation in Searles Valley was the shift from alluvial to lacustrine deposition 3.18 m.y. B.P., possibly as a result of volcanic damming of a river channel across the Sierra Nevada that had previously allowed part of the Great Basin to drain externally. Subsequent changes in the mineralogy and amount of chemical sediment in the lacustrine deposits indicate marked fluctuations in lake level superimposed on a gradual increase in the salinity of the deeper lakes and a progressive change in the chemistry of their waters. Upon concentration or desiccation, the composition of the saline deposits changed accordingly.

Paleoclimatic reconstructions indicate a decrease over time in the amount of runoff that fed the lake, partly owing to continuing uplift of the Sierra Nevada that created an enlarging rain shadow, although climatically induced variations in runoff caused fluctuations in inflow that exceeded this more gradual change. Correlation of the perennial lake deposits in Searles Valley with the Sherwin Till and the McGee Till of the Sierra Nevada—a reasonable relation because of the inferred hydrologic connection between these areas—suggests that the Sherwin Glaciation began 1.28 m.y. B.P., waned 1.00 m.y. B.P., but did not cease until 0.57 m.y. B.P., and that the McGee Glaciation may have extended from 3.18 to 2.56 m.y. B.P.


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## INTRODUCTION

Searles Valley, containing Searles (dry) Lake, lies near the southwest corner of the Basin and Range province and about midway between the south ends of the Sierra Nevada and Death Valley (fig. 1). Before the turn of the 20th century, the geomorphic record of abandoned shorelines and bars in Searles and nearby valleys allowed geologists to conclude that these valleys once contained a chain of lakes that were nourished chiefly by waters flowing from the east side of the Sierra Nevada into the ancestral Owens River system (see summary by Smith, 1979, p. 6–7). Then, as now, the Owens River terminated in Owens Lake. When filled, Owens Lake overflowed southward into Indian Wells Valley to form China Lake; China Lake, in turn, overflowed eastward into Searles Valley to form Searles Lake. At their highest stages, Searles and China Lakes coalesced into one large lake that drained southeastward into a stream that led to Panamint Valley, to form Panamint Lake. That lake, filled only during the most intense pluvial episodes, overflowed eastward into Death Valley and thus contributed, along with the Mojave and Amargosa Rivers, to the formation of what has been designated Lake Manly.

The existence of lakes older than those responsible for the geomorphic record in Searles and the other closed valleys has long been suspected. Cores from Owens, China, Searles, Panamint, and Death Valleys show that the sediment deposited in perennial lakes extends to depths of at least 200 to 300 m (Smith and Pratt, 1957; Hunt and Mabey, 1966, table 19). The age of this deeper sediment was commonly estimated at early or middle Pleistocene. Lakebeds of comparable age crop out along the flanks of these valleys, and projections of the fine-grained facies suggest that deep lakes once occupied large areas now covered by playa or alluvial sediment. Lakebeds, many slightly deformed, also crop out east of Long Valley (Rinehart and Ross, 1957; Bailey and others, 1976), east of the central part of Owens Valley (Walcott, 1897; Hopper, 1947 p. 418), southeast of Owens Lake (Schultz, 1938, p. 78; Hopper, 1947, p. 415-416; Duffield and Bacon, 1977), north of Indian Wells Valley (Duffield and Bacon, 1977), south of Searles Valley (Smith, 1964, p. 40-42), and on the periphery of much of Death Valley (Hunt and Mabey, 1966, p. A69-A72).

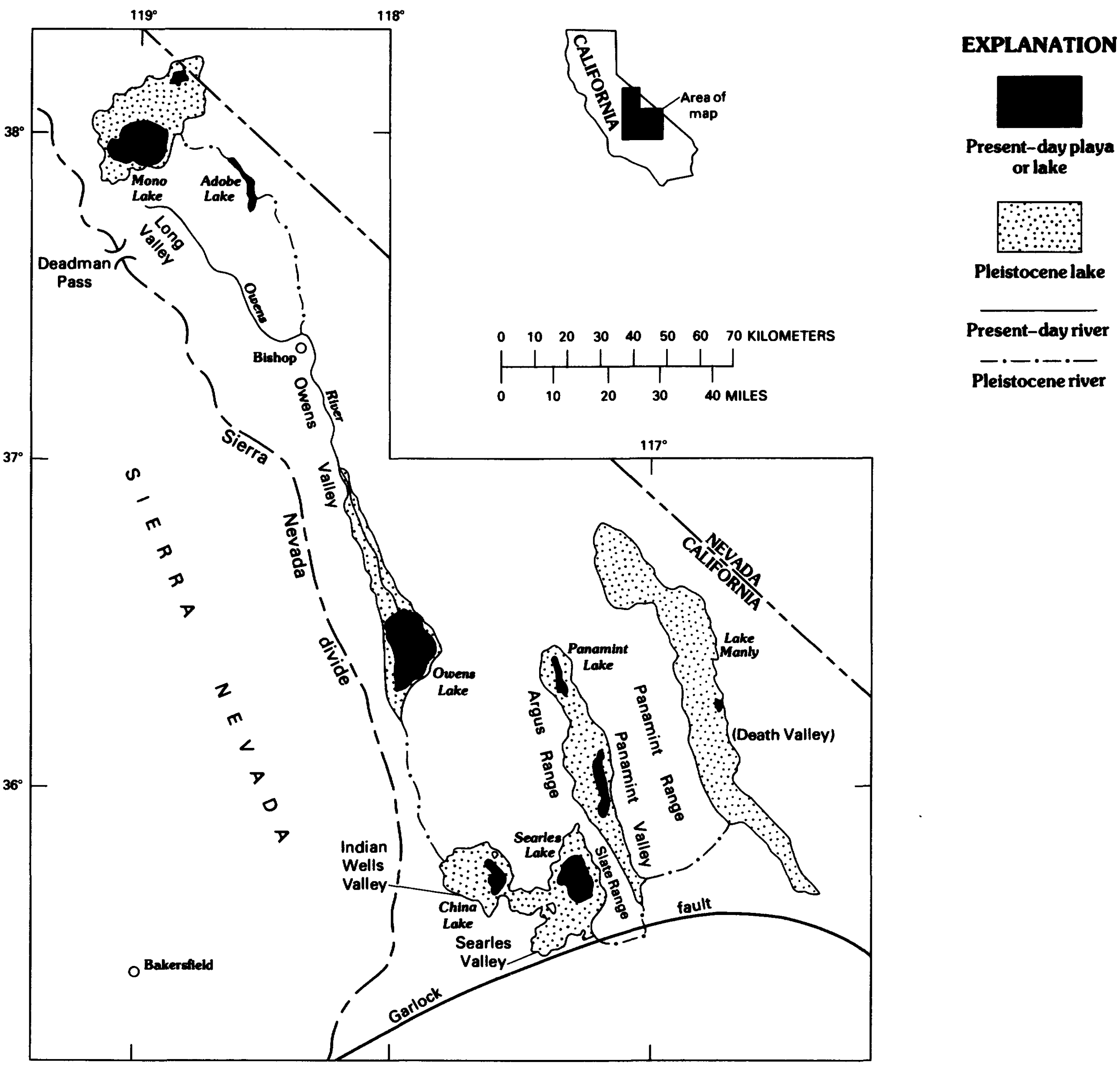


FIGURE 1.—Positions of late Pleistocene and present-day lakes in the chain that included Searles Lake.

The core described in this report documents for the first time that lakes have existed in the depression now known as Searles Valley for more than 3 m.y., a length of time exceeding that assigned to the Quaternary Period. The age of the sediment at 267 m in the deepest core previously available from Searles Lake was estimated to be 0.5 to 1.0 m.y. (Smith, 1979, p. 109).

## HISTORY OF CORING IN SEARLES VALLEY

Several hundred cores representative of the upper 50 m of sediment beneath the present surface of Searles Valley have been described previously (Gale, 1914; Haines, 1959; Smith, 1979). These cores were mostly taken in the course of commercial exploration and development by the several industrial chemical companies that have been extracting concentrated brines from this saline deposit during most of the 20th century, although about 40 cores to this depth were obtained by the U.S. Geological Survey during the 1950's to define better the geology of the deposit. The aggregate value of chemicals produced from the brines of Searles Lake is about $2 billion. Subsurface deposits to the depth of 50 m are alternating layers of mud[4] (indicating large and relatively fresh lakes) and salts (indicating small saline or dry lakes), in about equal volumes. Two deeper cores, taken as part of special exploration programs, extend to depths of 191 and 267 m (Gale, 1914; Smith and Pratt, 1957).

In 1967, the Kerr-McGee Chemical Corp. (KMCC) absorbed the holdings of the American Potash & Chemical Corp. in Searles Valley, including its fee land near the middle of Searles Lake. On July 5, 1968, KMCC started drilling an exploratory corehole in this area and designated it KM-3 (fig. 2). Coring reached bedrock in September 1968 at a depth of 915 m; an additional 15 m of drilling in bedrock brought the total depth on September 6 to 930 m. On June 3, 1976, permission was granted by D. A. McGee, Chairman of the Kerr-McGee Corp., (parent to KMCC), for the U.S. Geological Survey to study the company's internal report, a highly detailed description of the core (Barczak and Petticrew, 1969), to make additional studies of the preserved core, and to publish a description of it using the company data. In this report, we (1) present a description of the core, with emphasis on its chemistry, mineralogy, and lithology; (2) interpret the various depositional environments indicated by its components and establish stratigraphic units on that basis (table 1); and (3) discuss the implied climates and their relation to Sierra Nevada glacial stages.

## METHODS OF STUDY

### LITHOLOGY

Core KM-3, approximately 8 cm in diameter, was logged at the drill site by T. S. Melancon of KMCC, and several hundred lithologic units were identified and described. The saline minerals were identified at that time by megascopic methods, and the logged descriptions of the fine-grained mud zones included grain

[4]The term "mud" as used in this report is an all-inclusive term for clay, silt, and marl that were moist and plastic when first extracted as core. The deeper sediment may have been more indurated and could be more correctly named using rock terms, but the field log implies an absence of induration by using the term "mud" throughout the lacustrine section. The field log describes the alluvial sand and gravel as "arkose," implying greater induration, but we have used sediment terms for that part of the section as well because the lithology of these segments of the core can be more accurately described in this way.

TABLE 1.—*Summary of stratigraphic units in core KM-3*

[Ages to 0.032 m.y. are based on $^{14}C$ dates; ages to 0.13 m.y. were estimated by extrapolation from depositional rates (Smith, 1979, p. 77–78). Older ages are based on extrapolation or interpolation between nearest dated paleomagnetic boundaries, located with accuracies ranging from 0.1 to 10.6 m (Liddicoat and others, 1980)]

| Stratigraphic unit | Depth to base (m) | Thickness (m) | Dominant lithology | Age of base (m.y.) | Length of depositional period ($10^3$ yr) |
|---|---|---|---|---|---|
| Overburden Mud | 5.8 | 5.8 | Mud [1] | 0.006 | 6(?) |
| Upper Salt | 19.9 | 14.1 | Salines | .010 | 4(?) |
| Parting Mud | 25.0 | 5.1 | Mud | .024 | 14 |
| Lower Salt | 37.9 | 12.9 | Salines and mud | .032 | 8 |
| Bottom Mud | [2]69.0 | 31.1 | Mud | .13 | 98 |
| Mixed Layer | | | | | |
| Unit A+B | 114.0 | 45.0 | Salines and mud | .31 | 180 |
| Unit C | 166.4 | 52.4 | Salines | .57 | 260 |
| Unit D+E | 227.7 | 61.3 | Mud, some salines | 1.00 | 430 |
| Unit F | 291.1 | 63.4 | Mud | 1.28 | 280 |
| Unit G | 425.5 | 134.4 | Salines and mud | 2.04 | 760 |
| Unit H | 541.6 | 138.4 | Mud | 2.56 | 520 |
| Unit I | 693.4 | 151.8 | --do | 3.18 | 620 |
| Alluvial sand and gravel | 915.5 | 221.9 | Coarse sand and gravel | ? | ? |
| Bedrock | 929.6 | 14.1+ | Quartz monzonite | --- | --- |

[1]Not recovered as core by KM-3. [2]Depth in core 289M, 150 m north of KM-3.

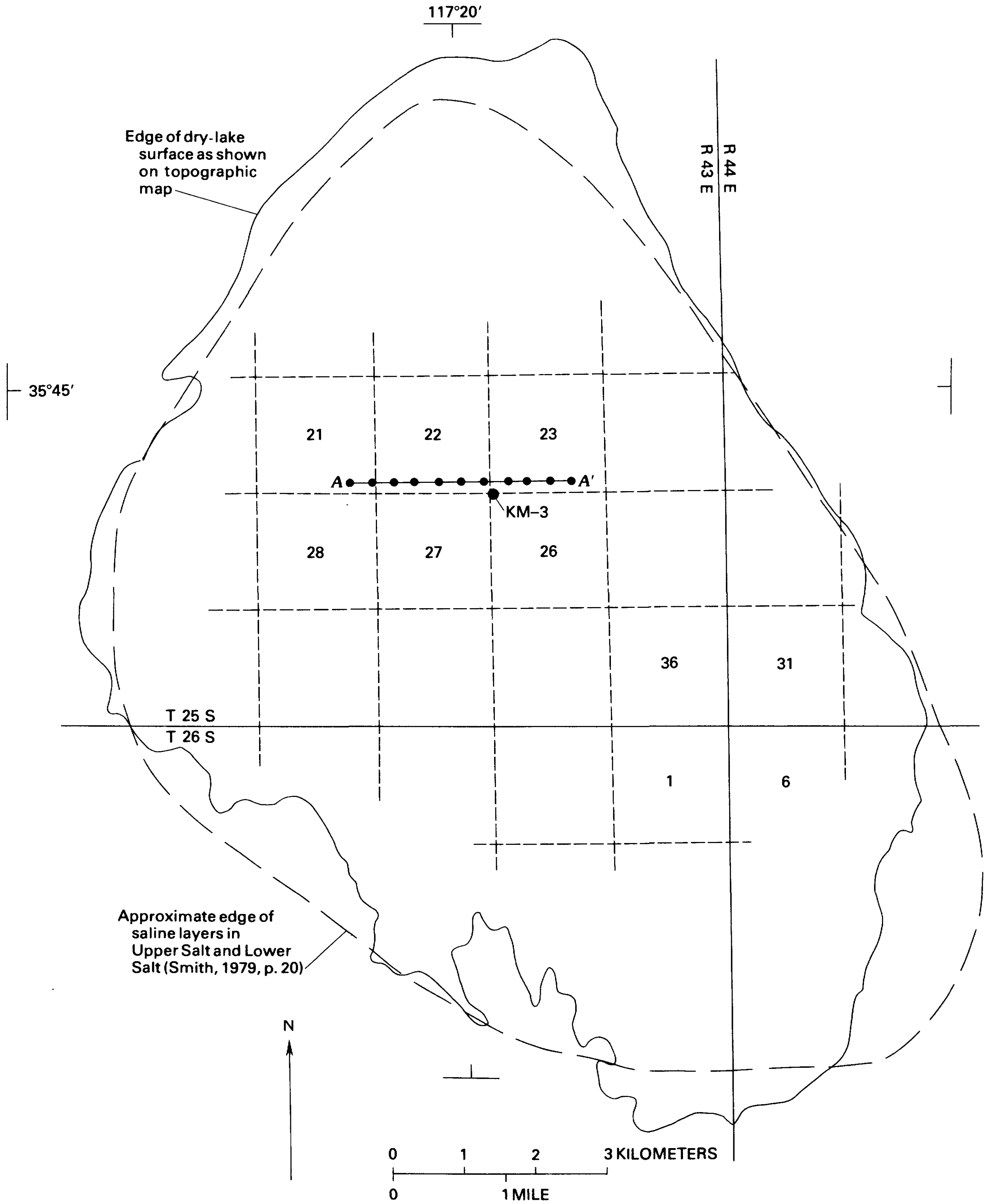


FIGURE 2.—Searles (dry) Lake, showing location of corehole KM-3, locations of cross section *A-A′* and coreholes plotted in figure 5, and approximate limits of dry lake using two criteria.

size, bedding character, and color. After logging, the core was split, and one face was photographed in color under standardized lighting conditions and with a gray density scale to assure uniformity of the prints. We later used these prints to modify and generalize the original field log and to assign standard rock colors (Goddard, 1948).

The descriptive log included here (table 2) lists the most conspicuous lithologies, minerals, textures, and colors, on the basis of the field log, the photographic record, the detailed mineralogic and chemical data later obtained by Kerr-McGee personnel at their Technical Center in Oklahoma City, and some reexamination of the preserved cores. For brevity, this descriptive log combines similar units so that it contains only about a fourth of the entries in the detailed log prepared for the chemical and mineralogic analysis and the company's internal report; we used that detailed log, however, to compile the graphic lithologic log (pl. 1).

TABLE 2.—*Generalized log of core KM-3*

| Depth to base of unit (m) | Thickness of unit (m) | Description |
|---|---|---|
| 5.8 | 5.8 | Not cored. Overburden Mud is included in this zone. |
| 19.9 | 14.1 | *Upper Salt.*—Salines, mostly trona and halite; abundant hanksite near top, borax at base; light- to medium-gray (N6-8) and yellowish-gray (5Y8/1), with some thin interbeds of olive-gray (5Y4/1) mud; mostly indistinctly bedded to massive, locally vuggy. |
| 25.0 | 5.1 | *Parting Mud.*—Megascopic crystals of gaylussite and pirssonite in soft mud composed of microscopic crystals of dolomite, halite, aragonite, other evaporite minerals, and clastic silicates; light- to moderate-olive-gray (5Y3-5/1-4); upper part finely laminated, lower part massive. |
| 37.9 | 12.9 | *Lower Salt.*—Seven saline layers interbedded with six mud layers; salines are mostly halite and trona in upper two layers, trona, halite, and burkeite in underlying two layers, and trona in lower three layers; interbedded mud layers contain megascopic crystals of gaylussite and pirssonite; salines range in color from white through dark gray to yellowish orange (N5-8, 10YR6/6), mud from dark olive gray to brown (5Y4-6/1-4); salts poorly bedded to massive; some mud layers have thin laminar bedding. |
| 69.0 | 31.1 | *Bottom Mud.*—Mud containing megascopic gaylussite crystals; mud is composed of microscopic crystals of dolomite, aragonite, calcite, and other carbonate minerals, and about 30 percent acid-insoluble silicates and organic residues; thin-bedded to massive, with some laminar bedding; medium- to dark-brown, brownish-gray, and olive (5YR4/4 to 5Y3-4/1-2). Discontinuous saline layers at 41.4 m (0.5 m thick), 48.5 m (0.4 m thick), and 54.4 m (0.8 m thick). |
| 90.8 | 21.8 | Interval of poor core recovery; recovered core (3.4 m) is composed of mud containing megascopic gaylussite crystals, massive, medium- to dark-brown and olive (5YR5/2 to 5Y3/2). Top of interval probably represents top of Mixed Layer. This and following three units probably represent Units A and B of Mixed Layer, of which most of the saline layers were lost during drilling (see text). |
| 95.4 | 4.6 | Salines, mostly trona, containing mud; faintly bedded to massive; moderate-brown to olive (5YR4/4 to 5Y5/1). |
| 99.8 | 4.4 | Mud, mostly acid-insoluble material, some dolomite; light-olive-gray (5Y5-6/1-2), thin-bedded. |
| 114.0 | 14.2 | Salines, mostly trona, with small amounts of other minerals and extensive mud impurities; light- to dark-green and brown (5GY5/1, 5Y4-6/1, 5YR3/4); faint bedding in lighter colored salines, with interbeds of mud common near base. Contact between Units B and C of Mixed Layer is at base of this interval. |
| 124.0 | 10.0 | Salines, with some interbedded mud; saline minerals are mostly halite, with smaller amounts of trona and other evaporite minerals; indistinct bedding, beds mostly 1 to 2 cm thick; salines light- to dark-olive-gray (5Y4-7/1-2) and moderate-brown (10YR4-6/2-4). |
| 130.4 | 6.4 | Salines and some mud; salines are about two-thirds halite and one-third trona, with some thenardite; yellowish-gray (5Y5-7/2); upper part of unit contains largest percentage of mud impurities. |
| 135.6 | 5.2 | Salines, mostly halite, with minor trona and thenardite; dark- to medium-gray (N3-5); upper part of unit contains mud impurities. |
| 151.2 | 15.6 | Interbedded mud and salines; salines are mostly halite, with some trona; salines olive-gray (5Y4/1 to 5Y6/1), mud brownish-black (5YR2/1); saline layers, 0.3 to 0.6 m thick, constitute about one-third of zone. |
| 166.4 | 15.2 | Salines, mostly halite, with smaller amounts of trona and thenardite, nearly pure in lower part; mostly gray to yellowish-gray (N4-7 to 5Y4-6/1); bedding 1 to 2 cm thick, some zones porous but most nonporous. Contact between Units C and D+E of Mixed Layer is at base of this interval. |
| 178.6 | 12.2 | Mud containing megascopic crystals of gaylussite and pirssonite, microscopic crystals of |

TABLE 2.—*Generalized log of core KM-3*—Continued

| Depth to base of unit (m) | Thickness of unit (m) | Description |
|---|---|---|
| | | dolomite, halite, and probably other acid-soluble minerals; brownish-black (5YR2/1) in upper and lower part, moderate-brown (5YR3/4) in middle. |
| 186.5 | 7.9 | Mud, with interbedded salts at 179 and 184 m; salts, in beds 0.1 and 0.6 m thick, are mostly halite and trona, with some thenardite and northupite; mud is composed largely of microscopic crystals of dolomite and other carbonates; olive to brownish-black (5Y2/1 to 5YR2/1). |
| 192.0 | 5.5 | Salines interbedded with mud containing scattered saline crystals; salines are mostly halite, with subordinate trona, thenardite, and other minerals; salines olive-gray and medium- to dark-gray (5Y6/1 to N4–6), mud dark-olive-black (5Y1–2/1). |
| 196.1 | 4.1 | Mud, dark-olive-black (5Y1–2/1). |
| 196.6 | 0.5 | Salines, mostly halite; olive-gray (5Y4/1). |
| 204.5 | 7.9 | Mostly mud, with some disseminated saline crystals; brown (5YR3/4) in upper part, olive-gray (5Y4/1) in lower. |
| 207.4 | 2.9 | Salines, with interbedded mud; salines are mostly halite, distinctly bedded, averaging 1 cm in thickness; salines yellowish-gray (5Y7/2), mud olive-gray (5Y4/1). |
| 210.9 | 3.5 | Mud, moderate-brown (5YR4/4) in upper half, olive-black (5Y2/1) in lower part. |
| 213.6 | 2.7 | Salines, mostly halite, with mud impurities; olive-black (5Y2/1) to light-olive-gray (5Y6/1); upper part faintly bedded, lower part massive to mottled. |
| 218.4 | 4.7 | Mud, massive, olive-black (5Y3/1). |
| 218.5 | 0.1 | Salines, trona and halite. |
| 227.4 | 8.9 | Mud, massive, olive-black (5Y2/1). |
| 227.7 | 0.3 | Salines, trona and halite. Contact between Units D+E and F of Mixed Layer is at base of this interval. |
| 248.1 | 20.4 | Mud, mostly grayish-olive (5GY4/1), with a grayish-brown (5YR3/2) zone at 236–238 m and a greenish-gray (5GY6/2) zone at 244–245 m. |
| 249.5 | 1.4 | Mud, dark-greenish-gray (5GY4/1), mottled to faintly bedded; lower half extremely hard (limestone). |
| 271.4 | 21.9 | Mud, with irregular concentrations of a few mottled areas caused by light-colored dolomite or salts; mostly pale- to grayish-green (10G4–6/2), upper 3 m grayish-olive-green (5GY3/2); massive except near 260 and 268 m, where thin to laminar bedding is defined by pale-orange (10YR6–8/2–4) layers (dolomite?). |
| 276.9 | 5.5 | Mud, similar to interval above but containing searlesite. |
| 291.1 | 14.2 | Mud, similar to that at 249.5 m. Contact between Units F and G (new) of Mixed Layer is at base of this interval. |
| 294.4 | 3.3 | Impure salines with mud impurities similar to interval above; salines, mostly halite and thenardite, are mottled aggregates surrounded by mud. |
| 299.3 | 4.9 | Mud, dusky-yellow-green (5GY5/2); upper part mottled, lower part has buff laminae and thin beds. |
| 306.3 | 7.0 | Salines and some mud; salines are chiefly halite and thenardite, white to light-gray (N5-8); mud pale-green (10G6/2); upper part faintly bedded, lower part mottled. |
| 324.3 | 18.0 | Two saltbeds separated by mudbeds (see pl. 1); salts, largely halite, massive, light-greenish-gray (5GY6-8/1); muds massive, greenish-gray (5G6/1). |
| 333.1 | 8.8 | Three mud and two impure salt layers (pl. 1); mud pale-green (10G6/2), massive, with dispersed salts; saline layers, consisting of mottled zones of lighter colored secondary crystals oriented randomly in mud matrix, are halite, with some thenardite, glauberite, and anhydrite. |
| 334.7 | 1.6 | Impure salts, halite; dark-greenish-gray (5GY4/1). |
| 337.3 | 2.6 | Mud containing some halite; brownish-gray (5YR4/1). |
| 341.1 | 3.8 | Muddy salt grading downward into impure mud; salts largely halite and anhydrite; mud dark-greenish-gray (5GY4/1). |
| 345.3 | 4.2 | Mud with some dispersed salts; massive, faint mottled coloring; olive-gray (5Y4/1). |
| 405.7 | 60.4 | Nine alternating salt and mud layers in nearly equal volumes, with individual layers generally 4 to 6 m thick (see pl. 1); salts are halite and other saline minerals, mostly light- through medium-gray (N5–7) to light-olive-gray (5Y6/1) and grayish-orange-pink (5YR7/2); mud greenish-gray (5G4-6/1) to dark-greenish-gray (5GY4/1); mud is massive except in 0.5-m-thick zone below saltbeds, where it is thin bedded; salts are faintly bedded to massive. |
| 413.3 | 7.6 | Mud; inadvertently not photographed, but reported by field log as green to brown. |
| 422.5 | 19.3 | Core not recovered. |
| 425.5 | 22.3 | Mud, soft and plastic, olive-black (5Y2/1). Contact between Units G and H (new) of Mixed Layer is at base of this interval. |
| 437.7 | 12.2 | Mud, with small crystals of thenardite dispersed randomly; more coherent than interval above; average moderate-brown (5YR3/4). |
| 444.6 | 6.9 | Mud, soft and plastic, olive-black (5Y2/1). |

TABLE 2.—*Generalized log of core KM-3*—Continued

| Depth to base of unit (m) | Thickness of unit (m) | Description |
|---|---|---|
| 449.6 | 5.0 | Mud, more coherent than interval above; moderate-brown (5YR3/4). |
| 451.4 | 1.8 | Salts and mud; salts in thin beds and mottled areas, yellowish-gray (5Y8/1), chiefly glauberite and anhydrite, with some halite; mud massive, olive-gray (5Y4/1). |
| 482.5 | 31.1 | Mud, moderate-brown (5YR3/4), with some zones of light-olive-gray (5Y5-6/1-2); salts largely halite and anhydrite, both dispersed and concentrated in mottled zones. |
| 483.4 | 0.9 | Mud and some salts; mud olive-gray (5Y4/1), thin bedded; salts are chiefly anhydrite and halite. |
| 494.4 | 11.0 | Mud, moderate-yellowish- to pale-brown (10YR5/2-4), massive. |
| 507.5 | 13.1 | Mud, light-olive-gray (5Y5/2) to pale-yellowish-brown(10YR/2), 2-m-thick zone at 502 m is pale brown (5YR5/2). |
| 507.8 | 0.3 | Mud and salt; mud light-olive-gray (5Y5/2); salts are mostly glauberite. |
| 516.6 | 8.8 | Mud and disseminated salts; light-olive-gray (5Y6/1) to pale-yellowish-brown (10YR6/2). |
| 524.0 | 7.4 | Mud; moderate-brown (5YR4/4) in upper part, yellowish-brown (10YR6/2) to pale-brown (5YR5/2) in lower part. |
| 530.1 | 6.1 | Mud; upper part greenish-gray (5GY6/1), mottled, thin-bedded to massive; lower part yellowish-brown (10YR6/2), thin-bedded. |
| 541.6 | 11.5 | Mud, mottled, pale-brown (5YR5/2) to pale-yellowish-brown (10YR6/2). Contact between Units H and I (new) of Mixed Layer is at base of this interval. |
| 582.2 | 40.6 | Mud, olive-gray (5Y4/1) down to 558 m, light-olive-gray (5Y6/1) below that depth, with 2-m-thick pale-brown (5YR5/2) zone at base. |
| 634.0 | 51.8 | Mud, light-olive-gray (5Y5-6/1-2). |
| 640.1 | 6.1 | Mud, brownish- black (5YR2/1) to olive-black (5Y2/1). |
| 649.2 | 9.1 | Mud, light-olive-gray (5Y5-6/1-2) and pale-olive (10Y6/2). |
| 658.7 | 9.5 | Mud; grayish-olive (10Y4/2) in upper part, yellowish-gray (5Y6/2) in lower part. |
| 681.5 | 22.8 | Mud, mostly pale-olive (10Y6/2) to yellowish-gray (5Y7/2), with zones near-olive-gray (5Y4/1) at 662, 665, and 669 m. |
| 684.0 | 2.4 | Tuff mixed with mud, grading down into pure tuff; impure tuff is olive-gray (5Y4/1), pure tuff yellowish-gray (5Y7/2); well indurated in basal 40 cm. |
| 690.4 | 6.4 | Mud, silt- to sand-size; mottled, ranging in color from olive gray (5Y4/1) to dark yellowish brown (10YR4/2) |
| 690.9 | 0.5 | Tuff, yellowish-gray (5Y6-8/1), well-indurated, crossbedded. |
| 693.4 | 2.5 | Mud and sand; faint to conspicuous thin beds, light-olive-gray (5Y5/2), with streaks of pale-brown (5YR5/2). Contact between Unit I of Mixed Layer and alluvial sand and gravel is at base of this interval. |
| 915.3 | 211.9 | Pebbly arkosic sand and gravel, most commonly moderate brown (5YR3-4/4), with zones that average light brown (5YR6/4) in color between 726-740 and 748-798 m; mostly coarse to very coarse sand, poorly sorted, containing quartz monzonite and volcanic-rock fragments, as large as 15 cm in diameter; faintly bedded to massive; not cored between 748.3-793.4, 804.7-826.3, and 839.1-903.1 m. |
| 929.6 | 14.3 | Quartz monzonite, light- to medium-gray (N5-7), with pale-brown (5YR5/2) stains along fractures extending through cored interval; rock bit was used from 915.3 to 926.3 m, and so no core was recovered. |

## CHEMISTRY

The half of the core not photographed was again cut lengthwise, and one part was sent to the Kerr-McGee Technical Center in Oklahoma City for mineralogic and arc-emission spectrographic analyses; the other part was sent to the KMCC laboratories at Whittier, Calif. At Oklahoma City, the core was divided into 254 intervals on the basis of lithology, and chemical analyses of the same intervals were performed at the Whittier laboratories. The percentage of the acid-insoluble residue, and the percentages of seven elements in the acid-soluble fraction (Na, K, $CO_3$, $SO_4$, Cl, $B_4O_7$, Br), were determined in all 254 samples, as well as the percentages of three more elements in the acid-soluble fraction (Ca, Mg, Li) in a slightly smaller number of samples.

The results of the analyses on 254 samples have been reduced here to 144 units by calculating and combining weighted averages for successions of analyses of similar materials. The percentages of acid-soluble Ca, Na, $CO_3$, $SO_4$, and Cl, and of the acid-insoluble residue, are plotted in stratigraphic order on plate 2. Samples not analyzed for Ca are known to be low and are plotted as if they contained none. Figure 3 plots the contents of K, Li, Br, and $B_4O_7$, which gener-

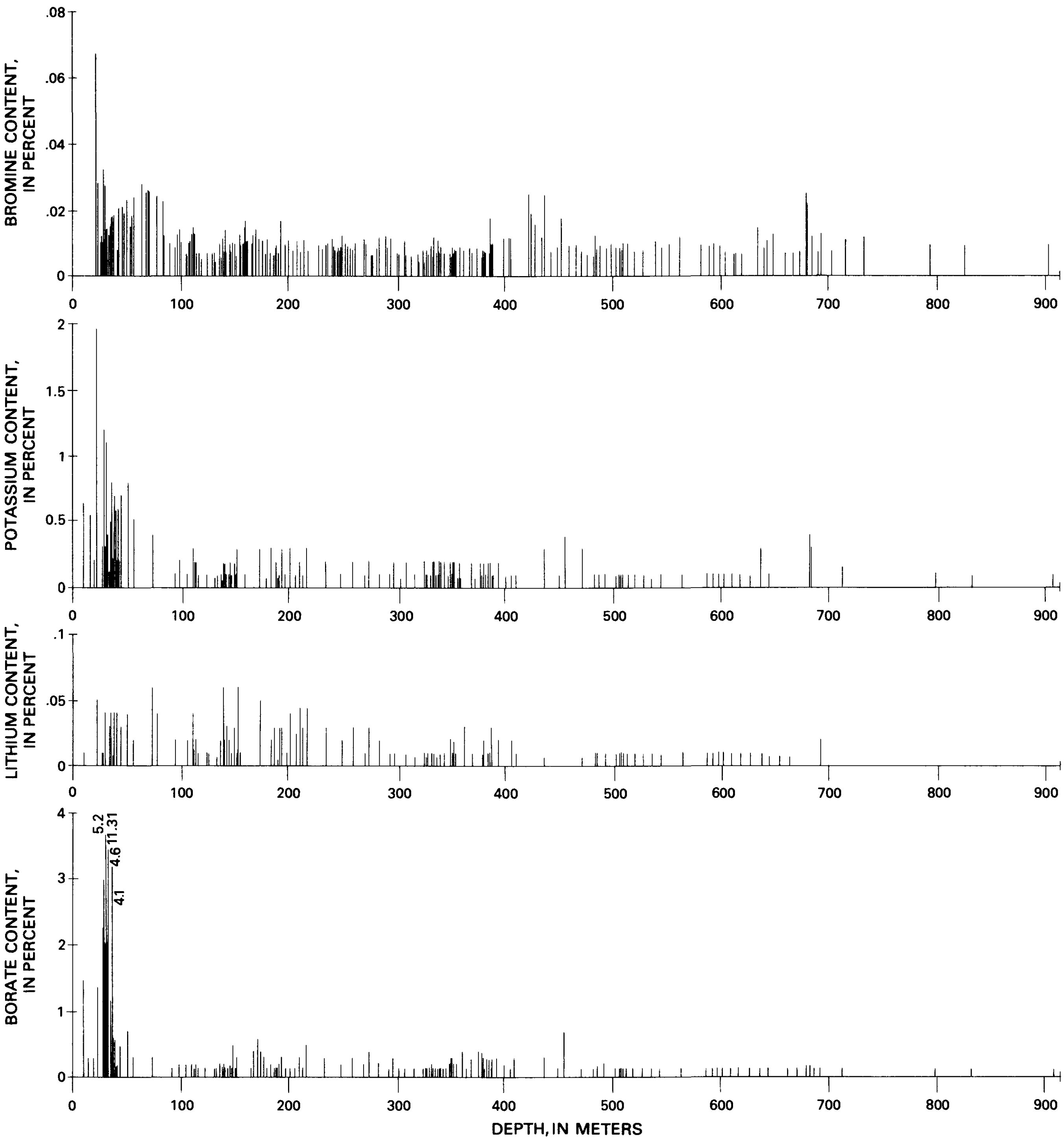


FIGURE 3.—Chemical analyses of samples from core KM-3 for borate ($B_4O_7$), lithium (Li), potassium (K), and bromine (Br).

ally exist in smaller amounts. On plate 2, the sums of acid-soluble cations and anions plus acid-insoluble material are less than 100 because the percentage of $H_2O$ was not determined, and the less abundant components (fig. 3) combine to account for several percent of the sample. Arc-emission spectrographic analyses for Mn, Mo, Ti, and V in selected samples from core KM-3 (fig. 4) indicate the amounts of these elements present in the total sample.

## MINERALOGY

X-ray diffraction methods provide the primary basis for identification of the mineral species in core KM-3. Most minerals reported to exist in amounts greater than about 5 percent were observed on X-ray diffraction charts, and some were checked microscopically. The names and chemical compositions of the nonclastic minerals found in core KM-3 are as follows:

| *Mineral* | *Composition* |
|---|---|
| Analcime | $NaAlSi_2O_6 \cdot H_2O$ |
| Anhydrite | $CaSO_4$ |
| Aragonite | $CaCO_3$ |
| Borax | $Na_2B_4O_7 \cdot 10H_2O$ |
| Burkeite | $2Na_2SO_4 \cdot Na_2CO_3$ |
| Calcite | $CaCO_3$ |
| Celestite | $(Sr, Ba) SO_4$ |
| Dolomite | $CaMg (CO_3)_2$ |
| Gaylussite | $CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$ |

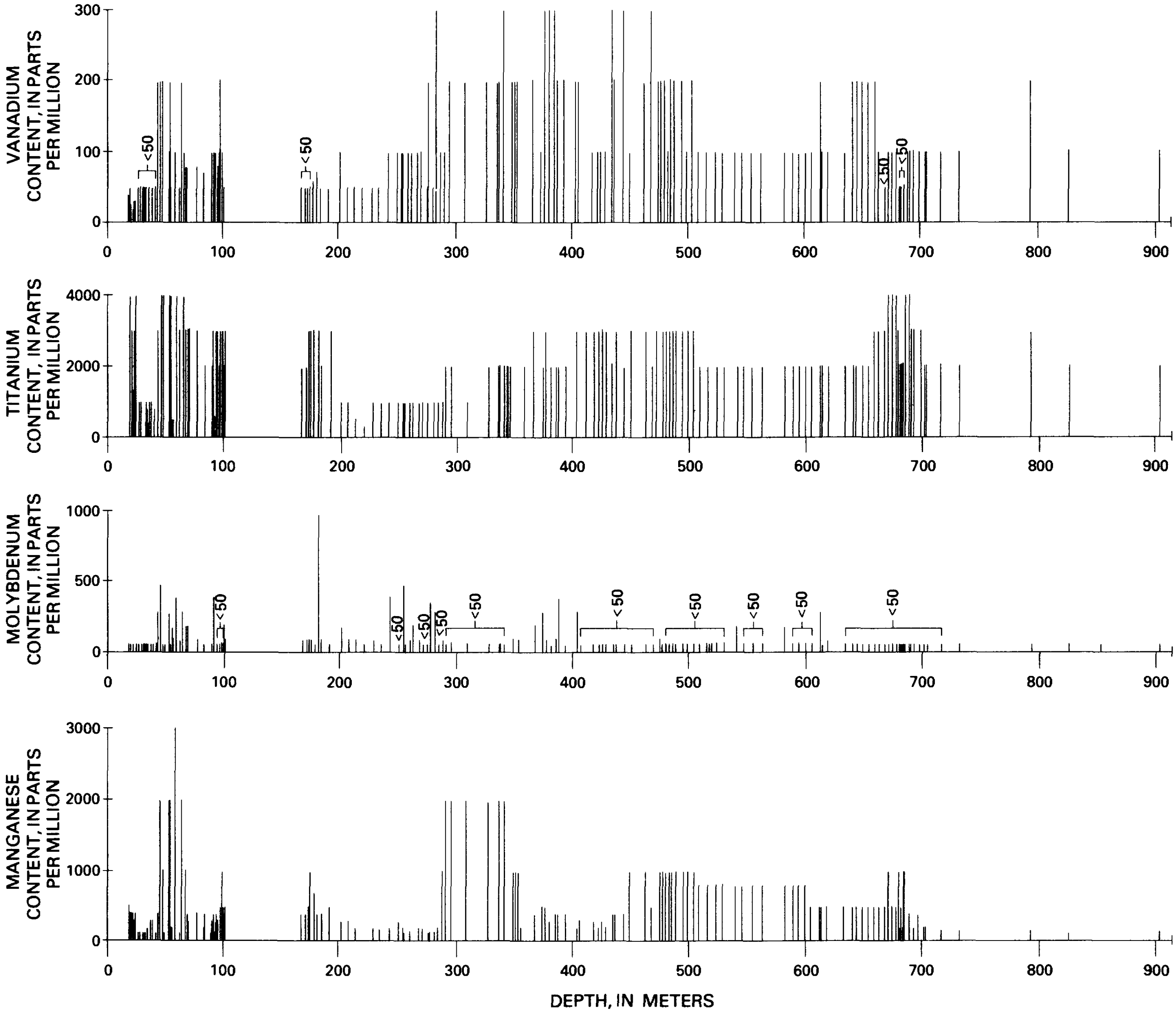


FIGURE 4.—Arc-emission spectrographic analyses of samples from core KM-3 for manganese (Mn), molybdenum (Mo), titanium (Ti), and vanadium (V).

| *Mineral* | *Composition* |
|---|---|
| Glauberite | $Na_2SO_4 \cdot CaSO_4$ |
| Gypsum | $CaSO_4 \cdot 2H_2O$ |
| Halite | NaCl |
| Hanksite | $9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$ |
| Heulandite | $CaO \cdot Al_2O_3 \cdot 6SiO_2 \cdot 5H_2O$ |
| Magnesite | $MgCO_3$ |
| Nahcolite | $NaHCO_3$ |
| Northupite | $Na_2CO_3 \cdot MgCO_3 \cdot NaCl$ |
| Pirssonite | $CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$ |
| Searlesite | $NaBSi_2O_6 \cdot H_2O$ |
| Thenardite | $Na_2SO_4$ |
| Tincalconite | $Na_2B_4O_7 \cdot 5H_2O$ |
| Trona | $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$ |

Most of these minerals have been previously reported from Searles Lake (Smith and Haines, 1964; Smith, 1979), but six are new. Glauberite and anhydrite, which occur in appreciable amounts in core KM-3, have not been reliably identified in other cores. Glauberite was confirmed by X-ray diffraction of several samples from intervals 341.1–345.3, 425.5–459.6, and 513.6–518.5 m; and anhydrite was confirmed in samples from intervals 334.4–340.5, 518.5–538.0, and 546.2–681.8 m. Gale (1914, p. 289, 297, 302–303) reported glauberite, anhydrite, and gypsum from Searles Lake, though probably without good basis; he presented no evidence of confirmation by petrographic examination and cited a specific occurrence only for glauberite—in a core from a shallow zone, since sampled by hundreds of cores without glauberite being reported. Small amounts of gypsum (at 385.6 m), heulandite (at 585.5-695.2 m), celestite (at 622.7 m), and magnesite (at 375.7 m), confirmed by X-ray diffraction of one or more samples from the depths indicated, also represent new minerals from Searles Lake.

Quantitative estimates of the percentages of acid-soluble minerals in each analyzed unit were made by converting the chemical analyses into normative compositions. A computer program was established that converted the percentages of major components into percentages of probable minerals, based on the suite of minerals normally observed in cores from Searles Lake plus the species detected by X-ray diffraction in that segment of core. Because many of the minerals found in the upper part of the core (for example, hanksite, burkeite, and northupite) were absent in the lower part, a slightly different program was used for samples from below 304.8 m (1,000 ft). In the upper part, where trona was abundant, the program reconstructed its abundance, although it did not differentiate between trona and nacholite; in the lower part, trona was eliminated as a phase, and glauberite anp anhydrite were added as more probable phases, according to the X-ray diffraction data.

After calculation of the normative compositions, the mineral percentages were recalculated so that their sums, plus the acid-insoluble residue, equaled 100 percent. Of the 254 intervals selected for chemical analyses and normative reconstruction, 24 had a cation-anion imbalance greater than 0.1 mol percent/g, and 5 of these 24 intervals had a cation-anion imbalance greater than 0.2 mol percent/g. An imbalance of 0.1 mol percent Na, for example, means that 2.3 percent more or less than the reported amount would be required to form the normative suite.

## DATING

The ages of the younger units in core KM-3 are based on $^{14}C$ dates and on estimates of the sedimentation rates derived from them (Stuiver and Smith, 1979, p. 74–75); the ages of older units are based on paleomagnetic stratigraphy (Liddicoat and others, 1980). Attempts are in progress to correlate the thick volcanic ash layers in core KM-3 (near 685 m) with ash layers that crop out in other nearby areas, but the results thus far are inconclusive. The ages of all paleomagnetic horizons, and all cited dates from other sources that are based on K-Ar ages, have been corrected for the revised decay and abundance constants (Dalrymple, 1979) and conform to the polarity time scale of Mankinen and Dalrymple (1979).

The precision of dating the contacts between units varies greatly, and the citing of their ages to the nearest 0.01 m.y. does not imply confidence at this level. Younger samples dated by $^{14}C$ techniques probably are accurate to within 5 to 10 percent when the laboratory uncertainty and sample contamination or bias errors are combined. Reasonable estimates of the age of the base of the Bottom Mud, discussed elsewhere (Smith, 1979, p. 77–78), vary by several tens of thousands of years. In the Mixed Layer, the ages of the bases of Units D+E, G, H, and I are best controlled because they lie near closely spaced paleomagnetically dated horizons; the ages of the bases of Units C and F have greater uncertainties. The base of Unit F is dated by interpolation between horizons that are separated from the dated contacts by many beds of salts that probably were first deposited more rapidly than the mud and then became horizons representing virtual nondeposition. The base of Unit C is dated by extrapolation from the nearby, but only approximately located, boundary between the Brunhes Normal and Matuyama Reversed Epochs at 185±10.0 m (Liddicoat and others, 1980, table 1), although evidence described in a later section suggests that the inferred age is nearly correct. The age of the base of Unit A+B is least well known because it is separated from the nearest paleomagnetically dated horizon by thick beds of salt and from the base of the Bottom Mud, itself dated only approximately, by more than 100 m of salts and mud. Ages of this contact, calculated using a number of reasonable assumptions, ranged from 0.2 to 0.4 m.y; the age of 0.31 m.y. (table 1) is based on extrapolation from the estimated age of the base of the Bottom Mud, using a net sedimentation rate of 25 cm/1,000 yr, midway between the 30-cm/1,000-yr value used in estimating the age of the Bottom Mud (Smith, 1979, p. 77) and a rounded value of 20 cm/1,000 yr based on the rates calculated for Units D through G (see table 3).

### ACKNOWLEDGMENTS

The data in this report represent the contributions of many people in the Kerr-McGee Corp. and its subsidiaries. We express our appreciation first to D. A. McGee for granting us permission to make additional studies of this core and to publish our results. F. C. Hohne provided guidance and support throughout this project. We especially acknowledge the efforts of T. S. Melancon for his observations at the drill site and his care in cutting and shipping the core; of A. C. Gonzales for most of the core photography; of K. A. Smitheman, R. Pai-Ritchie, and coworkers in Whittier Calif., for analyzing the core; of C. H. Long and his group at the Kerr-McGee Technical Center, Oklahoma City, for the X-ray and arc-emission analyses; of R. M. Becker for writing the normative-mineral computer program; of R. W. Petticrew for assisting with core logging, materials-balance calculations, and compiling of data; of C. W. Cowie for compiling the data and cross sections of Units A and B of the Mixed Layer; and of many others who contributed in numerous ways. G. Winston of the U.S. Geological Survey reduced the numerical data of the original Kerr-McGee Corp. report to the graphic form used in plates 2 through 4; and R. Aquino of the Survey helped compile the data presented in the tables.

## STRATIGRAPHY

### SUMMARY

The sediment and rocks in core KM-3 are of three major types:

| *Depth (m)* | *Description* |
|---|---|
| 0–693 | Mud and evaporites, deposited in standing water by perennial or seasonal lakes. |
| 693–915 | Alluvial sand and gravel, deposited by intermittent streams flowing on the surfaces of fans. |
| 915–930 | Quartz monzonite, crystallized at depth from magma. |

The lacustrine section, both mud and evaporites, is the main subject of this report, and that section is herein subdivided into 14 informal stratigraphic units, 3 of which are new. The alluvial sand and gravel and the quartz monzonite are also described briefly. Table 1 lists these units, their dominant lithologies, and their ages.

The upper five units in the lacustrine section—informally designated the Overburden Mud, the Upper Salt, the Parting Mud, the Lower Salt, and the Bottom Mud—were defined and described previously (Flint and Gale, 1958, Smith, 1962, 1979; Smith and Haines, 1964); descriptions of them are repeated here only to the extent found in tables 1 and 2. All underlying lacustrine sediment was informally designated by Flint and Gale (1958) as the "Mixed Layer," and six stratigraphic subdivisions of it, based on the 200 m of sediment from this zone known at that time, were proposed and defined by Smith (1962). The subdivisions of the Mixed Layer designated Units A (at the top) and B cannot be separated in core KM-3 but are described and redefined here on the basis of new data from other cores. Unit C is described as observed in core KM-3. The lithologies originally assigned to Units D and E can be identified in core KM-3 but the boundary between them cannot; because future work may determine a valid division, these two units are retained and described together here as Unit D+E. Unit F was defined by Smith (1962, p. C68) on the basis of about 25 m of sediment at the bottom of the deepest core available; it now appears that this section was the upper two-thirds of a unit composed of similar sediment, and so the name is here retained, and the description of the unit is amplified to include its lower part. Units G through I are identified, defined, and described here for the first time.

The criteria used to establish Units A through F of the Mixed Layer (Smith, 1962; 1979, p. 108–109) were that they identify relatively thick sections of lacustrine sediment characterized by (1) the dominance of a certain lithology (mud, salines, or a cyclic alternation of the two), or (2) a saline-mineral content that indicates a relatively consistent chemical or physical character of the lake in which the unit was deposited. The same criteria are used here, along with those described below that help separate lacustrine Units G through I of the Mixed Layer from each other and from the underlying alluvial sand and gravel.

Coring since publication of the original definition of the Mixed Layer units has shown that the division between Units A and B of the Mixed Layer on the basis of saline mineralogy is impractical because there is a demonstrable lateral variation in the mineral composition of the saltbeds. The mudbeds, however, record depositional events that affected large parts of the lake at the same time, and mud deposits are less likely than saltbeds to alter diagenetically. For these reasons, we are here modifying the earlier definitions of Units A and B and placing the boundary between them at the base of a distinctive mud layer.

In distinguishing between all units, the color of the mud layers is taken as an important criterion in identifying modes of deposition that differ significantly. The hues of the mud zones are indicated on the graphic log (pl. 1) and for convenience are divided into groups that might be described as distinctly green, yellow, or orange (when light), or as olive, olive brown, or brown (when dark). Green and olive hues are considered to be evidence of deposition in a perennial lake that was characterized by reducing conditions in the accumulating layer of mud as a result of a great depth or stratification. Yellow and olive-brown hues are considered indicative of deposition in a shallower or better oxygenated lake that produced only a partially reducing environment in the mud. Orange or brown hues are inferred to indicate oxidizing environments. Thick zones having these orange and brown colors are thought to indicate an environment in which the accumulating lake sediment was exposed to the atmosphere during part of each year, as in a playa; thin zones having these colors may represent the top of a mud unit that was deposited in a reducing environment but later exposed to the atmosphere long enough for oxidation and, possibly, soil-forming processes to be effective near the exposed surface.

The criterion used to separate the Mixed Layer from the underlying alluvial sand and gravel is the great contrast in their depositional environments. In the Mixed Layer, restricted by definition to lacustrine deposits (including playa deposits), the sorting and bedding characteristics indicative of deposition in standing water are consistently observed, even though the water body may have been saline or ephemeral. In the alluvial sand and gravel, the dominance of red arkosic sand and the common presence of angular pebbles and cobbles clearly indicate subaerial deposition as an alluvial fan.

## DESCRIPTION OF UNITS OF THE MIXED LAYER

### UNIT A

Unit A of the Mixed Layer was originally defined as the uppermost zone composed of interbedded saline and mud layers in which the saline beds included trona and nahcolite but not halite (Smith, 1962, p. C68; 1979, p. 14). The upper contact was placed at the top of the uppermost saline layer. In many cores, this contact is difficult to identify with precision because the saline layers of this unit tend to be thin, lenticular, and impure. Therefore, practical considerations have led to the use of a combination of lithologic and electric-log criteria in placing the contact, although we are uncertain whether these indicators reconstruct a contact that has the same age in all places.

Unit A is not well represented in core KM-3. Other cores from areas near corehole KM-3 show depths to the top of Unit A mostly between 60 and 70 m, and to the base mostly between 100 and 110 m. In core KM-3, only 16 percent of the interval 69-91 m is represented by recovered core, and none of it includes saline beds, although this segment probably represents most of Unit A. In a more complete core (289M) drilled at a site 150 m north of corehole KM-3, layers of trona and nahcolite assigned to Unit A were recovered between 67.9 m and the base of that unit at 105.4 m; because we consider core 289M to be more representative, it is plotted on the graphic log (pl. 1) beside core KM-3 to show this part of the section.

A better understanding of this part of the section is provided by combining the data from several cores. Figure 5 presents an east-west cross section of Unit A, based on 11 cores along the line in figure 2. These cores show that Unit A of the Mixed Layer can be divided into two informally named subunits on the basis of their physical properties as revealed by electric logs and their lithology as recorded in core logs; these subunits are here termed, in ascending order, the Main A Zone and the Upper A Zone.

The Main A Zone is further subdivided into five saline layers (S-1 through S-5) and five mud layers (fig. 5). All the saline layers except S-2 can be traced laterally over a large area. The basal saline layer in the Main A Zone, which resembles the overlying two saline beds, is composed predominantly of trona but also contains thin mudbeds and varies laterally in saline-mineral composition. The layer ranges in thickness from a few centimeters near the edges of the lake to 6 m in the center and has the largest areal extent of the Main A Zone salt layers (although it does not cover so large an area as the Unit B salts, described below). Near the edge of the lake, nahcolite has been observed in this layer; in the northern part of the body, massive halite has been found; and in the southern and eastern parts, thenardite and halite have been recovered, generally from the lower part of the layer. The upper two saline beds of the Main A Zone, S-4 and S-5, are composed of impure mixtures of trona and mud in which the trona was generally recrystallized into interlocking networks of acicular and tabular crystals.

The basal mud zone in the Main A Zone is a conspicuous bed, 3 to 5 m thick, composed of green, tan, or black mud, commonly laminated. This bed, which is characterized by megascopic crystals of gaylussite and trona in the upper part and by a significant percentage of northupite crystals (1-20 mm diam) in the lower part, is easily identified on electric logs. The overlying four mud layers that separate the saline layers in the Main A Zone are massive black marls containing megascopic crystals of gaylussite.

The Upper A Zone includes a basal mudbed that is overlain by a saline zone characterized by numerous thin discontinuous beds of finely crystalline trona and nahcolite. This basal mudbed, commonly about 1 m thick, contains abundant crystals of gaylussite and is typically massive.

### UNIT B

In core KM-3, Unit B of the Mixed Layer is not separable from Unit A, partly because much of the core in this interval was not recovered. The difficulty in separating them also stems from the original description of Unit B (Smith, 1962, p. C68; 1979, p. 14), which relied on the smaller amounts of nahcolite and the presence of halite in Unit B as the major distinction between it and Unit A. We now find that some beds of trona and nahcolite of Unit A grade laterally into halite-rich zones, that Unit B contains several continuous halite-free beds of trona that can be traced over large areas, and that Unit B is also characterized by a considerable amount of thenardite. Therefore, we here abandon the mineralogic distinction between these two units and, on the basis of either core or electric logs, separate Unit A from Unit B at the base of the conspicuous northupite-bearing mud layer described above at the base of the Main A Zone of Unit A. Less information is available about the composition of Unit B than that of Unit A, although core data obtained since publication of the latest description of the unit indicate that the saline beds in Unit B, besides containing thenardite, are areally more extensive than any saline bed in Unit A.

### UNIT C

Halite dominates Unit C in core KM-3, as in the originally defined unit (Smith, 1962), and its abundance still provides a satisfactory method of separating this unit from Unit B above and Unit D+E below. In the salt layers, bedding is mostly faint, thin, and defined by variations in silt or clay impurities; the colors range from medium to light shades of green or gray. The mud layers, most numerous in two zones near 140 and 150 m, are generally dark brown.

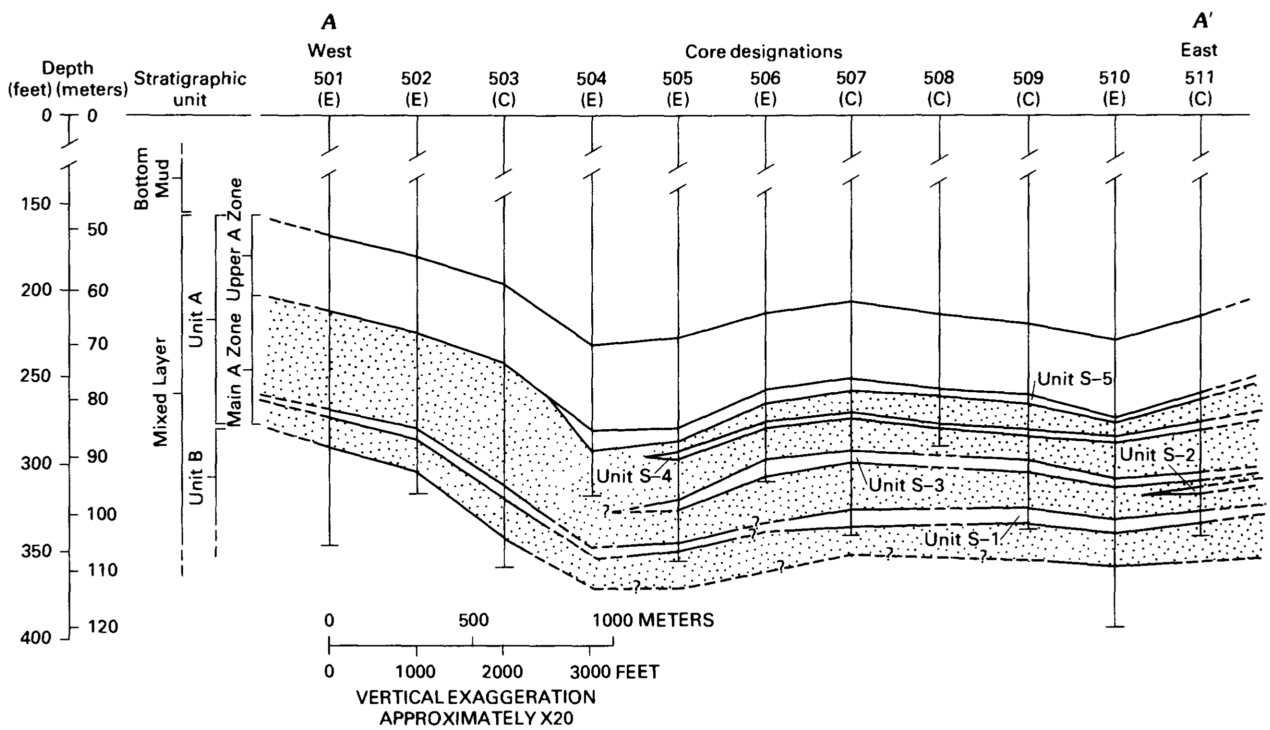


FIGURE 5.—East-west section through 11 cores, showing stratigraphic relations between Bottom Mud and Units A and B of Mixed Layer, and lateral variations of subunits within Unit A (Upper A Zone and Main A Zone with its saline subunits S-1 to S-5). Mud layers within Main A Zone are stippled. Letters in parentheses below well numbers indicate basis for stratigraphic boundaries: (E), electric log; (C), core log. See figure 2 for locations of section line and cores.

Normative compositions of the saline layers in Unit C show that halite accounts for 65 to 95 percent of the total; thenardite makes up more than 15 percent of one zone and 5 to 10 percent of most others; and trona makes up 2 to 15 percent of most beds. The normative compositions of the mud layers are about half acid-insoluble material, with a varying amount of dolomite; the mud generally includes 25 percent or more saline minerals.

### UNIT D+E

Unit D+E in core KM-3 is composed mostly of mud layers, although two thick saline zones occur in the lower half of the unit and several thinner ones in the upper half. Most of the mud layers are distinctly massive and generally dark olive brown to brown; the saline units are thin bedded and impure. Unit D was distinguished from Unit E in earlier reports (Smith, 1962, p. C68; 1979, p. 15) by the presence of nahcolite and trona in Unit D and the absence of these minerals in Unit E. In core KM-3, the presence of trona in two beds near the base of the combined unit makes this criterion for separating Unit D from Unit E inapplicable.

About equal amounts of pirssonite, dolomite, and acid-insoluble materials, with a little magnesite, characterize the normative compositions of the mud that constitutes most of Units D+E in core KM-3, although magnesite was not identified in any X-ray patterns from this unit. Halite, trona, and thenardite, in decreasing order of abundance, make up the few saline layers.

### UNIT F

Unit F, originally defined on the basis of the lowermost 25 m of nearly pure mud in core L-W-D (Smith, 1962, p. C62), is here redefined to include deeper sediment and a description of its basal contact. Almost the entire unit is mud, mostly green to olive; the upper part is very dark and nearly massive, whereas the lower part is lighter colored and mostly well bedded.

The mud of this unit contains large amounts of acid-soluble pirssonite and dolomite, and smaller amounts of searlesite and (normative) magnesite; acid-insoluble materials generally account for 25 to 50 percent of the normative composition, and dolomite accounts for 10 to 20 percent of the total. Pirssonite ranges in abundance from less than 10 to more than 40 percent and averages about 20 percent; the absence of this mineral in deeper units provides a mineralogic criterion, in addition to the lithologic criterion, for separating Unit F from Unit G.[5] Normative saline-mineral percentages are uniformly low.

### UNIT G

Unit G is a new unit defined here. Its most evident characteristic is the cyclic pattern of salt layers alternating with mud layers, each commonly 2 to 10 m thick and averaging 3.4 m in thickness; a total of 17 salt layers can be identified (pl. 1). Some of these mud layers are distinctly bedded, but many are mottled as if deformed by postdepositional bioturbation, soft-sediment deformation, or diagenetic saline-mineral growth. With three exceptions, the mud layers are light to medium green or greenish gray. Most of the salt layers are massive and coarse grained. About two-thirds are relatively mud free and have gray or yellow hues; the less pure beds are light green. The presence of numerous thick salt layers distinguishes this unit from Unit F above, and the green color of the mud layers distinguishes it from Unit H below.

Except for a few beds in the lower third of the unit, the amount of normative dolomite in the mud is mostly between 10 and 20 percent, less than in Unit F above. The amount of calcite is about half that of dolomite but distinctly greater than in all but the basal zone of the overlying unit; normative and observed magnesite occur in one bed. Acid-insoluble minerals in the mud range from 50 to 75 percent. The salines are dominated by halite, but notable concentrations of thenardite occur near the top of the unit. A few percent of glauberite and anhydrite occur in beds composed of impure halite.

### UNIT H

Unit H is another new unit defined here. The lithologic features that distinguish it from the overlying and underlying units are its persistent yellow to brown colors, its massiveness and mottling, and its characteristic irregular concentrations (rather than beds) of anhydrite and glauberite. Much of the unit is composed of material estimated to be silt size.

The normative composition of Unit H is dominated by acid-insoluble minerals, on the average accounting for 75 percent of the total. A few horizons have concentrations of thenardite, glauberite, and anhydrite with distribution and shapes similar to those of calcium carbonate in calcic soils; these similarities suggest crystallization of the sulfate minerals from vertically migrating capillary waters beneath

[5]The computer program used to calculate the normative compositions from chemical analyses was changed to exclude pirssonite and trona below 305 m, which is near the top of Unit G. The result is possibly an exaggeration of the abruptness with which these minerals die out downward, although neither the X-ray data nor the field log reports them below the depths shown on plates 3 and 4.

the floors of playa lakes. Some normative dolomite persists throughout the interval, but it is consistently sparse.

### UNIT I

Unit I is the third new unit defined here. Its dominant lithology is mud. Except for the upper 3 m, which is darker and mottled, the unit is characterized by medium- to light-olive-gray color, thin faint bedding, and an absence of bedded saline minerals. Its contact with the overlying Unit H is placed at the top of the uppermost thick bed characterized by olive hues.

The normative composition of Unit I is largely acid-insoluble minerals. Concentrations of normative anhydrite are found in the transitional zone near the top, and 5 to 10 percent normative dolomite characterizes most of the unit.

Two layers of moderately indurated tuff lie near the base of Unit I. The upper bed consists of glass shards (refractive index, 1.495) in a fine-grained anisotropic matrix; glass makes up about 50 percent of the rock. Also present are minor amounts of K-feldspar, plagioclase, biotite, an expansive clay, and an unidentified elongate mineral that has been entirely altered. The glass shards have acicular shapes and sharp points that indicate little, if any, stream transport. Analysis shows that 17 percent of this material is soluble in water and that the insoluble fraction consists of 66.4 weight percent $SiO_2$, 14.4 weight percent $Al_2O_3$, and 19.2 weight percent of other components. The vitreous material in the lower tuff bed is almost entirely altered to analcime; it also contains small amounts of sanidine, plagioclase, biotite, hornblende, an expansive clay, and opaque minerals.

### ALLUVIAL SAND AND GRAVEL

More than 200 m of moderately well indurated coarse sand and gravel underlie the lacustrine units of the Mixed Layer. Although 60 percent of this interval was not cored, drilling characteristics gave no indications of other lithologies. In the samples recovered, some zones have a very faint bedding defined by alinement of similar-size fragments, but most zones are massive. Colors typically are medium to dark brown, hues imparted chiefly by hematitic inclusions in the cement. Thin-section study of a sample from 836 m confirms that the sand grains are angular, poorly sorted, and composed of an arkosic-mineral assemblage; they are cemented and locally replaced by dolomite and analcime.

Seven partial analyses of the acid-soluble fraction of this sand and gravel—presumably, mostly cementing and replacement minerals—differ little. The average values and ranges of individual percentages are:

| | *Average* | *Range* |
|---|---|---|
| Ca | 0.94 | 0.76 - 1.3 |
| Mg | .55 | .35 - 0.93 |
| Na | 1.45 | 1.09 - 1.89 |
| $CO_3$ | 3.21 | 2.22 - 4.53 |
| $SO_4$ | .59 | .46 - 0.76 |
| Cl | 1.65 | 1.25 - 2.15 |
| Acid insoluble | 82.48 | 75.57 - 87.32 |

Angular to slightly rounded fragments of igneous rocks ranging in size from 3 to 15 cm were recovered in the core at depths of 698, 699, 717, 718, 733, 742, 747, and 821 m. Thin-section study of a cobble from 698 m showed it to be a porphyritic granite composed of an estimated 50 percent K-feldspar, 15 percent plagioclase ($An_{35}$), 5 percent quartz, 3 percent green hornblende, 2 percent microcline, a trace of biotite, and about 20 percent calcite or dolomite that has replaced some minerals. Study of a cobble from 699 m showed it to be a dacite or andesite; its estimated composition was 20 percent normally zoned euhedral plagioclase ($An_{45}$), 10 percent brown hornblende, and 2 percent pyroxene, in a matrix composed of crystalline to hemicrystalline material.

### BEDROCK

The bottom 15 m of core KM-3 is in quartz monzonite, the material that makes up almost all the bedrock west of Searles Valley but only part of it to the east. Because the upper 11 m of bedrock was penetrated with a rock bit, no core was recovered, and so the depth and character of the surface-weathering profile is not known, except that it did not extend below this depth. Below 11 m, the rock is slightly fractured, shows some iron oxide stains on the crack surfaces, but is not weathered. Thin-section study of a sample from 929 m shows the quartz monzonite to be medium grained (2-4 mm) and composed of an estimated 40 percent K-feldspar, 40 percent plagioclase ($An_{30}$), 8 percent quartz, 7 percent biotite, 4 percent hornblende, and trace amounts of apatite, sphene, zircon, and opaque minerals.

## HISTORY OF SEDIMENTATION

The depositional environments responsible for the sediment present in the Mixed Layer and below it in core KM-3 can be reconstructed in large part by using the criteria established to separate the stratigraphic units, as described briefly in the previous section and in more detail elsewhere (Smith, 1979, p. 78–85, 108–109). Each stratigraphic unit in the Mixed Layer (table 1) represents a long interval, most several hundred thousand years, when the depositional mode remained relatively constant even though the constant characteristic of that environment might have been one of no change or of repeated cyclic change. Depositional environments of the sediment younger than the Mixed Layer were described elsewhere (Smith, 1979, p. 79-96, 109-112); those environments responsible for the Mixed Layer units younger than Unit F are only summarized below, except where the environments inferred here differ from those suggested earlier.

#### FROM MIOCENE OR EARLY PLIOCENE TIME TO 3.18 m.y. B.P.—ALLUVIAL SAND AND GRAVEL

Coarse alluvial sand and gravel, probably derived from the ancestral Argus Range area to the west, built fans that sloped to a low point somewhere east of the site of corehole KM-3. Their arkosic composition indicates a plutonic-rock source area, as do most of the larger fragments. The southern Argus Range (fig. 1) is now composed largely of quartz monzonitic to granitic rocks. The absence of metamorphic-rock fragments in the core makes the ancestral Slate Range area, east of the drill site, an unlikely source for this sediment. A source for the dacitic cobbles is not known. The poorly sorted and bedded alluvial sediment indicates deposition by intermittent streams, presumably in an arid or semiarid region. In contrast, the evidence provided by the pervasive red, orange, or brown color suggests that the terrane undergoing erosion was deeply weathered; possibly this coloration reflects an earlier climate that was humid, or a surrounding terrane that previously was tectonically stable long enough to become deeply weathered under semiarid conditions.

It is not known when deposition began in the basin; the estimate here of Miocene to early Pliocene is based on an extension of observations made in the northern part of Searles Valley. There, late Tertiary volcanic flows, which rest on snail-bearing sediment no older than middle Miocene, were deposited on an east-sloping surface that predates the downwarping responsible for the creation of the northern part of Searles Valley (Smith and others, 1968, p. 13-14, 25; Smith and Church, 1980, p. 528-529, fig. 4). The age of the now-deformed volcanic rocks provides a lower limit for the age of the deformation that created the northern part of the valley. We assume that the same episode of deformation affected areas to the south, including the site of corehole KM-3, and that it was responsible for initiation of the basin of sedimentation that is now Searles Valley.

#### 3.18-2.56 m.y. B.P.—UNIT I, MIXED LAYER

Unit I of the Mixed Layer is composed almost entirely of brown to olive lacustrine sediment. The fine grain size, absence of saline layers, faint thin bedding, and low percentages of normative calcite and dolomite all indicate a persistent deep freshwater lake as the depositional environment. Thin zones at 582 and 640 m characterized by brown hues may record two periods of desiccation when oxidation occurred at the surface; if they do, the absence of accompanying salts would confirm the inferred freshness of the lake water. The light color of much of the sediment suggests either that the lake and its sediment originally had a low organic carbon content or that the carbon has been removed by diagenetic processes.

#### 2.56-2.04 m.y. B.P.—UNIT H

Unit H of the Mixed Layer is composed predominantly of mottled faintly bedded yellow to brown clay and silt that is inferred to have been deposited in a playa or an intermittent shallow lake. Concentrations of glauberite and anhydrite, generally in the form of veins and pods, are inferred to have crystallized within the weathering zone or in the capillary zone; they may represent times when playa sedimentation slowed or ceased. Relatively brief periods of perennial lakes may be represented by the dark-olive mud near 440 m and the green mud near 526 m, but the three thin zones of yellow to olivebrown mud that lie between those layers contain disseminated salts that probably document them as products of ephemeral lakes.

#### 2.04-1.28 m.y. B.P.—UNIT G

Unit G of the Mixed Layer is characterized by cyclic deposition of mud and saline layers. A total of 17 saline layers (pl. 1), indicative of nearly complete or complete desiccation, are separated by mud with, in all but three layers, olive to green hues thought to be indicative of deep perennial lakes. The significance of the mottling of many of these mud layers is unclear, although some variation in this type of depositional depositional environment might be inferred. The mud layers have thicknesses that imply deposition over periods of several thousand to a few tens of thousands of years (Smith, 1979, p. 76-78). The mud-free saline layers have lithologies that are best explained by uninterrupted deposition from a rapidly shrinking lake; beds of these thicknesses could be attained by crystallization over periods of less than half a century (Smith, 1979, p. 75-76). The less pure saline layers may represent dry-season crystallization of salts that was interrupted by wet-season influxes of sediment and water, thus reflecting a slower overall process of deposition. The layers composed of bedded thenardite and halite are likelier to indicate periods of desiccation than are those characterized by only one saline mineral, because cocrystallization of two phases generally indicates higher brine concentrations. Because of the inferred contrast in the depositional rates of salines and mud, most of the period represented by Unit G is believed to have been characterized by deposition of fine clastic material in a perennial lake that evaporated rapidly to dryness or near-dryness at least 17 times.

### 1.28–1.00 m.y. B.P.—UNIT F

Unit F is mostly green to olive mud, much of it distinctly bedded; the green (almost blue) hues of the lower half of the unit are especially distinctive. Deposition in a perennial stable lake seems to be the most likely explanation for the dominant lithologies and mineral components present. Two zones near the top, characterized by orange to brown hues, may represent periods of dryness during which the mud underwent oxidation at the surface. The absence of saltbeds at these times of possible desiccation implies that previous high stands of the lake were deep enough to overflow, so that the accumulation of large amounts of saline components in the lake water was prevented. The small amounts of normative pirssonite, searlesite, trona, northupite, and magnesite mixed with clastic materials document the first accumulation of new components in the waters entering the basin, especially near the end of this period, and, probably, their incorporation into the sediment interstitial brines. Other inferences about the style of sedimentation represented by the upper part of this unit, based on other cores, were made elsewhere (Smith, 1979, p. 108–109).

### 1.00–0.57 m.y. B.P.—UNIT D+E

The mud and subordinate amounts of bedded salts in Unit D+E appear to record a fluctuating and occasionally small or dry lake. The olive-brown to brown color of most of the mud layers suggests that even the more permanent lakes were well oxygenated. The continued presence of several new saline minerals in the salt layers shows that the evolution of lake-water chemistry which began during the previous episode was continuing, and the several phases of minerals crystallized during periods of saline deposition probably indicate desiccation rather than the existence of a shallow perennial saline lake that was crystallizing an incomplete suite of its dissolved salts.

Evidence from outcrops suggests that the age assigned to the upper contact of Unit D+E is approximately correct. In the Lava Mountains, which form the south edge of Searles Valley, the Christmas Canyon Formation (Smith, 1964, fig. 15) grades northward from its type section into about 30 m of lacustrine deposits that do not have their basal contact exposed and have a layer of volcanic ash 1 to 2 m below their top. This ash has been identified as Perlette type O (G. A. Izett, written commun., 1978), and its recalibrated age of 0.62 m.y. shows that a large lake existed in Searles Valley until shortly after that time. A zone of thin tuff beds, characterized by poorly defined platy shards similar to those of the Perlette ash, has also been identified in core KM-3 near the top of Unit D+E, between 168.6 and 169.8 m (R. L. Hay, written commun., 1981), but the tuff is too highly altered for positive identification. We think it reasonable, therefore, to correlate the Christmas Canyon Formation with Units F and D+E in core KM-3 because their inferred depositional environments are similar and the interpolated age of 0.57 m.y. assigned to the upper contact of the subsurface Unit D+E is close to the probable age of the top of the Christmas Canyon Formation.

### 0.57–0.31 m.y. B.P.—UNIT C

Saline layers dominate Unit C. Halite is the most abundant saline mineral, but the amounts of normative thenardite and trona suggest that desiccation was complete most of the time and that Searles Lake was a dry salt flat during most of the 260,000 years assigned to this unit. The two zones near 140 and 150 m containing numerous layers of brown mud represent sediment deposited in a succession of lakes that were perennial over periods of probably centuries to ten or more thousands of years, although this time represents only a minor part of the total.

### 0.31–0.13 m.y. B.P.—UNITS A AND B

Units A and B of the Mixed Layer are so incompletely represented in core KM-3 that a satisfactory reconstruction of the depositional environment is not possible from this core. Earlier studies (Smith, 1979, p. 84–85, 108–109) concluded that deposition took place in fluctuating shallow saline lakes whose anion composition during deposition of Unit B was largely carbonate plus some chloride, whereas deposition of Unit A was from a more nearly pure sodium carbonate water. The presence of halite in some parts of the central facies of Unit A in the more recently obtained cores described here indicates that a significant amount of chloride was present in the lake waters responsible for both Units A and B—as it is in virtually all natural waters in this geologic province today. The halite-bearing layers may indicate desiccation.

Those layers in Units A and B that appear to be truly monomineralic, composed of nahcolite or trona in all parts of the depositional basin, we now infer to reflect depositional conditions similar to those suggested elsewhere to explain monomineralic beds of sodium carbonate and sulfate in the Bottom Mud (Smith, 1979, 85-86, 109-111). Those beds crystallized from lakes that had estimated salinities of between 5 and 15 percent, as well as large percentages of dissolved salts whose solubilities vary greatly in response to temperature. (For example, winter cooling of Owens Lake surface waters produced monomineralic deposits of natron that converted diagenetically within months to trona or nahcolite [Smith, 1979, p. 83].) The interbedded thin layers of mud in Units A and B are presumed to represent periods when the lake was slightly too deep and dilute for salts to crystallize out during winter, or periods when the winters were not so cold.

## RATES OF SEDIMENTATION

The overall apparent sedimentation rate of the lacustrine sediment in core KM-3 is about 22 cm/1,000 yr. The rates of deposition of the sediment that lies between paleomagnetically dated horizons in core KM-3 (table 3) are mostly between about 10 and 30 cm/1,000 yr, although the net sedimentation rate for the paleomagnetically dated section between 185.0 and 683.9 m is 20.6 cm/1,000 yr. The anomalous rates calculated between closely spaced horizons that fall in Unit G probably reflect actual variations that characterize the deposition of sections that include salts, as opposed to those composed largely of mud deposited in perennial lakes. Units younger than the Mixed Layer have more rapid apparent rates of deposition. The rate from the base of the Bottom Mud to the surface is 53 cm/1,000 yr; rates in the Parting Mud range from 26 to 42 cm/1,000 yr, and in the Bottom Mud are 22 cm/1,000 yr; and rates for the units composed mostly of salines are somewhat higher (Smith, 1979, p. 1, 77).

TABLE 3.—*Sedimentation rates between paleomagnetically dated horizons in core KM-3*

[Data from Liddicoat and others (1980, table 1)]

| Depth of dated horizon (m) | Age (m.y.) | Calculated depositional rate (cm/10$^3$ yr) | Units in Mixed Layer |
|---|---|---|---|
| 185.0±10.0 | 0.73 | 11.7 | D+E |
| 204.9±0.1 | .90 | 23.3 | D+E |
| 221.2±10.6 | .97 | 22.5 | D+E, F, G |
| 378.5±1.1 | 1.67 | 10.2 | G |
| 398.9±0.4 | 1.87 | 6.7 | G |
| 408.3±4.2 | 2.01 | 54.7 | G |
| 424.7±1.7 | 2.04 | 28.4 | G, H |
| 447.4±1.6 | 2.12 | 43.0 | H |
| 456.0±4.6 | 2.14 | 19.7 | H |
| 522.9±1.2 | 2.48 | 21.2 | H, I |
| 616.2±1.5 | 2.92 | 29.9 | I |
| 643.1±2.6 | 3.01 | 21.5 | I |
| 651.7±2.2 | 3.05 | 32.2 | I |
| 683.9±4.2 | 3.15 | | |

## TRENDS IN SEDIMENTATION AND THEIR SIGNIFICANCE

### CHANGE FROM ALLUVIAL TO LACUSTRINE SEDIMENT

The abrupt change from alluvial to lacustrine sediment at 693 m represents the most extreme change in depositional environments in core KM-3. In outcrops of Cenozoic sediment deposited in closed basins, alluvial sections that grade upward (or laterally) into lake deposits almost all have a transition zone composed of alternating lacustrine and alluvial material because closed-basin lake levels change from year to year, sometimes by several meters, and areas destined soon to be "permanently" covered by water commonly are inundated briefly one or more times before the final change takes place.

The absence of such a transition near the alluvium-lakebed contact in core KM-3 suggests that the flooding of Searles Valley was a rapid event. Such flooding could have been due to one or more of the following causes. (1) The eruption of volcanic flows in the Deadman Pass area (fig. 1) of the central Sierra Nevada 3.2 m.y. B.P. (Dalrymple, 1964) blocked the channel through which the ancestral San Joaquin River had previously cut across the Sierra Nevada and drained part of eastern California and Nevada (N. K. Huber, 1981); after that eruption, the integrated drainage just east of the Sierra Nevada appears to have been permanently diverted into the ancestral Owens Valley and other valleys to the south. (2) The global climatic change that first generated ice sheets large enough to raise the $^{18}O$ content of the oceans above that of their present interglacial level about 3.2 m.y. B.P. (Shackleton and Opdyke, 1977) may have caused a marked increase in precipitation in this continental area. (3) A major vertical displacement along the Garlock or another fault (fig. 1) created or raised the spillway threshold of Searles Valley, so that waters flowing into Searles Valley immediately formed a new or greatly enlarged lake that permanently covered the alluvial fan at the site of corehole KM-3. (4) Headward erosion by a stream that drained into Searles Valley captured the drainage from the east slopes of the ancestral Sierra Nevada area and diverted it from a former course that led to another area. The coincidence between the documented ages of causes 1 and 2 and the age of the base of lacustrine sediment in core KM-3 (table 1) provides strong circumstantial evidence that either or both causes were responsible, although either cause 3 or 4 also is certainly possible. Of the two dated events, however, evidence that the flooding of Searles Valley was rapid favors strongly, in our view, the explanation that involves volcanic damming of the ancestral San Joaquin River at Deadman Pass over the more gradual global climatic change.

#### INCREASES IN THE PERCENTAGE OF CHEMICAL SEDIMENT

The low percentage of nonclastic minerals and the absence of bedded saline minerals in Units H and I suggest that the lakes in Searles Valley during those periods contained only small amounts of dissolved solids. These lakes must have overflowed much of the time they were enlarged, and received little inflow during the time they were playas. When they dried—briefly, as suggested by the relatively thin zones of orange sediment in Unit I; or for long periods, as suggested by accumulation of the playa sediment that constitutes Unit H—the volume of dissolved solids was too small to form beds of salt minerals. The relatively insoluble salines that did accumulate as the lakes shrank to low levels are either disseminated throughout the clastic materials or concentrated in patchy zones that are inferred to be products of postdepositional processes.

Once lacustrine deposition of Units H and I had ceased, there followed a gradual, but inexorable, increase in the relative percentage of acid-soluble chemical sediment in the mud layers, accompanied by a relative decrease in clastic components (pl. 2). Dolomite and calcite increased most notably in Unit G, pirssonite and dolomite in Units F, E, and D, and gaylussite, dolomite, and aragonite in the younger units (pl. 4). This trend is believed to indicate a gradual decrease in the volume of water entering Searles Valley, which would have decreased the volume of clastic material and increased the salinity of the lakes in Searles Valley. As explained elsewhere (Smith, 1979), dolomite, considered to be a primary mineral in the Searles Lake deposits, is probably an indicator of lake waters with a moderately high pH and total salinity (p. 81); pirssonite and gaylussite, though diagenetic minerals, are considered indices of the amount of $CaCO_3$ in the sediment before its reaction with Na-rich solutions (p. 101–103); and a large amount of inferred or observed $CaCO_3$ in the sediment deposited in high-pH lake waters is believed to indicate a deposit formed in lakes that were chemically stratified (p. 79–80).

#### CHANGES IN COMPOSITION OF THE LAKE WATER

The chemical composition of the acid-soluble fraction of the cores (pl. 2) and the suites of nonclastic normative minerals (pls. 3, 4) allow the changing chemistry of the lake waters to be reconstructed. In Units H and I, the consistently small amounts of acid-soluble components, and their identification as relatively insoluble calcium-bearing minerals, show that the earliest lake waters in Searles Valley contained $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $SO_4^{2-}$, and $CO_3^{2-}$, and that these ions reached concentrations in the interstitial brines that were high enough to cause postdepositional crystallization. Lake waters present when the saline layers in Unit G were deposited reached higher salinities than in any previous lake in the valley. These waters were dominated by $Na^+$ and $Cl^-$, and the absence of normative or observed sodium carbonate or sodium borate minerals indicates that the saline lakes were not alkaline.

The carbonate in Unit F, nearly twice as abundant as in the underlying units, is mostly present in the mud layers as normative dolomite and pirssonite, and a little as calcite. The appearance of a large amount of normative pirssonite and small amounts of trona and northupite is not an artifact of the computer-program change; those minerals were added to the program for the normative-mineral assemblage and applied to data 17 m lower in the core than their first reported normative occurrence. We interpret this change to mean that the lakes depositing the mud did contain a little more $Na^+$ than previously, so that some normative trona, thenardite, and northupite formed, but that downward-moving interstitial $Na^+$-rich brines later introduced all the sodium present in pirssonite (Hardt and others, 1972, fig. 20; Smith, 1979, p. 100–103; Friedman and others, 1982). The total amounts of carbonate in Unit D+E and Unit C are about the same as in Unit F, and the normative minerals show that slightly less of this component crystallized in the mud layers as dolomite and pirssonite, and more of it in the saline layers as trona and northupite. As in Unit G, high concentrations of $Cl^-$ continued to characterize the saline lakes, but an abrupt increase in the concentration of $SO_4^{2-}$ early during the deposition of Unit C resulted in the crystallization of more thenardite.

The minerals in Units A and B indicate that beginning about 0.31 m.y. B.P., high-pH lakes containing large amounts of $Na^+$ and $CO_3^{2-}$ in their waters occupied the basin. This compositional change we believe to be a consequence of the hydrothermal activity that reached its peak about 0.3 m.y. B.P. in the Long Valley caldera area (Bailey and others, 1976, p. 738), which is considered to have been the chief source of mineral components in the upper part of the Searles Lake deposits (Smith, 1976). Beds containing halite and thenardite, such as the lower three saline beds in the Main A Zone and parts of Unit B, document salinities exceeding about 20 percent. However, lake-water salinities appear to have remained in the range 5–15 percent for long periods, probably spanning hundreds to thousands of years, when winter cooling generated successions of monomineralic layers of crystals, such as those present in the upper part of the Upper A Zone, in the upper two saline horizons in the Main A Zone, and in parts of Unit B. Lake-level increases—possibly small—resulted in periods of comparable length when lake waters had lower salinities and salts did not form. Saline crystallization during winter requires salinities to be near their maximum during that season. Such a regime could have been provided by a climate in which most precipitation in the tributary area fell as snow in the mountains during winter; such a climate would have produced the maximum flow of fresh melt water during late spring and early summer and permitted winter crystallization of salines in a downstream lake.

The mud layers above the Mixed Layer—the Bottom Mud and the Parting Mud—also contain minerals indicating that $Na^+$ and $CO_3^{2-}$ continued to dominate the lake waters, although the $Cl^-$ content also was high when the Parting Mud was deposited (Smith, 1979, p. 79–82). In the saline units of the overlying Lower Salt and Upper Salt, sodium carbonate and chloride minerals crystallized in sequences dictated by their phase relations, and the appearance in these sequences of sodium and sodium-potassium sulfate minerals shows that these components reached greater concentrations in those lakes than at any earlier time.

#### CHANGES IN CARBONATE MINERALS IN MUD LAYERS

The major $CO_3$-bearing minerals in the mud units are gaylussite, pirssonite, calcite, aragonite, and dolomite (pl. 4). Their distribution is a result both of primary crystallization patterns that reflect lake chemistry and of diagenesis that reflects interstitial-brine compositions and migration patterns. Dolomite persists throughout the entire section, and, as noted above, its percentage increases gradually upward. Aragonite is present in most cores only at depths less than about 40 m (Smith, 1979, p. 104), although it is found in core KM-3 down to 65 m.

Gaylussite, pirssonite, and calcite are almost mutually exclusive. Of these three, only calcite is detected below the base of Unit F; pirssonite is most abundant from the top of a transition zone at the base of Unit F to the middle of Unit C; and gaylussite dominates from that horizon upward. The apparent replacement of primary calcite by diagenetic pirssonite and the abruptness of the base of the pirssonite-bearing zone suggest that this is the maximum depth to which interstitial $Na^+$-rich brines moved downward before moving outward from Searles Valley (Hardt and others, 1972, fig. 10; Smith, 1979, p. 100–103; Friedman and others, 1982). The change from pirssonite to gaylussite in Unit C is apparently controlled by temperature; the temperature at that depth is estimated to be near 35°C, which approximates the temperature that laboratory studies of these phases, corrected for higher salinity, would indicate for this mineral transformation (Smith, 1979, p. 103).

## PALEOCLIMATIC INTERPRETATION

### HISTORY OF SEARLES LAKE

A 3.2-m.y. history of the lakes in Searles Valley can be interpreted using the following assumptions: (1) Mud layers (except playa-lake sediment) represent perennial lakes, and salt layers saline or dry lakes; (2) green mud represents deep lakes, and yellow mud shallower lakes; (3) thin orange oxidized zones, soil-profile textures, and playa sediment represent persistent dry lakes; and (4) the ages of all beds are proportional to their positions between the nearest dated horizons. Figure 6 plots the generalized history of the lake inferred from these assumptions.

Two aspects of this interpreted history are especially notable. One is that during about three-quarters of the past 3.2 m.y., medium-size to large pluvial lakes have occupied Searles Valley; interpluvial regimes have been much less frequent, and their durations have shortened over time. The first part of this conclusion is similar to one based on deep-sea-core evidence indicative of polar-ice-sheet sizes and global climates; this conclusion infers that it is the interglacial climates during this period which are atypical (Shackleton and Opdyke, 1973, 1976; Ruddiman and McIntyre, 1976; van Donk, 1976). The other notable aspect of this history is that some stratigraphic units, representing periods of hundreds of thousands of years, are characterized by little recorded climatic variation (Units C, F, H, I), whereas other units, also representing periods of significant duration, are characterized by repeated variations (Lower Salt and Units A+B, D+E, G). Minor climatic variations during times when the lake was continuously large or overflowing (parts or all of Units F and I) might not be recorded by this type of evidence, although significantly more pluvial variations should be recorded by the deposits of arid periods (Units C, H).

### HISTORY OF OWENS RIVER FLOW, AS INDICATED BY THE SIZE OF SEARLES LAKE

Variations in the volume of water that reached Searles Valley during its 3.2-m.y. lacustrine history are primarily interpreted to record variations in the regional climate as expressed by the volume of water flowing in the ancestral Owens River. During late Quaternary time, when its drainage area and the orographic influence of the Sierra Nevada on precipitation in the Great Basin were about the same as at present, the volume of water carried by the Owens River and the lakes filled by it served as a relatively quantitative record of variations in the precipitation within its drainage area, especially the east slope of the Sierra Nevada. Estimates of this water volume, based on the amount calculated as necessary under present climatic conditions to offset evaporation from the several lakes in the chain, suggest that three times the present average flow of the Owens River would create a small saline lake in Searles Valley, five times the present flow would form a large, but slightly saline, lake, and six times or greater flow would cause overflowing and thus create a freshwater lake (Smith, 1976, table 1; Smith and Street-Perrott, 1982). If pluvial-period air temperatures at that time were 5° to 10°C lower than at present and evaporation rates were reduced accordingly, inferred streamflow volumes would still have been 50 to 75 percent of these amounts. Translation of changes in the flow of the Owens River into changes in regional precipitation is difficult; this relation is by no means linear, partly because of the multiplicity of hydrologic factors that control runoff. A more significant factor in Owens Valley is that most of the present runoff comes from less than 20 percent of the total drainage area, and when climatic change produced some runoff from additional areas, the total flow increased disproportionately (Lee, 1912, p. 9, 32-44). For some purposes, however, an accurate history of the changes in streamflow is as useful as, or even more useful than, accurate data on the changes in actual precipitation.

Expanding the lake history plotted in figure 6 to reconstruct the history of flow in the Owens River before late Quaternary time becomes more uncertain as the age of the deposits increases. The size of the drainage area 3.2 m.y. B.P., the sizes and numbers of upstream lakes, and the evaporation rates could have differed substantially. Also, during the early part of that time, the Sierra Nevada had not yet been elevated to its present level, and so its effectiveness as a barrier to the eastward movement of airmasses bringing storms was less. The central part of the range is estimated to have been 950 m lower 3 m.y. B.P. than at present (Huber, 1981), and one climatologic model (see below) suggests that the precipitation in areas east of an ancestral Sierra Nevada crest that was lower in

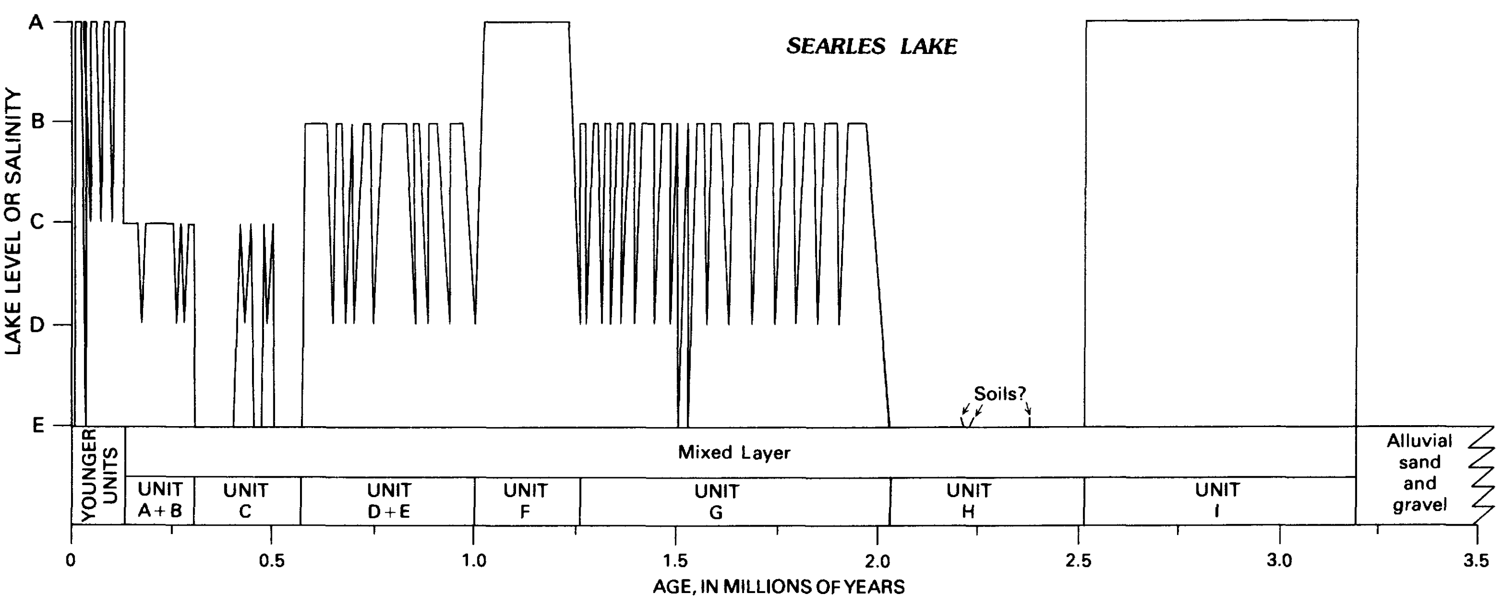


FIGURE 6.—Reconstructed history of Searles Lake, based primarily on Core KM-3. Inferred lake level or salinity indicated by letters: *A*, Lake deep, fresh, overflowing most of time. *B*, Lake deep, slightly saline, overflowing only part of time. *C*, Lake shallow, moderately saline, overflowing rarely if at all; thin saltbeds deposited intermittently as result of winter cooling. *D*, Lake shallow to dry, very saline; salts deposited during most of year. *E*, Lake a playa or salt flat most of year, flooded intermittently. Brief possible fluctuations during deposition of Units F, H, and I are not plotted.

elevation by that amount might have been 50 percent greater than now. This model would help explain an ancestral Owens River flow that was greater and thus able to support lakes that were larger and more persistent than those characterizing the past million years. However, the long dry period 2.56–2.04 m.y. B.P. and the sporadic dry periods between 2.04 and 1.28 m.y. B.P. must correspond to periods of markedly decreased precipitation and streamflow; geologically brief and reversible changes in drainage area, lake area, or mountain-range elevation during those times are unlikely.

### RELATION BETWEEN SEARLES LAKE HISTORY AND SIERRA NEVADA GLACIAL STAGES

Correlations of the Tahoe and Mono Basin Glaciations with the Bottom Mud, of the Tioga Glaciation with the Parting Mud, and of the Tenaya Glaciation of Sharp and Birman (1963) with the upper part of the Lower Salt have been made (Smith, 1968, p. 307–308; 1979, p. 116, fig. 42). The record from core KM-3 now enables us to correlate the older Sierra Nevada glacial stages with Searles Lake history. We correlate the most extensive deposits of the Sherwin Glaciation with Unit F of the Mixed Layer and infer less extensive glacial deposits that are correlative with the less persistent pluvial period represented by Unit D+E. The age of the base of the Sherwin Till, therefore, would be about 1.28 m.y., an age allowed by Sharp's (1968, p. 355) interpretation of "Sherwin outwash" that rests on basalt dated at 3.4 m.y. (recalc). The age of the top of Unit F in core KM-3 is estimated at 1.00 m.y. Sharp (1968, p. 361) estimated the weathered upper surface on the extensive deposits of the Sherwin Till that lie east of the present range to be a few tens of thousands of years older than the 0.73-m.y.-old Bishop Tuff, although he noted other evidence that could indicate an older age for the till. Although most of Unit D+E is older than 0.73 m.y, the inferred perennial lakes characterizing Searles Valley up to the end of deposition of Unit D+E and the nearby outcropping lacustrine sediment of the Christmas Canyon Formation indicate that pluvial conditions persisted in the area until approximately 0.57 m.y. B.P. Significant-size glaciers might have persisted in the deep valleys of the eastern Sierra Nevada 150,000 years longer than east of the range, where the Sherwin Till is overlain by the Bishop Tuff. In fact, evidence of such glaciation in the Sierra Nevada during that period was presented by Rinehart and Ross (1964, p. 68) and Bailey and others (1976, p. 732, 735), who reported ice-rafted morainal material on an island in Pleistocene Long Valley Lake, which formed 0.75–0.65 m.y. B.P. (recalc) as a resurgent dome grew in the Long Valley caldera. The 1- to 2-m sizes of the blocks virtually require that debris-bearing glaciers extended to at least the edge of the lake (2,320-m elev), where blocks from them calved directly into the waters, floated eastward to the shore of the rising dome, and melted. Glaciers in this area extended as much as 125 m below this elevation during subsequent glaciations (Rinehart and Ross, 1964, pl. 1), whereas during the present interglacial period they terminate about 1,000 m above this elevation.

This discussion revives a question posed earlier (Smith, 1968) on the nature of western Great Basin climate during the nearly half a million years between the pluvial episodes represented by Unit D+E and that represented by the Bottom Mud, which began approximately 0.13 m.y. B.P. Except for two zones of perennial-lake mud in Unit C (the thickest of which is 4 m, possibly representing 10,000–30,000 thousand years of pluvial climate), that unit appears to represent 0.26 m.y. of dominantly interpluvial climate. The following 0.18 m.y., represented by Units A and B, is also dominated by salts deposited under conditions that apparently ranged from interpluvial to semipluvial. These two units contain numerous mud layers, although individual-bed thicknesses do not exceed a few meters. These mudbeds may each represent a few tens of thousands of years of lakes that were too deep to allow salt deposition, although most of the beds are much thinner and presumably represent periods only hundreds or thousands of years long. It appears from the lacustrine record in Searles Lake, therefore, that during 0.57–0.13 m.y. B.P., first interpluvial and then semipluvial climate characterized this part of western North America, and although sporadic periods of fully pluvial climate may have interrupted this regime, they rarely lasted more than a few tens of thousands of years. The absence of dated glacial deposits in the Sierra Nevada during this period allows an interpretation that major glaciations in that area were similarly brief or absent.

The pluvial period represented by Unit I may be correlative with a glacial stage in the Sierra Nevada. The age which that unit represents (2.56–3.18 m.y.) includes the age assigned to the Deadman Pass Till (Curry, 1966), which is overlain and underlain by volcanic rocks dated (using new constants) at 2.8 and 3.2 m.y., respectively; it also includes the possible age of the McGee Till, which rests on basalt dated at 2.7 m.y. (Dalrymple, 1963, p. 387). Recent studies by Huber (1981) suggest, however, that at 3 m.y. B.P. (1) the crest of the Sierra Nevada near the Deadman Pass area was 950 m lower than now, (2) glaciers might not have been able to form because of this lower elevation, and (3) the clast composition of the Deadman Pass Till indicates transport from the north rather than the west, a direction that is difficult to reconcile with a glacial origin for the deposit. Huber, therefore, has suggested that the McGee Till is no more than 1.5 m.y. old and that the deposits at Deadman Pass may not be till. If Huber's inference is correct about the unfavorability of summit elevations for glacier development 3.0 m.y. B.P., the pluvial deposits in core KM-3 that can be correlated with the McGee Till would be limited to those units also correlated with the Sherwin Till, namely, Unit F and parts of Unit D+E. But the great differences in the thickness and preserved extent of the Sherwin Till and the McGee Till (Rinehart and Ross, 1964, pl. 1, fig. 31) suggest that they differ in age, and the pluvial period identified here on the basis of Unit I in core KM-3 provides a climatic basis on which to infer an earlier glaciation in the ancestral Sierra Nevada—possibly the McGee Glaciation—that began during late Pliocene time and ended about 2.6 m.y. B.P., 1.3 m.y. before the onset of the Sherwin Glaciation.

### NATURE OF THE CLIMATE 3-1 m.y. B.P.

If the central Sierra Nevada was 950 m lower 3 m.y. B.P. (Huber, 1981) and if most of the mountain range was that much lower, precipitation in the area to the east at that time could have been significantly greater than at present. Assuming that large-scale atmospheric circulation and East Pacific sea-surface temperatures were similar to those of the present, and that we can apply low-level pseudoadiabatic charts as used elsewhere to model precipitation in this area (Smith and others, 1979, p. 173-174, fig. 2), we can estimate the decrease in aridity. For example, mountain barriers that are now about 2,500 m high (such as the Sierra Nevada south of lat 36° N.) would then have been about 1,550 m high and, therefore, would have adiabatically cooled the airmasses flowing over them about 6.5°C less than now and allowed them to retain almost 50 percent more moisture; barriers now 4,000 m high (such as the Sierra Nevada west of Owens Valley), then 3,050 m high, would have cooled passing airmasses almost 7°C less and allowed slightly more than 50 percent more moisture to reach areas to the east. Translating this increased amount of moisture into precipitation is difficult, but we can say that 3 m.y. B.P., about 50 percent more moisture could have been available for condensation and precipitation within the ancestral Owens River drainage.

If precipitation increased by 50 percent, the resulting increase in runoff would probably have been somewhat greater, possibly 75 to 100 percent. As stated above, however, the present topography of the drainage area, and reasonable projections of the earlier Pleistocene hydrology and climate, would not create permanent lakes in Searles Valley unless Owens River flow was several times greater than the present flow. If the drainage leading to Searles Lake was anything like it is now, then more than a lowering of mountain barriers would be required to explain lakes in the now dry closed basins of the western Great Basin, and warmer Pacific sea-surface temperatures and more humid climates seem to be indicated. East Pacific sea-surface temperatures 10°C above those of the present, for example, would result in nearly 90 percent more moisture in the eastward-moving airmasses at sea level and nearly 250 percent more at the level of the 950-m-lower range crest. It appears, then, that a persistent lake like the one that deposited Unit I in ancestral Searles Valley required a warmer and more humid regional climate than now, that the playa lake which followed and was responsible for Unit H required a significant drying of this climate, and that the cyclic deposition recorded by the sediment and salts of Unit G was due to repeated oscillation between two climatic balances, possibly centered around a climate intermediate between these extremes. Unit F was deposited during a period that ended 1.0 m.y. B.P., after 70 percent of this entire period of lacustrine deposition had elapsed; the then-existing drainage patterns and climatic regimes were presumably approaching those that characterized late Quaternary and Holocene time, and this unit clearly documents a period of pluvial climate relative to that at present.

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