Lake Cahuilla: late quaternary lacustrine history of the Salton Trough, California

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LAKE CAHUILLA: LATE QUATERNARY LACUSTRINE
HISTORY OF THE SALTON TROUGH, CALIFORNIA

by
Michael Richard Waters

A Thesis Submitted to the Faculty of the
DEPARTMENT OF GEOSCIENCES
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1980
STATEMENT BY AUTHOR

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[Signature]  March 5, 1980
WILLIAM B. BULL  Date
Professor of Geosciences
ACKNOWLEDGMENTS

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Numerous stands of freshwater Lake Cahuilla formed intermittently in the Salton Trough, California, during the late Quaternary. This lake formed behind the subaerial Colorado River delta whenever the Colorado River was diverted to the northwest. The level of Lake Cahuilla was controlled by the amount and duration of river discharge, evaporation, and overflow altitude of the delta threshold. Late Quaternary lake stands have been identified between altitudes of 52 and 12 meters above mean sea level. Six high stands of Lake Cahuilla, ranging in altitude from 52 to 31 meters, occurred during the late Pleistocene. The most prominent shoreline in the Salton Trough occurs at an altitude of 12 meters. Four lacustral intervals reached this level during the last 2,000 years.

The eastern late Holocene shoreline ranges in altitude from 18 to 10 meters and the western shoreline from 20 to 9 meters. This difference in altitude can be attributed in part to differences in wave intensities and also to upwarping of the northern shorelines and subsidence of southern shorelines.

Archaeological material of the Malpais and San Dieguito I complexes and the Lowland Patayan culture are present in the Salton Trough. Artifacts and features of the Malpais and San Dieguito I complexes are temporally unassociated with any known high stand of Lake Cahuilla. Lowland Patayan occupation is temporally associated with the 12-meter shoreline.
INTRODUCTION

The Salton Trough of southern California is the landward extension of the depression filled by the Gulf of California. The trough extends 225 km northwestward from the head of the Gulf of California to the Coachella Valley. It ranges in width from a few kilometers at the northwest end to 110 km at the American-Mexican border (fig. 1). Over 5,400 km² of the 26,000 km² of the trough lie below sea level. The barrier formed by the subaerial delta of the Colorado River separates the Salton Trough from the Gulf of California and has a minimum crest altitude of 11 meters (Thompson, 1968, p. 7). This is the most recent reported minimum delta crest altitude, with estimates ranging from 9 to 14 meters.

The Gulf of California and the Salton Trough evolved during the late Cenozoic. The Gulf of California is inferred to be the locus of spreading ridges rifting Baja California away from the mainland of Mexico, resulting in the formation of the gulf and the Salton Trough (Larson, Menard, and Smith, 1968).

Cenozoic-age deposits in the Salton Trough were deposited under a combination of marine, freshwater, and terrestrial environments. Deposition was largely controlled by the Colorado River and the minimum threshold-overflow delta crest altitude. A maximum of 6,100 meters of Cenozoic-age sediments have accumulated in the central portion of the trough (Kovach, Allen, and Press, 1968).

These Cenozoic-age sediments are of two types: (1) coarse debris—fanglomerates, conglomerates, breccias, and arkosic sandstones of
Figure 1. Geographic map of the Salton Trough, California

Explanation

A - Yuma
B - El Centro
C - Mexicali
D - Plaster City
E - Niland
F - Indio
G - Box Canyon
H - Pinto Wash
I - Mt. Signal
J - Cerro Prieto
K - Volcano Lake
L - Pilot Knob
M - Coyote Mountains
N - Superstition Mountains
O - Travertine Point
P - Imperial Valley
Q - Coachella Valley
the Split Mountain Formation, Canebrake Conglomerate, Ocotillo Conglomerate, and Holocene alluvium; (2) fine sediment composed of clays, silts, and fine sands of the Imperial, Palm Spring, Borrego, and Brawley Formations, and Holocene silts (Merriam and Bandy, 1965; Van de Kamp, 1973) (fig. 2). The coarse material represents deposits of local origin around the edges of the basin, whereas the finer material, the basinward equivalents of the coarser units, was deposited by the Colorado River (Merriam and Bandy, 1965).

The late Cenozoic depositional history of the Salton Trough is briefly reviewed to establish a background for future discussions dealing with late Quarternary Lake Cahuilla. During the Miocene epoch a marine embayment extended into the Salton Trough as far as the Fish Creek Mountains, resulting in deposition of the Split Mountain Formation (Tarbet and Holman, 1944). A major marine transgression occurred during the late Miocene to Pliocene, resulting in deposition of the Imperial Formation. This marine invasion extended as far north as the northern Coachella Valley (Woodring, 1932). The Canebrake Conglomerate interfingers with the Imperial and later formations along the edge of the trough (Dibblee, 1954). During this time the Colorado Delta was developing a barrier separating the Salton Trough from the Gulf of California. The last brackish marine water deposits to be found in the trough occur in the basal portion of the Palm Spring Formation (Downs and Woodard, 1961). Depositional environments change after this time from marine to non-marine, dominated by terrestrial and lacustrine settings. This implies that the delta had become a barrier of sufficient magnitude to exclude marine waters from the Salton Trough. The Palm Spring Formation represents
Figure 2. Generalized stratigraphic section of the late Cenozoic stratigraphy of the Salton Trough, California
various terrestrial environments and contains an Irvingtonian and Blancan fauna (Opdyke and others, 1977). The Palm Spring Formation contains magnetic events that range from below the Cochiti event at its base to the Matuyama reversed magnetic epoch at the top of the unit (Opdyke and others, 1977). The remainder of the Pleistocene is dominated by lacustrine sedimentation in the center of the trough and local deposition at the edges. The Borrego Formation of lacustrine clays and silts interfingers with and overlies the Palm Spring Formation (Dibblee, 1954). A 1.5-meter-thick volcanic ash occurs within the Borrego Formation in the Durmid Hills (Babcock, 1974). Merriam and Bischoff (1975) regarded the ash to be correlative to the Bishop Tuff (0.7 m.y. B.P.). Wagoner (1977) reported that the ash may be the correlative of the Friant Pumice (0.6±0.02 m.y. B.P.) based on neutron activation analysis of the glass shards separated from the ash. Unconformably overlying the Borrego Formation is the lacustrine Brawley Formation, whose deposits interfinger with the local Ocotillo Conglomerate (Dibblee, 1954). Overlying this are Holocene alluvium and lacustrine deposits (Van de Kamp, 1973).

**Purpose and Scope of the Study**

Field work was conducted in the Salton Trough, California, from January to May 1979 with subsequent laboratory work to achieve the following objectives:

1. To establish a relative and absolute chronology for late Quaternary stands of Lake Cahuilla. Emphasis was placed on the reconstruction of the late Holocene chronology with less emphasis on the late Pleistocene chronology.
2. To correct inconsistencies in the literature dealing with Lake Cahuilla.

3. To examine and describe the character and distribution of shoreline features of Lake Cahuilla.

4. To examine postdepositional deformation of the shoreline.

5. To determine the temporal association of archaeological material with the shorelines of Lake Cahuilla.

Field work encompassed almost the entire Salton Trough. A search was made in the literature and on aerial photographs for shorelines. All reported localities and those observed on the photographs were visited. Carbon-14 and sediment samples were collected, soil profiles were described, and other observations and measurements made wherever possible. All localities were examined for the temporal association of artifacts. Washes and man-made exposures were examined for Holocene stratigraphy and carbon-14 samples were collected from three sections. Subsequent laboratory work included a particle-size analysis and examination of tufa. Sixteen carbon-14 samples were collected and sent to the radiocarbon laboratory at the University of California, Riverside.

Terminology of Late Quaternary Lakes Formed in the Salton Trough

Several names have been applied to the lakes that filled the Salton Trough during the late Quaternary. Originally all names were applied only to the late Holocene stand of the lake, but they have since been used to designate the late Pleistocene lake stands. To establish priority, these names will be traced in sequence as they were proposed.
Bailey (1902, p. 12) proposed the name "Lake Le Conte" in honor of Joseph Le Conte, a pioneer field geologist. This designation was accepted by several other geologists and occurs in the literature with later spelling modifications: Lake LeConte or Lake Leconte. Five years later Blake (1907, p. 803) proposed the name "Lake Cahuilla" for this same body of water for the Cahuilla Indians he found occupying the valley during his original investigations in 1853. Mendenhall (1909, p. 20) accepted the name Lake Cahuilla but stated that he had intended to propose the name "Blakes Sea" in honor of Blake until he read Blake's proposal 2 years earlier. Free (1914, p. 24) proposed discarding all the previous names applied to the lake stands and suggested the name "Blake Sea" be used to commemorate Blake's 1853 expedition. Hanna (1926, p. 15) changed the spelling of Lake Cahuilla to "Lake Coahuilla." Proctor (1968, p. 21) has proposed the name "Lake Brawley" for the late Pleistocene stands of the lake. Childers (1977a, p. 13) has suggested that the late Pleistocene stands be referred to as Lake LeConte and that Lake Cahuilla be reserved for the late Holocene stands.

A single name for both the late Pleistocene and Holocene stands of the lake is more suitable than separate names for each. Although the name "Lake Le Conte" has priority, "Lake Cahuilla" is well established in the recent literature and the name "Lake Cahuilla" will be used here to designate all late Quaternary stands of this lake.
LATE PLEISTOCENE STANDS OF LAKE CAHUILLA

Character and Distribution of Shorelines and Deposits

Six late Pleistocene shorelines of Lake Cahuilla occur between altitudes of 52 and 31 meters (for uniformity all altitudes are measured at the base of the beach, fig. 3). These shorelines have been extensively eroded and are preserved as isolated remnants on the western side of the Salton Trough where beaches were developed on pediments protected from erosion. The absence of the shorelines on the eastern side of the trough is a result of active erosion in this area.

The beach remnants have a very subdued topographic expression with a convex profile gently dipping landward and lakeward. Desert-varnished pavement surfaces with red argillic soil horizons and thick accumulations of calcium carbonate, including calcareous root casts, have formed on most beach remnants (figs. 4 and 5). These features are preserved to varying degrees, depending on the geographic position of the shoreline. All stands except the 52-meter stand contain freshwater mollusks, and all shorelines have associated tufa deposits.

The highest shoreline remnant, 2.4 km in length, occurs at an altitude of 52 meters on a pediment west of Plaster City (fig. 3). This is the only recognized remnant of this high stand in the trough, with the rest of the shoreline being eroded. It occurs as a beachbar deposit of well- to moderate-sorted coarse sand and gravel with foreset beds dipping lakeward (east) at 10°-15° and backset beds dipping landward (west) at a lesser 5°-10° angle. This shoreline remnant is deformed toward the
Figure 3. Aerial photograph of the late Pleistocene shorelines of Lake Cahuilla, west of Plaster City, California

Shorelines: A-52 m; B-46 m; C-40 m; D-38 m; E-36 m; F-31 m.
Figure 4. Thirty-one-meter shoreline at the base of the Sierra Cocopa, Mexico
Figure 5. Thirty-one-meter beach in cross section with alluvium unconformably overlying beach deposits
south (slopes and thins southward) and is truncated by the next lower shoreline, which stands at an altitude of 46 meters.

The 46-meter stand of the lake was first reported by Stanley (1962) and later by Thomas (1963). This shoreline (fig. 3) is preserved as isolated remnants on the west side of the trough from Plaster City to the international border near Mt. Signal and as far north as the Borrego Valley. This shoreline includes mostly beach deposits of well- to moderately sorted coarse sand and gravel but is also marked by a wave-cut bench and slope. Stanley (1965) postulated that this shoreline was subsided and downfaulted 116 feet in altitude "over a littoral distance" of 24 km from Plaster City to the American-Mexican border and 24 km farther south where it is truncated and buried beneath the lowest 12-meter (Holocene) stand of Lake Cahuilla. My field work did not substantiate this observation. The 46-meter shoreline is not preserved farther south than Mt. Signal. Stanley did not recognize several lower stands of Lake Cahuilla between altitudes of 40 and 31 meters and in surveying what he believed was the 46-meter shoreline confused these different stands thinking that they represented a singular shoreline. Loeltz and others (1975) and Robison (1965) discussed and mapped a shoreline on the eastern side of the trough that they considered to be correlative with the 46-meter shoreline on the west side. It was mapped along the base of the Algodones Dunes where it reportedly occurs at an altitude of 49 meters at the south end and is deformed sloping northwest, truncated north of Niland by the 12-meter (Holocene) stand of Lake Cahuilla. I could not find beach deposits (see page 31 for definition of beach) along the base of the Algodones Dunes or elsewhere on the eastern side of the
trough where mapped by Loeltz and others. A ridge appears on aerial photographs along the base of the Algodones Dunes, but this is a well-consolidated fossil dune ridge. This dune ridge may have been what Loeltz and others mapped as the 46-meter shoreline.

High stands at altitudes of 40, 38, and 36 meters occur as beaches on the pediment west of Plaster City (fig. 3). These deposits occur as short beach remnants that consist of well- to moderately sorted coarse sand and gravel with 10°-15° lakeward-dipping foreset beds. These high stands are limited in extent and cannot be traced beyond the Plaster City area.

A shoreline at an altitude of 31 meters was first reported by Thomas (1963). This shoreline (fig. 3) is traceable from Plaster City south to the border as isolated remnants and 25 km farther south around Mt. Signal and along the base of the Sierra Cocopas. Still farther south it is present at the northern base of Cerro Prieto. A few isolated remnants of this shoreline are present to the north in the Borrego Valley. This shoreline occurs mostly as well- to moderately sorted coarse sand and gravel beaches with 10°-15° lakeward-dipping foreset beds, with a segment of shoreline occurring as a wave-cut bench and slope. Twenty-five kilometers south of the border along the base of the Sierra Cocopas a 23-meter-long offshore bar associated with the 31-meter stand is overlain by beach deposits of the 12-meter (Holocene) stand of Lake Cahuilla. The 31-meter shoreline is preserved behind and to the south of this locality. The bar and 31-meter beach exhibit the same degree of soil development. This is the shoreline and situation that confused Stanley's (1965) interpretation of the tectonic warping of the 46-meter stand. As mentioned
previously he probably confused the different high stands thinking that they represented a single shoreline and misidentified the offshore bar as a remnant of the 46-meter beach overlain by the beach deposits of the 12-meter (Holocene) stand. In a few places beach deposits of the 31-meter stand are overlain by a 15-to-30-cm layer of alluvium (fig. 5). The shoreline slopes southward, from an altitude of 33 meters near Plaster City, to 31 meters farther south, to 27 meters along the base of the Sierra Cocopas.

The lacustrine Brawley Formation and Ocotillo Conglomerate are temporally associated with the late Pleistocene topographic high stands of Lake Cahuilla. Bowersox (1972) informally refers to these formations as the "Le Conte group." The association between the formations and the high shorelines is inferred because the Brawley Formation always crops out at altitudes less than the previously discussed high beach stands. Also, numerous late Pleistocene carbon-14 dates ranging between 37,000 and 26,000 B.P. (see following section) have been obtained on tufa encrusting cobbles in a fanglomerate from Box Canyon, Riverside County, California, mapped by Dibblee (1954) as the Ocotillo Conglomerate. This range of dates obtained from the tufa corresponds well with carbon-14 dates obtained from tufa and shell from the beach deposits on the west side of the trough. Wagoner's (1977) work with the Brawley Formation in the San Felipe Hills has shown several lacustral intervals separated by periods of erosion.

**Chronology of Late Pleistocene Lake Cahuilla**

A chronology of the high stands of late Pleistocene Lake Cahuilla can be established by using relative (table 1) and absolute criteria. The shorelines show a general relationship of decreasing age with decreasing
Table 1. Relative geomorphic characteristics of the Lake Cahuilla shorelines

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<tr>
<td></td>
<td>52-m</td>
</tr>
<tr>
<td>Desert pavement$^a$</td>
<td>P</td>
</tr>
<tr>
<td>Desert varnish$^a$</td>
<td>P</td>
</tr>
<tr>
<td>Soil horizon$^a$</td>
<td></td>
</tr>
<tr>
<td>Bt</td>
<td>P</td>
</tr>
<tr>
<td>Cca</td>
<td>P</td>
</tr>
<tr>
<td>Freshwater shell preservation$^b$</td>
<td>D</td>
</tr>
<tr>
<td>Granite pebble preservation$^c$</td>
<td>R</td>
</tr>
<tr>
<td>Beach preservation$^d$</td>
<td>VHE</td>
</tr>
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a. P = present; A = absent

b. D = dissolved; C = calcitic; Ag = aragonitic

c. R = rotted; F = fresh.

d. VHE = very heavily eroded; HE = heavily eroded; SE = slightly eroded.
altitude, with the 52-meter shoreline the oldest and the 31-meter stand
the youngest.

Eighteen carbon-14 dates that relate to the six late Pleistocene
high stands of Lake Cahuilla have been reported in the literature and two
new dates are reported here. All dates are derived from carbonates,
and a brief discussion of the major problems involved in dating carbonates
follows.

A major problem in interpreting carbonate dates is in determining
the initial \(^{14}\text{C} - ^{12}\text{C}\) ratio of the carbonate material (Broecker and Orr,
1958). The initial \(^{14}\text{C} - ^{12}\text{C}\) ratio must be equal to that of atmospheric \(\text{CO}_2\)
if the carbon-14 date is to be accurate. If the bicarbonate from which
the carbonate was precipitated was partly derived from solution of older
carbonates the initial \(^{14}\text{C} - ^{12}\text{C}\) ratio would be much less than that for at-
mospheric \(\text{CO}_2\). The result would be an apparent carbon-14 age greater
than the true age of the precipitated carbonate (Williams and Polach,
1971). All reported dates from Lake Cahuilla suffer from this problem,
and it is not possible to determine the magnitude of this problem in each
sample because no \(^{12}\text{C}/^{13}\text{C}\) corrections were made.

A second problem in dating carbonates is postdepositional surface
contamination by secondary carbon-14 (Broecker and Orr, 1958). Signifi-
cant errors can result from exchange of atmospheric \(\text{CO}_2\) with the surface
layers of \(\text{CaCO}_3\). Diffusion of carbonate ions into the lattice will yield a
"too young age" or a minimum date (Williams and Polach, 1971). A similar
exchange can occur with dead carbon, resulting in an older than true age
date. This problem of postdepositional exchange with either dead or
modern carbon affects all samples from Lake Cahuilla to varying degrees.
The problem can be qualitatively evaluated by examining the sample and its provenance. Laboratory pretreatment procedures can also help to eliminate the effects of this problem.

The carbon-14 ages and the problems of dating carbonates allows two interpretations to be made from these data. The first interpretation is that these dates can be regarded as minimum ages, allowing an absolute chronology to be established with some dates eliminated due to problems of contamination (fig. 6). The second interpretation is that these dates are inaccurate and misleading. The former interpretation will be considered first.

Two finite dates from the 46-meter stand west of Plaster City have been reported (Hubbs, Bien, and Suess, 1963, 1965) and are in close agreement: 37,100±2,000 B.P. (LJ-504) on freshwater calcitic gastropods (*Physa*) collected from beach gravels and 37,400±2,000 B.P (LJ-959) on tufa collected from the surface of a beach remnant. These dates could be considered as an approximate minimum age for this stand, because of their close agreement and provenance, both of which suggest that exchange with dead carbon was not significant. The 46-meter stand of Lake Cahuilla is clearly not Sangamon, as suggested by Thomas (1963).

One sample of freshwater mussel (*Anodonta*) was collected by me from beach gravels of the 38-meter shoreline. This sample yielded a carbon-14 date of >39,900 B.P. (UCR-988). This sample has probably undergone much exchange with dead carbon, possibly through exchange with ground water, making the age too old. The 38-meter shoreline is younger than the 46-meter shoreline (minimum age of about 37,000 B.P.) in a relative sequence.
Figure 6. Chronology of late Pleistocene high stands of Lake Cahuilla, Salton Trough, California

Explanation

B - LJ-1633, tufa  G - LJ-1628, tufa  L - GX-3396, shell
C - LJ-450, tufa  H - LJ-1631, tufa  M - LJ-1636, tufa
D - LJ-959, tufa  I - UCLA-189, shell  N - LJ-1637, tufa
E - LJ-504, shell  J - LJ-1630, tufa
Four dates have been reported for the 31-meter stand of Lake Cahuilla (Hubbs and others, 1965; Hubbs and Bien, 1967; Childers, 1977a). Two dates, both from Mexico on freshwater mussel (*Anodonta*), were greater than 50,000 B.P. (LJ-928; LJ-954). These dates came from a marble terrain where the samples could easily exchange with dead carbon, resulting in an erroneous age. Another date from Mexico of 4800±500 B.P. (LJ-GAP-70) was obtained from *Anodonta* taken from the locality that yielded one of the >50,000 B.P. dates. This date is disregarded because of laboratory problems (Hubbs and Bien, 1967). I collected another sample of *Anodonta* from a locality of the 31-meter stand in Mexico. The carbon-14 date is >33,780 B.P. (UCR-989). This sample came from a marble terrain where the shell could have easily exchanged with dead carbon, resulting in a too old date. The only finite date for the 31-meter shoreline is 26,000±1570-1325 B.P. (GX-3396) obtained near Plaster City on *Anodonta* collected from beach gravels (Childers, 1977a). This date should be regarded as an approximate minimum age for this shoreline because the provenance of the sample suggests that exchange with dead carbon was not significant. This stand is not early Wisconsinan as suggested by Thomas (1963) but may instead date from the beginning of the last full glacial period.

No dates exist for the 52-, 40-, or 37-meter stands of Lake Cahuilla. The 52-meter stand, because of its relative chronological position to the 46-meter stand must be older than about 37,000 B.P. The 40-, 38-, and 37-meter stands lie chronologically between the 46- and 31-meter shorelines and must fall between about 37,000 and 26,000 years B.P.
Ten dates are reported from the eastern side of the Salton Trough from the Box Canyon locality in Riverside County (Hubbs and others, 1963; Bien and Pandolfi, 1972). All carbon-14 dates are on thin (<0.5 cm) layers of coralline tufa encrusted on cobbles of various non-carbonate lithologies in a fanglomerate mapped by Dibblee (1954) as the Ocotillo Conglomerate. This conglomerate contains normal faults with several distinct beds of tufa encrusted cobbles between altitudes of 33 and 48 meters. These beds may correspond with the shorelines on the western side of the trough. In evaluating the dates, four groupings appear: (1) >45,000 B.P. (LJ-1625; LJ-1633); (2) 36,000±2000 B.P. (LJ-1628), 36,900±1900 (LJ-1635), and >35,000 B.P. (LJ-450); (3) 30,600±1500 B.P. (LJ-GAP-0093), 31,200±1600 B.P. (LJ-1630), and 33,400±1700 B.P. (LJ-1631); and (4) 26,200±1500 B.P. (LJ-1636) and 25,600±1300 B.P. (LJ-1637). These dates may be regarded as approximate minimum ages when considering the provenance of the samples. The problem of exchange with dead carbon at this locality does not appear to be an acute problem. Date groupings 2 and 4 correspond well with the minimum ages for the 46- and 31-meter shorelines west of Plaster City. Date grouping 3 may correspond with the intermediate shoreline altitudes at 40, 38, and 36 meters, and date grouping 1 may correspond with the 52-meter stand (fig. 6).

Two carbon-14 dates have been reported by Fergusson and Libby (1963) on marine shells from the trough: 32,200±2000 B.P. (UCLA-189) on *Rangia* and >34,000 B.P. (UCLA-191) on *Chione*. Revisiting the localities where these samples were collected, I could not find *Chione* but did find many *Rangia*. The *Chione* were probably an
exotic and a fortuitous find. The *Rangia*, however, are eroding from the Brawley Formation, suggesting again the Brawley's temporal association with the late Pleistocene shorelines. These marine shells occur at elevations lower than 48 meters below sea level in the trough. Van de Kamp (1973) and Bowersox (1972) have shown that when Lake Cahuilla fell to this elevation the salinity rose to a level capable of supporting a brackish marine fauna if fortuitously introduced from the gulf possibly by migratory birds. The 32,200±2000 B.P. (UCLA-189) date may represent a time when such a condition of this lake existed.

The 20 carbonate carbon-14 dates previously discussed can be interpreted in another way. All these dates could be in error and lead to an incorrect interpretation. The two approximately 37,000 B.P. dates (LJ-504; LJ-959) from the 46-meter stand are very close to the limits of the carbon-14 dating method. Only a very minute amount (102%) of modern carbon would be necessary to change an infinite date into a finite date. This may be the case with these dates, because an infinite date of >39,900 B.P. (UCR-988) is reported from the 38-meter shoreline. The grouping of carbon-14 dates from the Box Canyon locality may be fortuitous. Because the samples dated were 0.5 cm or less thick layers of tufa, these samples could have easily exchanged carbon with the atmosphere to varying degrees, making infinite dates finite and thus accounting for the range of dates from >45,000 (LJ-1625) to 25,600±1300 B.P. (LJ-1637). The high stands from 52 to 37 meters could be considered beyond the limits of the carbon-14 method; all >40,000 years old with reported finite dates the results of atmospheric exchange with modern
carbon. The 26,000 +1570 - 1325 B.P. (GX-3396) date for the 31-meter shoreline may be valid as a minimum age for this stand.

Until other dating techniques are used on the shoreline carbonates it is impossible to evaluate which interpretation is the more accurate and which carbon-14 dates approximate the true ages.

**Hydrologic and Tectonic Aspects of Lake Cahuilla**

Intermittent northwest diversion of the Colorado River into the Salton Trough during the Quaternary is responsible for the formation of the different stands of Lake Cahuilla. This diversion is expected considering the general physiography of the delta and the instability of meandering channels across the delta.

The crest of the present deltaic cone trends southwest from an altitude of 43 meters near Yuma, Arizona, to a minimum altitude of 11 meters near Cerro Prieto 25 km south of Mexicali, Baja California. To the north, the delta surface slopes into the Salton Trough (minimum elevation at the bottom of the Salton Sea is 84 meters below sea level) at a gradient of 0.8 m/km. The gulf side has a southwest gradient of 0.4 m/km to the 5-meter altitude contour at a latitude of 32° N. Southeast of the 5-meter contour, the Gulf of California tides influenced the gradient, which is 0.02 m/km to the higher high tide line near the river mouth.

Major and minor channels were continually shifting position on the delta. Occasionally, channels overflowed and then cut through their natural levees toward the north, causing water to flow down the steeper northern gradient of the delta into the Salton Trough. This base level change caused rapid headcutting and enlargement of the channel. When
this cutting reached the apex of the delta cone a pattern of discharge into
the trough was well established. The lake filled rapidly at first, then
more slowly as evaporation increased with increase in lake surface area.
The lake filled to the minimum threshold-overflow altitude of the delta
barrier with excess water overflowing this barrier at a point east of Cerro
Prieto. A deep channel draining north to south known as the Rio Hardy
occurs south of Cerro Prieto along the margin of the Sierra Cocopas. It
truncates alluvial fans and pediments, with multiple stream terraces
developed on tributary streams. This channel may be the overflow chan­
nel of the prehistoric lakes. Prolonged diversion of the Colorado River
made the lake the site of millions of tons of silt deposition. This deposi­
tion flattened the stream gradient until the channel reached a point where
the gradient to the south was steeper. When this occurred, the river
rediverted its discharge south to the gulf. The isolated lake left in the
Salton Trough eventually dried.

The formation of the Salton Sea by an accidental man-made diver­
sion of the Colorado River into the Salton Trough in 1904-07 serves as a
modern analog to the formation of older lakes. The New River, the major
distributary of the northern delta slope, eroded headward after flood
waters from the Colorado River were diverted into its channel. A cataract
150-300 meters wide moved upstream for a short time at a rate of 0.8 km
per day, carving out a channel 15-25 meters deep (Davis, 1907; Newell,
1907). In the Alamo River a cataract 9 meters or more high and 75 to 90
meters wide was formed and retreated headward for many days at a rate
of 0.3 meters a minute. Corey (1915) gave the volume of earth removed
from the New and Alamo Rivers in 9 months as 344,000 cubic meters. In
only 2 years a lake of more than 1,300 km$^2$ was formed. The formation of a larger lake was averted only by a man-made effort that returned the Colorado River to its former course. The original channel to the south was aggraded by minor southern outflow and was overgrown by dense vegetation. This caused the Colorado River to occupy a variety of alternative courses across the delta since 1907 with no restoration of a stable channel to the gulf (Sykes, 1937). Normally, the Salton Sea would eventually dry, but excess water from irrigation maintains its present level.

The Pleistocene stands of Lake Cahuilla in contrast to the Pleistocene stands of lakes in the Great Basin were not "pluvial" in the sense that each stand represented a time of increased precipitation or cooler temperatures. Instead the stands of Lake Cahuilla occurred predominantly in response to northwesterly diversion of the Colorado River, with the maximum attainable height of each stand dependent on the minimum threshold-overflow altitude of the delta. It is believed that the high Pleistocene stands represented stable stands of the lake at threshold-overflow altitudes with excess discharge overflowing the delta at the point of minimum altitude just east of Cerro Prieto.

The high late Pleistocene shorelines, with the exception of the 52-meter stand present on the pediment west of Plaster City appear to have suffered little tectonic disturbance, except for a southerly subsidence, contrary to White, Carter, and Childers (n.d.). The position of the six high shorelines probably represent close approximations of the true lake surface altitudes during Lake Cahuilla's various stands throughout the late Pleistocene. The minimum altitude of the delta crest today is 11 meters; lakes at altitudes of 52 to 31 meters could not form under
existing delta conditions. The Colorado River delta undoubtedly stood at higher altitudes acting as a southern barrier, a dam, allowing larger lakes to form in the Salton Trough. Subsidence and erosion have decreased the aerial extent and altitude of the delta with time. Thompson (1968) has speculated that the distribution of older intertidal mud-flat-type deposits of various ages along the western coastline plain of the Gulf of California attests to a progressive decrease in the aerial extent of the Colorado Delta from a maximum in the early Pleistocene to a minimum at present. This would account for the lowering of shorelines of Lake Cahuilla with time.

Several authors have proposed that these shorelines represent one or more marine stands rather than freshwater lake stands. Hubbs and Miller (1948) were the first to propose a marine stage of the lake, and Robison (1965) and Loeltz and others (1975) suggested that the shorelines are marine rather than freshwater features. These authors found physiographic evidence conflicting with the idea that these shorelines developed around freshwater lakes and could not understand how the gulf waters could be excluded or how freshwater lakes could exist behind the Colorado Delta. Much of their argument is based on the eastern shoreline's being tilted northwestward "opposite to the direction of tilt required if there had been original separation of the Gulf" (Loeltz and others, 1975, p. K13). They also had problems accepting the erosion of the delta barrier and suggested that this "problem" would not exist if the shorelines were marine.

Field observations made by me conflict with the idea that these shorelines were marine. Firstly, the paleontological evidence conflicts
with this idea. Only freshwater gastropods and mollusks are associated with the high stands occurring in the shoreline deposits. Marine brackish water fauna are found only at elevations of 46 meters below sea level or less where saline conditions would develop in response to evaporation of freshwater, allowing brackish water forms to thrive if fortuitously introduced (Van de Kamp, 1973; Bowersox, 1972). Secondly, what was previously reported as the eastern shoreline is actually a dune ridge (see page 12). This eliminates their problem of the shoreline's showing an "opposite direction of tilt." Thirdly, there is no correspondence between the lake shoreline altitudes and sea level, if the carbon-14 dates of about 37,000 B.P. from the 46-meter shoreline and the 26,000 B.P. date from the 31-meter stand are valid and these dates are compared to the sea-level curve for the past 40,000 years (Dillen and Oldale, 1978). Fourthly, I believe that erosion along the outflow channel, coupled with an unknown amount of subsidence of the delta barrier from at least an altitude of 52 meters to 11 meters, is very plausible considering the interval of time involved—at least 37,000 years and probably even longer.
LATE HOLOCENE STANDS OF LAKE CAHUILLA

The most prominent shoreline of Lake Cahuilla stands at an altitude of about 12 meters and was first reported in the literature by Blake (1854). The shoreline features are well preserved and are almost continuous around the perimeter of the trough. This lake had a surface area of over 5,700 km² and a maximum depth of 96 meters. The 12-meter altitude represents the threshold-overflow altitude of the delta during this stand of Lake Cahuilla.

There has been much speculation as to the age, origin, number of fluctuations, and duration of this stand of Lake Cahuilla. Stratigraphic evidence and carbon-14 dating indicate that there were four lacustral intervals to the 12-meter shoreline during the last 2000 years.

Character and Distribution of Shorelines and Deposits

The late Holocene lake deposits can be divided into two major types: (1) quiet-water clay, silt, and very fine sand and (2) beach sand and gravel.

Fine sand, silt, and clay deposited in quiet water make up most of the Holocene stratigraphic record in the central and southern parts of the trough and are interbedded with alluvium in the northwest part of the trough. The layers of fine sand to clay have horizontal and ripple laminations or are massive and occasionally contain freshwater gastropods. The mica-rich fine sand deposited along the edge of the trough were derived from local stream runoff. The mineralogy of the fines in the central
and southern portions of the lake indicate that they were derived from the Colorado River (Van de Kamp, 1973).

A variety of topographic lacustrine features developed along the 480-km shoreline perimeter of Lake Cahuilla (fig. 7). These shoreline features were produced by erosion and deposition.

Erosional Features

Erosional features—wave-cut slopes and benches—make up 20 percent of the shoreline. A wave-cut slope is defined as an oversteepened hillslope with slight convexity formed by wave erosion (fig. 8). Wave-cut slopes are similar to "sea cliffs," (Gilbert, 1890, p. 34) but differ in that they are not necessarily undercut vertical cliffs. Generally associated with wave-cut slopes are platforms, known as wave-cut benches, that slope gently toward deeper water (Johnson, 1919, p. 162). These are produced by erosion and retreat of the wave-cut slope. All wave-cut slopes of late Holocene Lake Cahuilla are cut into unconsolidated materials such as fanglomerates and older Cenozoic formations. Seventy-five percent of the wave-cut slopes occur on the northeastern shoreline where they range from 15 to 5 meters in height. These features tend to straighten the eastern shoreline and may have been produced by strong wind-generated wave erosion toward the east. Wave-cut slopes on the western shoreline are generally less conspicuous, ranging from 5 to 1.5 meters in height. They commonly occur where promontories protrude into the lake and were notched by longshore currents.

Depositional Features

Depositional features make up the remaining 80 percent of the shoreline. These are a combination of beaches and prominent tufa
Figure 7. Late Holocene Lake Cahuilla
Figure 8. Wave-cut slope and bench with baymouth bar bridging a small reentrant, late Holocene 12-meter shoreline
deposits. Other depositional features occur along the shoreline, and these include a variety of embankments.

A beach is defined as a body of cohesionless sediment along a shoreline that is subject to the effects of breaking waves. Beaches take the form of a ridge of sand and gravel piled on the shore above the level of still water by the action of waves. The beach occupies a narrow elevation interval and conforms to the contours of the surface on which it was deposited. These are the most common constructional features of the shorelines (fig. 9). Soil development on the beaches of late Holocene Lake Cahuilla is slight with the development of either a 5-to-8-cm-thick A2 or O1 horizons. No desert varnish or pavement is developed on the shoreline.

The beaches of the eastern shoreline are composed of unconsolidated, thinly bedded, well- to moderately sorted, very coarse sand to gravel with a very low percentage of fine sand. The beach sediments coarsen from south to north and are composed mostly of acidic volcanic, granitic, and other lithic fragments, finer particles of quartz and feldspar, and some fossil "hash." Lakeward-dipping foreset beds and more gently dipping landward backset beds are present. The beach profiles show a gentle rise from the lake floor with a more abrupt drop off on the landward side (fig. 9). The beaches range in height from 4.5 to 9 meters and the width ranges from 1 to 300 meters with the widest beaches occupying the southeast part of the shoreline. Near the Orocopia Mountains the shoreline occurs as a shingle beach composed of clasts of foliated Orocopia Schist.
Figure 9. Late Holocene 12-meter beach in profile, eastern shoreline
The beaches of the western shoreline are finer grained than those of the eastern shoreline, ranging from very coarse to coarse sand, a result of the reworking of fine-grained Cenozoic formations (fig. 10). These beaches form a subdued topographic expression, generally stand only 1.5 to 4.5 meters in height, and range from 0.5 to 30 meters in width. The beach sand is well to moderately sorted and derived mostly from the erosion of calcareous sandstone, granite, gneiss, and schist. Beaches on alluvial fans near the Santa Rosa Mountains are formed by in situ reworking of fan gravels, resulting in coarse beach deposits standing only 0.5 to 1 meter in height (fig. 10).

Tufa forms a conspicuous shoreline or high-water mark where the waters of Lake Cahuilla washed directly against the bedrock outcrops that protruded into the lake (fig. 11). This type of shoreline is predominantly confined to the northwest side of the lake and the Fish Creek Mountains where the water was very placid and outcrops projected into the lake. The changes in altitude of the tufa 'line' in a reentrant in the Santa Rosa Mountains was surveyed by transit. This tufa line showed a change in altitude of only 1 meter from that of the promontories projecting into the lake to the rear of the reentrant. This small change in altitude indicates a quiet-water environment.

The tufa deposits of late Holocene Lake Cahuilla take two general forms: (1) lithoid tufa (two varieties) (Morrison, 1964) and (2) coralline tufa (Morrison, 1964).

Lithoid tufa is dense and thinly laminated and forms botryoidal or flat blanket deposits. It is commonly no more than 2 cm thick and is confined to the interiors of caves and under overhangs, wherever light
Figure 10. Size vs. sorting (standard deviation) plot for beach sands of the late Holocene (12-m) stand of Lake Cahuilla.

Mean phi size and standard deviation or sorting are those of Folk (1974)

Explanation

Field A – General limits of eastern beaches
Field B – General limits of western beaches
Field C – Western beaches formed on alluvial fans
▲ ▲ ▲ – Eastern shoreline
● ● ● ● – Western shoreline
Figure 11. Tufa marking late Holocene 12-meter shoreline of Lake Cahuilla, Santa Rosa Mountains, California
did not effectively penetrate. This tufa is relatively pure and never contains sand grains but does trap pockets of sediments or fossils. The other form of lithoid tufa has the same general characteristics except that it forms blanket deposits of coalesced colonies of upward- and outward-growing character. On vertical and overhanging slopes tonguelike protruberances are common, projecting outward and downward at low angles from the horizontal. The individual tongues are relatively smooth and dense. These two morphologic varieties grade into one another.

Coralline tufa is the most common and is often referred to as "reticulated" (fig. 12). It varies from individual heads to irregular coatings of variable thickness from a few millimeters to a meter. Coatings have a spongelike, or coralline, top surface. This tufa has a slight to pronounced branching habit and is porous and cellular. Gastropods and sand grains are commonly incorporated into the tufa. The tufa forms very large rounded lumps on boulders, welding individual rocks together.

The most impressive deposits of coralline tufa occur along the Santa Rosa Mountains where they mark the shoreline of the late Holocene lake stand (fig. 11). Here the tufa covers all the outcrops projecting into the lake with thicknesses up to 1 meter. The high-water mark is sharp and marked by a change in thickness of the tufa from centimeters to millimeters. Along most of the western shoreline, thin coatings of coralline tufa coat isolated rocks at the foot of beaches and cliffs. Tufa is less common on the eastern shoreline and is only found north of the Orocopia Mountains (fig. 7).

Embankment depositional features were developed in late Holocene Lake Cahuilla. An embankement is a ridge or mound of sediment built by
Figure 12. Coralline tufa encrusting rocks below the high-water mark (12 m) of late Holocene Lake Cahuilla, Santa Rosa Mountains, California
the deposition of shoredrift at its terminus. The transporting agent is a
longshore current, and deposition results from separation of the current
and wave action where a current continues past a shoreline reentrant or
where a current turns from the shore toward deeper water (Gilbert, 1890,
p. 26). Because it is constructed by the action of currents, the length
of the embankment parallels the direction of their line of movement. Em­
bankments of Lake Cahuilla include spits, baymouth bars, longshore bars,
and tombolos.

A spit is an embankment with a free or unattached terminus (Gil­
bert, 1890, p. 47). A well-developed spit was developed at the south end
of the Mecca Hills and extended southward into the lake. Another spit
extended one mile to the northeast from Bat Cave Buttes. Other smaller
spits occur in this area and are common on the east shoreline where long­
shore currents were well developed.

A baymouth bar extends across the mouth of a bay or reentrant
and is attached at both ends. These bars are very common on both sides
of Lake Cahuilla, bridging reentrants and commonly bridging stream
channels between wave-cut slopes (fig. 8). Behind these bars water from
stream runoff was dammed, producing small lagoons where freshwater
fauna could thrive.

A longshore bar is a subaqueous ridge of detrital sediment formed
roughly parallel to the shoreline. It lies in the breaker zone and is cre­
ated by action of waves and longshore currents. Longshore bars were
common on both sides of Lake Cahuilla in front of wave-cut slopes and
beaches.
A tombolo is a spit connecting an island to the mainland. One was built at Travertine Point where a ridge of sand extends from the Santa Rosa Mountains to the point.

**Probable Currents of Lake Cahuilla**

Hubbs and Miller (1948) believed that the currents and wave activity that affected Lake Cahuilla were very slight. Their belief is inconsistent with my own and other authors' field observations. Sykes (1914) first observed that the northeast shore had been subjected to intense wave action, which resulted in the formation of prominent cliffs. Norris and Norris (1961) agreed with Sykes and suggested that the northwesterly winds produced a strong southerly current parallel to the eastern shoreline. Arnal (1961) proposed that the currents of Lake Cahuilla were counterclockwise as are those today in the Salton Sea. This inference was based on the distribution of pumice from Pumice Buttes.

The linear morphology of the eastern shoreline suggests intense wave activity (fig. 7). Southeasterly blowing winds over the northern part of the lake were probably responsible for a strong southern current along the northeast shoreline, which is marked by steep wave-cut slopes. The eroded material from these slopes was transported southward and produced the large spit south of Mecca Hills. Northeasterly blowing winds notched the central portion of the eastern shoreline producing steep wave-cut slopes. A northerly longshore current paralleling the shoreline was probably established and is suggested by the transport of pumice from Pumice Buttes to areas north of the Orocopia Mountains (fig. 7). Along the southeast portion of the lake, wave energy was largely dissipated before reaching the shoreline by the shallow gradient of the lake. Here,
beaches were formed by the southerly transport of sediment, probably by wind-generated southerly longshore currents.

The western shoreline must have been subjected to less intense wave activity because the winds did not directly affect this side of the lake. Instead, the shoreline is embayed and irregular (fig. 7), beach deposits are less prominent, and there are fewer wave-cut features. The waters in the northwestern portion of the lake were placid, with beaches produced by in situ reworking of fan materials to heights of 1 meter or less. Tufa deposits mark the shoreline as encrustations on bedrock outcrops showing little change in altitude (see section on deposits). Minor currents must have existed in this portion of the lake to produce the tombolo at Travertine Point.

Along the southwestern shoreline a northerly longshore current is suggested by the orientation of redeposited concretions (Garner, 1936). "Macelike" concretions found in the beaches near Mt. Signal are oriented with the ball end southward and the stem end pointing northward (fig. 7). This northerly current probably continued northward, cutting a small wave-cut slope 1.5 to 3 meters high on a promontory protruding into the lake. The waters were placid around Fish Creek Mountains, with tufa deposits marking the shoreline on angular boulders.

Finally, local fossil deposits also accord with intense currents along the eastern shoreline. *Anodonta* live in an environment of slight wave activity (Bowersox, 1972).

**Stability of Lake Cahuilla**

To assess the stability of the late Holocene stand of Lake Cahuilla, its hydrologic regimen was examined. The method used was adapted from
Snyder and Langbein (1962) and Leopold (1951) for determining the hyrologic budget for a closed basin. This method views a closed basin in terms of equilibrium between precipitation, runoff, and evaporation. The basic equation states that change in volume of the lake (ΔV) is equal to gains by surface runoff (Is), ground-water inflow (Ig), and direct precipitation to the surface of the lake (P) minus the losses due to direct evaporation from the lake surface (E), or

\[ \Delta V = Is + Ig + P - E, \]

where P = precipitation (P') times area (A) and E = rate of evaporation (E') times area. When this method is employed, the major assumption made is that modern recorded climatic and discharge data can be applied to the last 2000 years.

Surface discharge from small drainage basins within the trough probably accounted for a minor portion of the discharge that flowed into Lake Cahuilla and will therefore be considered negligible in comparison to the discharge from the Colorado River. Whitewater Wash is the only stream in the Salton Trough with a drainage basin large enough to possibly affect the lake budget calculations. However, Weide (1976, p. 13) stated that the sediments exposed in the wash indicate that high-velocity discharge was rare and sporadic, and he suggests that such events occurred only once in several centuries. This suggests that input into the lake by surface discharge from ephemeral streams in the Salton Trough can be considered negligible in the lake budget calculations.

Discharge from the Colorado River accounted for almost all of the water supplied to Lake Cahuilla. A rough estimate of the average annual virgin flow of the Colorado River can be made by using records of flow
gaged at Yuma, Arizona. To make this estimate, the 28-year period 1903-1930 was used with corrections made for water removed for irrigation (Hely, 1969). After 1930, the discharge of the Colorado River was drastically changed by damming upstream. These records indicate an average flow of $2.0 \times 10^4$ hm$^3$/yr for the Colorado River (Hely, 1969).

This value may be compared with estimates of the virgin flow of the Colorado River made at Lees Ferry, Arizona. Thomas and others (1960) estimated that the average annual virgin flow at Lees Ferry for the last 650 years has been approximately $1.95 \times 10^4$ hm$^3$/yr. This estimate is based on extrapolation between tree ring records for the upper Colorado River basin and historic runoff records. A general correspondence between the tree growth index and the recorded average annual rainfall and runoff in the upper Colorado River basin was noted for the period 1900 to 1950. This allowed extrapolation of an average flow based on tree rings through A.D. 1288. Because Lees Ferry is north of Yuma, its data do not include the additional input from the Little Colorado, Bridal Veil, Virgin, Bill Williams, and Gila Rivers and lesser streams. These drainages contribute an additional $1.7 \times 10^3$ hm$^3$/yr (Hely, 1969) to this figure, making a total of $2.12$ hm$^3$/yr, but this new figure does not account for water lost by evaporation between Lees Ferry and Yuma. It is concluded that the estimate of $2.0$ hm$^3$/yr recorded at Yuma is valid to use as a first approximation for the average annual discharge of the Colorado River.

Ground-water seepage into the Salton Trough is considered negligible prior to the development of irrigated agriculture (Hely, Hughes, and Irelan, 1966) and will not be considered in the lake budget calculations. Precipitation is estimated at 6.4 cm/yr (Hely and others,
Evaporates from the surface of Lake Cahuilla is best estimated by comparison with that of the Salton Sea. Hely and others (1966) found that 1.75 meters evaporated annually from the surface of the Salton Sea, which agrees with other reported values. Since saline water evaporates at a rate 2 percent less than freshwater the annual evaporation rate can be corrected to 1.8 meters per year.

Another assumption is that the 12-meter shoreline represents the threshold altitude of Lake Cahuilla during the late Holocene and that this was the level to which the lake repeated filled and then overflowed. This would produce a lake area of 566,000 hm² (area calculated by digital planimetry).

Using these figures the following calculations can be made:

**Gains:**

\[
\begin{align*}
I_s &= 2.0 \times 10^4 \text{ hm}^3/\text{yr} \\
I_g &= 0 \\
P &= (P') (A) = (0.00064 \text{ hm/yr}) (566,000 \text{ hm}^2) \\
&= 362 \text{ hm}^3/\text{yr} = 0.04 \times 10^4 \text{ hm}^3/\text{yr} \\
\text{Total gain} &= (I_s + I_g + P) \\
&= 2.0 \times 10^4 \text{ hm}^3/\text{yr} + 0 + 0.04 \times 10^4 \text{ hm}^3/\text{yr} \\
&= 2.04 \times 10^4 \text{ hm}^3/\text{yr}
\end{align*}
\]

**Losses:**

\[
\begin{align*}
E &= (E') (A) = (0.018 \text{ hm/yr}) (566,000 \text{ hm}^2) \\
&= 10,188 \text{ hm}^3/\text{yr} = 1.02 \times 10^4 \text{ hm}^3/\text{yr} \\
\text{Total loss} &= E = 1.02 \times 10^4 \text{ hm}^3/\text{yr}
\end{align*}
\]

**Change in lake volume:**

\[
\Delta V = \text{Gains} - \text{Losses}
= 2.04 \times 10^4 \text{ hm}^3/\text{yr} - 1.02 \times 10^4 \text{ hm}^3/\text{yr}
= +1.02 \times 10^4 \text{ hm}^3/\text{yr}, \text{ a surplus.}
\]
This demonstrates that only approximately half the flow of the Colorado River was necessary to maintain a freshwater lake at an altitude of 12 meters. Any additional discharge of the Colorado River would overflow the delta threshold altitude. Wilke (1978a) calculated that it would take about 10 years or less to fill Lake Cahuilla to the 12-meter stand and about 60 years to evaporate a lake of this size if isolated from Colorado River inflow.

Chronology of Late Holocene Lake Cahuilla

The most recent chronologies for late Holocene Lake Cahuilla have been proposed by Stanley (1962, 1965) and Wilke (1978a). Stanley postulated repeated fillings of the basin to capacity to an altitude of 12 meters and suggested that there were at least three lacustral intervals of the lake. Wilke (1978a) has proposed the most recent chronology, suggesting, like Stanley, that there were at least three lacustral intervals of Lake Cahuilla (100 B.C.-A.D. 600, A.D. 900-1250, and A.D. 1300-1500), each representing an unknown number of stands of unknown duration. The dating of these stands was based on reinterpretation of the available published data.

Wilke (1978a) saw a clustering of published carbon-14 dates into three groups, which he interpreted as representing three lacustral intervals or stages of the lake. Most of the carbon-14 dates are from archaeological sites temporally associated with the lake, with a few dates on tufa, tule charcoal, and shell. The available carbon-14 dates suffer from several problems, and interpretations based on them should be cautiously evaluated. First, these dates are essentially random; the samples were not systematically collected within a meaningful geologic framework.
Second, the accuracy of many of the dates should be question in light of changes in methodology and theory since many of the dates were obtained. Third, the accuracy of some key samples can be questioned with respect to stratigraphic and mixing problems that were not recognized or that were introduced by the collector. Fourth, dates from an archaeological context should not be applied to a geologic situation with such precision. The clustering of carbon-14 dates reported by Wilke (1978a) may be fortuitous and may represent something other than lacustral intervals.

Wilke (1978a) suggested that the occurrence of obsidian from Obsidian Buttes in the Peppertree archaeological site (CA-Riv-463) indicates that there were one or more periods of complete desiccation of Lake Cahuilla after A.D. 900. The top of Obsidian Buttes, which is in the central portion of the Salton Trough approximately 295 km southeast of the site, is approximately 40 meters below sea level. At the Peppertree site obsidian artifacts were found from level g, dated 870±60 B.P. (UCLA-1815), through level d, dated 215±60 B.P. (UCLA-1816) (Wilke, 1974). He suggested that Lake Cahuilla must have dried, allowing man to quarry the obsidian normally covered by the lake.

Wilke (1978a) also used the 760±100 B.P. date of LJ-99 to suggest two lacustral intervals after A.D. 900. This date came from charcoal reported to be a tule fire dispersed in a silt unit on the west shore of the lake north of Travertine Point. It was interpreted by Stanley (the collector) and Wilke to represent the second of three lake inundations with silt units lying above and below this dated unit and separated by layers of beach gravels (Hubbs and others, 1960, p. 215).

Additional evidence of repeated fillings of Lake Cahuilla during late Holocene comes from tufa-coated petroglyphs near Travertine Point.
The petroglyphs were pecked into tufa during low stands of Lake Cahuilla, and tufa was subsequently deposited over the petroglyphs during a later rise of the lake.

Historic evidence suggests that the last high stand of Lake Cahuilla had ended or was desiccating by A.D. 1540. Many early explorers commented on the position of the Colorado River since 1540: Diaz and Alarcon, in A.D. 1540; Don Juan de Onate, in 1604; Padre Eusibio Francisco Kino, in 1701 and 1702; Ugarte, in 1721; Fernando Consag, in 1744; Padre Garces, in 1771 and 1776; Lieut. R. W. H. Hardy, in 1825; James P. Pattie, in 1827. Additional information can be found in later records of the pioneers of the settlements on the river and in the reports of the explorers Lieut G. H. Derby, in 1850-51, and Lieut. J. C. Ives, in 1857. From these sources, it is known that the Colorado River has maintained its present course from Yuma to the Gulf of California, making only changes of alignment for over 400 years.

Historic evidence indicates that the Salton Trough has not received large amounts of water from the Colorado River since A.D. 1540. A point is sometimes made of the map of Rocque issued about 1762, which shows the Colorado and Gila Rivers uniting and flowing into the northern end of a body of water detached from the Gulf of California. If this diversion took place it was not noted by Consag in 1746 or by Garces in 1771, who both found the Colorado River very much as it is today. The source of this map is unknown, and its general character is such that it may be regarded more as an inexact copy of other maps than as one that utilized the data of some exact forgotten observer (Sykes, 1914).
Further evidence of the age of late Holocene Lake Cahuilla comes from Thompson's (1968) work on the tidal flats of the Gulf of California. Whenever the Colorado River flowed into the Salton Trough it had a drastic effect on the supply of sediment to the gulf. Thompson (1968, p. 113) has documented a period of low mud supply to the gulf expressed in the development of his shoreline 2 (stage IV) that was initiated sometime about 1000-1500 B.P. on the basis of 17 carbon-14 dates from this shoreline. This curtailment of mud supply to the tidal flats of the gulf is obviously the result of the flowing of the Colorado River into the Salton Trough. These dates correspond roughly with the proposed time of the first filling of Lake Cahuilla.

Five Pleistocene carbon-14 dates have been reported from the late Holocene stand of the lake. These ages were obtained from tufa encrusted on marble south of Travertine Point. These dates are: 13,400±200 B.P. (LJ-457), 21,800±1000 B.P. (LJ-1632), 24,000±1200 B.P. (LJ-1634), 29,000±1500 B.P. (LJ-1627), 29,000±1500 (LJ-1629). There is a high probability that these five Pleistocene dates are in error because of isotopic exchange between the tufa and the "dead" carbon in the marble. All other dates obtained from the tufas along the Santa Rosa Mountains from this shoreline date to the late Holocene, 1800±200 B.P. (LJ-513) and 1890±500 B.P. (LJ-458), when not associated with marble or other carbonate rocks.

From the foregoing discussion it can be seen that a precise and accurate chronology for the late Holocene stands of Lake Cahuilla does not exist, but it is evident that numerous stands of the lake filled the Salton Trough to an altitude of 12 meters during the last 2000 years.
Stratigraphy examined for this study and 14 new carbon-14 dates obtained from three stratigraphic sections show that there were four lacustral intervals to the 12-meter shoreline during the last 2000 years. A chronology is presented and should be considered tentative until $^{14}\text{C}/^{12}\text{C}$ corrected dates are obtained from the carbon-14 laboratory at the University of California, Riverside. Also this chronology has not been calibrated against the bristlecone pine chronology, which should be done only after the other corrections are made.

This chronology is based on the previously discussed data and 14 new carbon-14 samples collected from three stratigraphic sections. These new dates are of two types: (1) aragonitic freshwater mussel ($Anodonta$) from the lacustrine units and (2) archaeological charcoal dates from hearths interstratified between lacustrine units.

All dates are sequentially consistent within the established stratigraphic framework when examining the two dated materials separately. Using the hearth charcoal dates as cross-checks (five cross-checks) on the accuracy of the aragonitic shell dates shows that the shell dates are too old by 525 to 225 years. Eliminating the maximum difference of 525 years, the four remaining cross-checks show that the shell dates range from 375 to 225 years to old, with an average difference of 300 years. This anomaly could be due to an initial low $^{14}\text{C}/^{12}\text{C}$ ratio at the time of $\text{CaCO}_3$ precipitation of the shell. A correction of 300 years is subtracted from all shell dates. This correction proved useful for a first approximation. When the $^{14}\text{C}/^{12}\text{C}$ corrected dates are available this technique may not be necessary.
A sedimentation rate was calculated on the basis of lacustral interval 1, locality 104 (fig. 13) where this unit is bracketed stratigraphically by archaeological hearth charcoal dates (fig. 14). This gave a sedimentation rate for this locality of about 0.4 cm/yr. This rate allows the calculation of the duration and ending dates for most of the lacustral intervals.

Using all these data and interpretations made from them, it was determined that there were four lacustral intervals during the last 2000 years (fig. 15). The dates suggested for the lacustral intervals are accurate and precise to ±50 years and should be considered tentative until corrected dates are available.

The first lacustral interval is directly dated and well bracketed in time. A hearth charcoal date of 1340±100 B.P. (UCR-990) was obtained from an alluvial unit 10 cm below the lower lacustrine contact (fig. 13). Three aragonitic shell dates, 1545±100 (UCR-996), 1615±100 (UCR-999), and 1650±100 B.P. (UCR-987), were obtained from the lower 10 cm of the lacustrine unit at three localities (figs. 13, 16, and 17). Subtracting 300 years from each date gives corrected ages of 1245, 1315, and 1350, respectively. On the basis of the calculated sedimentation rate it was inferred that this lacustral interval lasted 150 years. The sediments indicate that the lake was at its maximum altitude of 12 meters for all of this time. A beginning date of 1300 B.P. is assigned to this lacustral interval by averaging the three corrected shell dates. This age is also in agreement with the hearth date of 1340 B.P. located stratigraphically below the lacustrine unit. An ending date of 1150 B.P. is inferred from the hearth date of 1150±100 B.P. (UCR-991).
Figure 13. Generalized stratigraphic section of carbon-14 locality no. 104

Explanation

F - Fluvial sand and gravel units
L - Lacustrine silt units

Scale: 1 inch = 1 meter
All standard deviations ± 100 years
Figure 14. Archaeological hearth interbedded between lacustrine units at carbon-14 locality no. 104
Figure 15. Lacustrine chronology of Lake Cahuilla for the last 2000 years
Figure 16. Generalized stratigraphic section of carbon-14 locality no. 103

Explanation

F – Fluvial sand and gravel units
L – Lacustrine silt units

Scale: 1 inch = 1 meter

Standard deviations ± 100 years for upper three dates and ± 120 years for lower two dates
Explanation
F – Fluvial sand and gravel units
L – Lacustrine silt units
Scale: 1 inch = 1 meter
All standard deviations ± 100 years

Figure 17. Generalized stratigraphic section of carbon-14 locality no. 031
The second lacustral interval is not directly dated. It lies stratigraphically between lacustral interval 1 and 3 and therefore must lie in time between 1150 B.P. and 800 B.P. (fig. 13). Calculations based on the rate of sedimentation suggest that this lacustral interval lasted about 100 years. The sediments suggest that the lake was at its maximum 12-meter altitude during all of this time. It is suggested that this interval lasted between about 1050 B.P. and 950 B.P.

The third lacustral interval is directly dated. This lacustral unit is composed mostly of ripple-laminated very fine sand and silt with a few coarse sand lenses suggesting shallow-water deposition with some massive silts to fine sand suggesting quiet-water deposition. These sediments indicate that this lacustrine interval was unstable with the lake fluctuating from its maximum altitude of 12 meters to sea level. Interstratified in the ripple-laminated silts are three archaeological hearths containing burned shell and fish bone. Charcoal dates from the hearths are 770±100 B.P. (UCR-992) 10 cm from the basal contact, 750±100 B.P. (UCR-995) farther up in the unit, and 700±100 B.P. (UCR-994) still at a higher level (fig. 13). Also two aragonitic shell (Anodonta) dates were obtained: 1295±100 B.P. (UCR-993) stratigraphically above the hearth dated 770 B.P. (UCR-992) (fig. 13) and 1190±100 B.P. (UCR-998) from the lower 10 cm of the unit (fig. 16). Subtracting 300 years from each shell date gives a corrected age of 995 B.P. and 890 B.P., respectively. A date of 760±100 B.P. (LJ-99) on charcoal reported to be from a tule fire in lacustrine silts is reported in the literature (see p. 45). A lacustral interval of 150 years is calculated from the sedimentation rate. A beginning date for this lacustral interval is calculated from the 770 B.P.
(UCR-992) hearth charcoal date, which lies 10 cm above the basal contact in ripple-laminated lacustrine silts. This date combined with the amount of time calculated to deposit 10 cm of lacustrine silts suggests a beginning date of about 800 B.P. The ending date of about 650 B.P. is calculated on the basis of the sedimentation rate. All the reported dates fall within this interval with the exception of one shell date, 1295±100 B.P. (UCR-993). This date may be anomalous and will be reevaluated when 14C/12C-corrected dates are available.

The last, or fourth, lacustral interval is directly dated. Two aragonitic shell (*Anodonta*) dates were obtained of 820±100 B.P. (UCR-986) (fig. 17) and 780±100 B.P. (UCR-997) (fig. 16) form the base of the lacustrine unit. Subtracting 300 years for each date gives 520 B.P. and 480 B.P., respectively. Calculations based on the rate of sedimentation indicate that this interval lasted about 70 years. The sediments suggest that the lake was at its maximum altitude of 12 meters during all of this time. A beginning date of 500 B.P. is calculated by averaging the two corrected basal shell dates. The ending date of 430 B.P. is based on calculations from the rate of sedimentation and historical evidence suggesting that the lake was no longer receiving water from the Colorado River after A.D. 1540.

Two lacustral intervals are dated to pre-2000 B.P., 2630±120 B.P. (UCR-1000) and 2600±120 B.P. (UCR-1001) (fig. 16). These dates will be evaluated when 14C/12C-corrected dates are available, but these dates suggest that there were no lacustral intervals between 2000 B.P. and 1350 B.P.
In summary, the stratigraphy, carbon-14, and historical evidence suggests four fillings of Lake Cahuilla during the last 2000 years. These are dated tentatively between 1300 B.P. and 1150 B.P., 1050 B.P. and 950 B.P., 800 B.P. and 650 B.P., and 500 B.P. and 430 B.P. All are accurate to ±50 years. When corrected carbon-14 dates are available a more precise chronology will be presented.

Postdepositional Deformation of the Lake Shoreline

The late Holocene shoreline is traceable with only minor breaks around the perimeter of the Salton Trough. Norris and Norris (1961) noted a discrepancy of 11 meters in the altitude of the shoreline and were the first to suggest that this was due in part to "diastrophism" rather than entirely to differences in wave activity as suggested by Sykes (1914). The altitude of the lake shoreline was reexamined to look for effects of postdepositional tectonics.

Shoreline altitudes were estimated to ±1.5 meters from aerial photographs and topographic map interpretation. All altitude estimates were taken from the bases of beaches and wave-cut slopes. This procedure provides a consistent, minimum value for the altitude of the lake stands. To separate differences in altitude due to tectonics from those resulting from differences in wave intensity, the altitude differences of the east and west shorelines were considered separately. These data show that the shoreline has undergone some deformation since its formation (fig. 18). The eastern shoreline ranges in altitude from 18 to 10 meters—a difference of 8 meters. The western shoreline ranges in altitude from 20 to 9 meters—a difference of 11 meters. A comparison of
**Figure 18.** Variation in shoreline altitudes of late Holocene Lake Cahuilla

- Altitude of shoreline in meters
differences in altitudes of the eastern and western shorelines represents differences in wave intensity rather than differences in tectonic deformation. If a difference of 3 meters in altitude between the western and eastern shorelines (11 m - 8 m = 3 m) is used for differences in wave intensity between the two sides of the lake, then an anomaly of 8 meters on the western shoreline and an anomaly of 5 meters on the eastern shoreline remain. This anomaly is due to postdepositional tectonics. Hubbs and Miller (1948) and Norris and Norris (1961) reported that the 12-meter shoreline occurs at an altitude of 7.5 meters in Mexico. This increases the altitude differences due to postdepositional tectonics to approximately 9.5 meters on the west and 7.5 meters on the east shoreline. This difference in the shoreline altitudes can be attributed to relative doming of the shoreline in the north, possibly the result of isostatic rebound or recent tectonics and subsidence to the south.
Childers (1977a, p. 19) suggested that wave-cut benches and cliffs exist at altitudes of 135 and 130 meters north of Pinto Wash and on pediments in the Coyote Mountains. Minshall (1976) and Hayden (1976) also mentioned these features. My field work showed that these are not wave-cut benches and cliffs but faults scarps and stream terraces. The terraces north of Pinto Wash represent fault scarps and terraces of an ancestral Pinto Wash. The terraces in the Coyote Mountains area are fault scarps that offset the pediment and its capping alluvium. Hayden (1976, p. 287) reported a carbon-14 date of "24,000 B.P. on a tufa encrusted artifact" from the 135-meter terrace. This material is not tufa but instead is caliche, and the artifact was collected from a lower altitude.

Loeltz and others (1975, p. K12) reported shorelines cut into bedrock on the northwest flank of Superstition Mountain where "... they have been uplifted and tilted by movements along the San Jacinto fault. The oldest shoreline slopes about 10° southwestward and has an altitude of nearly 150 meters at its northeast end." These may possibly be faulted equivalents of the 46- and 31-meter shorelines.

A large span of time is unaccounted for in the lacustrine history of the Salton Trough from about 26,000 B.P. to 2000 B.P. There were undoubtedly other late Pleistocene stands of Lake Cahuilla, but these stands were not recorded by topographic lacustrine features. The only record of such fluctuations would be in the deposits of the Brawley Formation. There were also a number of lacustrine fluctuations of unknown
extent, age, and duration during the early and middle Holocene. Evidence of such fluctuations comes from the research of Van de Kamp (1973). He obtained a carbon-14 date of 5,740±360 B.P. on aquatic gastropods (*Physa*) removed from lacustrine silts at a depth of 7 meters below the surface. Lacustrine silts containing other freshwater fossils occur above and below this dated horizon and are present to considerable depth in Holocene sediments interbedded with fluvial gravels. This suggests that there were stages of Lake Cahuilla throughout the Holocene. These lakes must have been ephemeral and unreliable resources because little archaic Amargosan archaeological materials is found in the trough (Jay von Werlhof, 1979, oral commun.). It seems reasonable to speculate that if a lake similar to the 12-meter stand of Late Holocene age existed, it would have been extensively exploited by archaic people. This, however, was not the case.
HISTORIC LAKES IN THE SALTON TROUGH

Minor incursions of the Colorado River into the Salton Trough have been reported in historic times. Settlers alleged that water entered the trough in 1840, 1842, 1859, 1862, 1867, and 1891. During the summer flood of 1862 the mail stage between Yuma and San Diego was interrupted and a flat boat was used to cross the New River for several weeks. During the summer of 1891 water filled the Salton Sink (lowest portion of the trough) and formed a lake several kilometers in length (Sykes, 1914).

The most recent flooding occurred between 1904 and 1907 when flood waters of the Colorado River entered the irrigation system leading to the Salton Trough. In the winter of 1904-05 flood waters of the Colorado and Gila Rivers combined to produce an abnormally high discharge that flowed through an unprotected headgate and down the steeper grade of the canal into the trough. The canal and tributary channels began to cut and enlarge until almost the entire discharge of the Colorado River was flowing into the Salton Trough by 1905. The Colorado River was finally returned to its former channel by damming the breach at the headgate in February 1907. This incursion formed the Salton Sea.
ARCHAEOLOGY OF LAKE CAHUILLA

Lowland Patayan villages containing large amounts of locally made Salton Buff (Waters, n.d.), ground and chipped stone artifacts, fish traps, and other archaeological features are common along the 12-meter shoreline of late Holocene Lake Cahuilla. This implies a heavy use of the lake resources during the late Holocene.

Artifacts of the Malpais and San Dieguito I complexes (Hayden, 1976) and the Ridge Back complex (Childers, 1977b) have been reported from the higher late Pleistocene shorelines of Lake Cahuilla. Childers (1977a, 1977b) reported that these artifacts are coated with tufa and are temporally associated with the 46- and 31-meter shorelines. Further mention of temporal association of the high Pleistocene stands and this archaeological material have been made by White, Carter, and Childers (n.d.), Minshall (1976), and Hayden (1976). Childers (1977a) reported that artifacts of these complexes are found at altitudes above and below the late Pleistocene beaches and are found at Obsidian Buttes, 67 meters below sea level. Childers inferred from this distribution of artifacts that man was following the fluctuations of Pleistocene Lake Cahuilla.

It is my conclusion that no archaeological material is temporally associated with the known late Pleistocene stands of Lake Cahuilla. It can be shown that there is a temporal distinction between artifacts and the recognized late Pleistocene high stands of Lake Cahuilla. The 31-meter stand of the lake is well preserved on a pediment along the eastern flank of the Sierra Cocopas. In some places along the mountain front a
15- to 30-cm layer of alluvium unconformably overlies the beach deposits. A desert varnished pavement has developed on the beach and alluvial deposits with 46 cm of soil profile development (figs. 4 and 5). On and in this desert-varnished pavement surface are varnished artifacts and features of the Malpais and San Dieguito I complexes. These artifacts and features occur at altitudes above and below the beach. These tools are not temporally associated with this or any other high stand of Lake Ca-huilla, because the 31-meter stand of the lake, the youngest recognized late Pleistocene stand, was eroded and alluvium deposited over it before the tools were made and incorporated into the forming desert pavement. This demonstrates that the undated Malpais and San Dieguito I complexes are younger than the 31-meter stand, which has an assigned minimum age of 26,000 B.P. This does not infer that these artifacts are pre-Clovis in age, because the absolute time of deposition is unknown.
SUMMARY

Freshwater lakes formed in the Salton Trough, California, behind the barrier of the subaerial Colorado River delta, which separates the trough from the Gulf of California. This occurred whenever the Colorado River waters were diverted northwestward into the trough instead of south to the Gulf of California. The various stands of the lake are collectively known as Lake Cahuilla.

Six late Pleistocene shorelines of Lake Cahuilla are preserved in the trough. These shorelines occur at maximum altitudes of 52, 46, 40, 38, 36, and 31 meters. It is difficult to assign absolute ages to these stands when considering the complications of interpreting carbonate radiocarbon dates. A minimum age of 26,000 B.P. is assigned to the 31-meter stand based on carbon-14 dating of freshwater shell with the other stands beyond the limits of the carbon-14 method (i.e., >40,000 B.P.).

The late Pleistocene stands of Lake Cahuilla are not "pluvial" in the sense that they represent times of increased precipitation and (or) cooler temperatures but are instead the result of diversions of the Colorado River into the Salton Trough. It is suggested that each lake would fill until it reached the minimum threshold-overflow altitude of the delta barrier at which time excess water overflowed the delta. Each of these high stands is inferred to have been a stable lake and to represent changes in the minimum altitude of the delta threshold through time. If this is true, there has been a progressive lowering of the subaerial delta barrier with time due to erosion and subsidence.
A prominent shoreline that dates to the late Holocene (last 2000 years) occurs at an altitude of 12 meters. This lake had a surface area of over 4,700 km² with a maximum depth of 96 meters. A variety of shoreline features are well preserved around its 480-km perimeter; these include beaches, wave-cut slopes and benches, tufa, and numerous embankment features. The general configuration of the shoreline and the distribution and character of shoreline features suggest greater wave activity on the eastern shoreline than on the western shoreline. The late Holocene stand of the lake was probably maintained within the narrow limits of the 12-meter contour. A hydrologic budget of the lake shows that only half of the Colorado River was necessary to maintain this freshwater lake, with excess discharge overflowing the delta. The 12-meter altitude represents the minimum threshold-overflow altitude of the delta. There were four lacustral intervals to the 12-meter contour during the last 2,000 years. The late Holocene shoreline has been disturbed by a combination of tectonics and subsidence to the south. The western shoreline varies 11 meters in altitude, while the eastern shoreline varies 8 meters in altitude. Part of this difference can also be attributed to differences in wave intensities in different parts of the lake.

Lowland Patayan occupation was intensive along the late Holocene shoreline, with many artifacts and features associated with the beach. No artifacts are temporally associated with the higher late Pleistocene stands, and a post-26,000 B.P. date is suggested for the Malpais and San Dieguito I complexes.
APPENDIX

PARTICLE-SIZE ANALYSIS

Particle-size analyses were made on beach deposits of Lake Ca-
huilla to examine the size distribution of beach sediments. These
analyses helped to quantify differences between the eastern and western
shorelines and to infer possible sediment transport directions.

Individual sedimentation units, as defined by Otto (1938) were
sampled and mechanically sieved according to the method of Folk (1974).
Statistical parameters were calculated by the method given by Folk. The
results, given in Table A-1, are summarized in the text and on figure 10.
Table A-1. Particle-size analysis

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<th>$q_1^b$</th>
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<td>+0.70</td>
<td>0.00</td>
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</tr>
<tr>
<td>-1.67</td>
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<td>-0.54</td>
<td>0.78</td>
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</tr>
<tr>
<td>+0.67</td>
<td>0.97</td>
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<tr>
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<tr>
<td>+0.97</td>
<td>0.44</td>
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<tr>
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<tr>
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<tr>
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<td>0.50</td>
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<tr>
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<tr>
<td>-0.71</td>
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<tr>
<td>Sample Location</td>
<td>M_z^a</td>
<td>σ_I^b</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>12-meter Shoreline</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western, beach formed on fan</td>
<td>-0.65</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>+0.40</td>
<td>0.74</td>
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<tr>
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<td>-1.70</td>
<td>0.93</td>
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<tr>
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<td>0.99</td>
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<td>0.56</td>
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<td><strong>52-meter Shoreline</strong></td>
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</tr>
<tr>
<td></td>
<td>+1.00</td>
<td>0.95</td>
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<tr>
<td><strong>46-meter Shoreline</strong></td>
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<td>+1.00</td>
<td>0.62</td>
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<td><strong>40-meter Shoreline</strong></td>
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<td><strong>38-meter Shoreline</strong></td>
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<tr>
<td><strong>31-meter Shoreline</strong></td>
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<td>-0.47</td>
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<td>-1.74</td>
<td>1.12</td>
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a. M_z is the Graphic Mean of Folk (1974, p. 45) where 
M_z = (ϕ16 + ϕ50 + ϕ84)/3. The size is expressed in the ϕ scale.

b. σ_I is the Inclusive Graphic Standard Deviation of Folk (1974, 
p. 46) where σ_I = ((ϕ84 - ϕ16)/4) + ((ϕ95 - ϕ5)/6.6).
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Bowersox, R. J., 1972, Molluscan paleontology and paleoecology of Holocene Lake Cahuilla, California. Paper read at the 1973 Meeting of the Southern California Academy of Sciences, Long Beach, California.


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