Mono Lake:
The Past 4,000 Years

By

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. . . a single closed [lake] basin that never overflowed, was not an important contributor to a ground water basin, and never completely dried . . . would furnish the best regional climatic index for detailed analysis of past environments and their possible influence on Man.

-- Peter Mehringer, 1977

MONO LAKE:
THE PAST 4,000 YEARS

INTRODUCTION

Terminal Lakes as Paleoclimatic Indicators

Scientists have long recognized the paleoclimatic significance of closed (or "terminal") lakes (Halley, 1715; Jamieson, 1863; Whitney, 1865). Because they lack an outlet, these water bodies fluctuate in size in response to changes in inflow (including stream and groundwater inflow and precipitation on the lake surface) and outflow (evaporation from the lake surface). Terminal lakes expand when the amount of inflow exceeds evaporative loss, and shrink when the relationship is reversed. Insofar as lake inflow and outflow are directly controlled by climate, a graph describing secular fluctuations in lake size may provide a valuable measure of the timing and magnitude of regional climatic change.

During the past quarter-century earth scientists have constructed lake level curves spanning part or all of Holocene time for a number of terminal water bodies in the North American Great Basin, including Pyramid, Carson, and Walker lakes in Nevada (Born, 1972; Morrison, 1965; Benson,

1978; Davis, 1982); Searles Lake (Smith, 1979), China Lake (Smith and Davis, 1978), Little Lake (Mehringer, 1978), Mojave Lake (Ore and Warren, 1971) and "Death Valley Lake" (Hunt and Mabey, 1966) in California; and Great Salt Lake in Utah (Morrison, op cit; Currey, 1980; Currey, et al, 1983). These records are among the best known and most often cited indicators of Holocene climatic change in the western United States (Mehringer, 1977; Currey and James, 1982; Davis, op cit; Weide, 1982).[1]

Most of the lakes cited above, however, are characterized by hydrographic peculiarities that limit their usefulness, or in some cases render them wholly unsuitable, as indicators of climatic change. Some of the lakes (e.g. Pyramid and Great Salt lakes) overflowed (that is, they became "open lakes") one or more times during the Holocene. While these bodies of water show that the regional climate was sufficiently "hydric" (cool and/or moist) to cause spillage, they fail to provide a measure of how hydric the conditions ultimately became during the period of overflow. Some lakes (Searles, Carson, Walker, China, Mojave, Little, and Great Salt) were estinguished one or more times during the Holocene. These lakes leave unresolved the questions of ultimate xericity and climatic variability during the periods of desiccation.

Due to hydrographic and physiographic complexities within their dranage basins, most of the terminal lakes mentioned above respond to a climatic change in a manner grossly disproportionate to that change, thereby confounding quantitative paleoclimatic analysis. This occurs wherever a terminal lake occupies a large, hydrographically complex basin in which extensive groundwater reservoirs, extensive tracts of vegetation, and large up-basin lakes act either to amplify or absorb a change in climate. Consider, for example, Pyramid and Winnemucca lakes, which receive approximately 40% of their combined inflow from Lake Tahoe by way of the Truckee River. A drop in lake Tahoe to below its lip requires only that effective precipitation decrease about 25% below the mean historic value (Davis, et al, 1976). By isolating the Tahoe Basin from the Pyramid/Winnemucca Basin, however, a 25% drop in effective precipitation results in a decrease in inflow to Pyramid and Winnemucca lakes of approximately 55%.

Most importantly, some of the terminal lakes of the Great Basin have fluctuated substantially for non-climatic reasons. It appears, for instance, that several times during the Holocene the combined flow of the East and West Walker rivers shifted course, flowing alternately into Walker Lake and the Carson Sink (King, 1981). Changes in stream course during Holocene time also dictated the amount of Truckee

River water that flowed into Winnemucca Slough, rather than into Pyramid Lake (Harding, 1965).[2] Clearly, until that time when it is possible to distinguish climatically-induced fluctuations in lake level from those brought about by the migration of drainage lines, Carson, Walker, Pyramid, and Winnemucca lakes will be of dubious value as quantitative paleoclimatic indicators.

The Paleoclimatologic Potential of Mono Lake

Mono Lake in east central California (Figures 1a and 1b, Photo 1) occupies a small, hydrographically simple basin (the Mono Basin) that neither absorbs nor amplifies to any significant degree the effect of a climatic change upon lake level; the lake thus exhibits a relatively "true" response to a change in climate. The basin is hydrographically stable--that is, its streams have not undergone inter-basin shifts during Holocene time; for this reason the lake has, with minor exceptions, fluctuated exclusively in response to climatic factors.[3] Moreover, Mono Lake is a permanent terminal lake--in other words, it has neither desiccated nor overflowed during Holocene time; it can thus be expected to have recorded all secular changes in Holocene climate, regardless of magnitude or sign. In short, from the standpoint of the standpoint of basin hydrography and

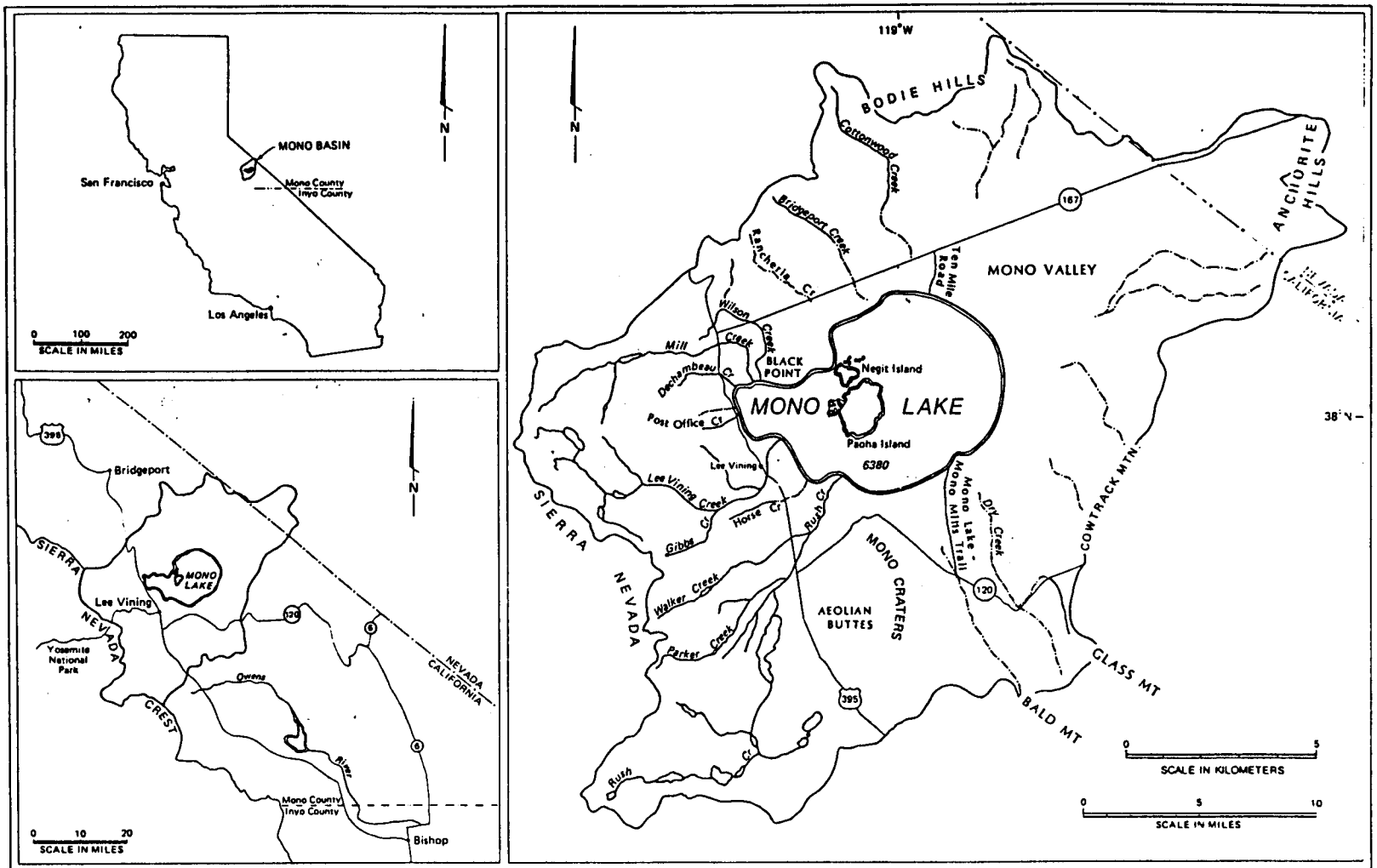


Figure 1a. Index map of the Mono Basin.

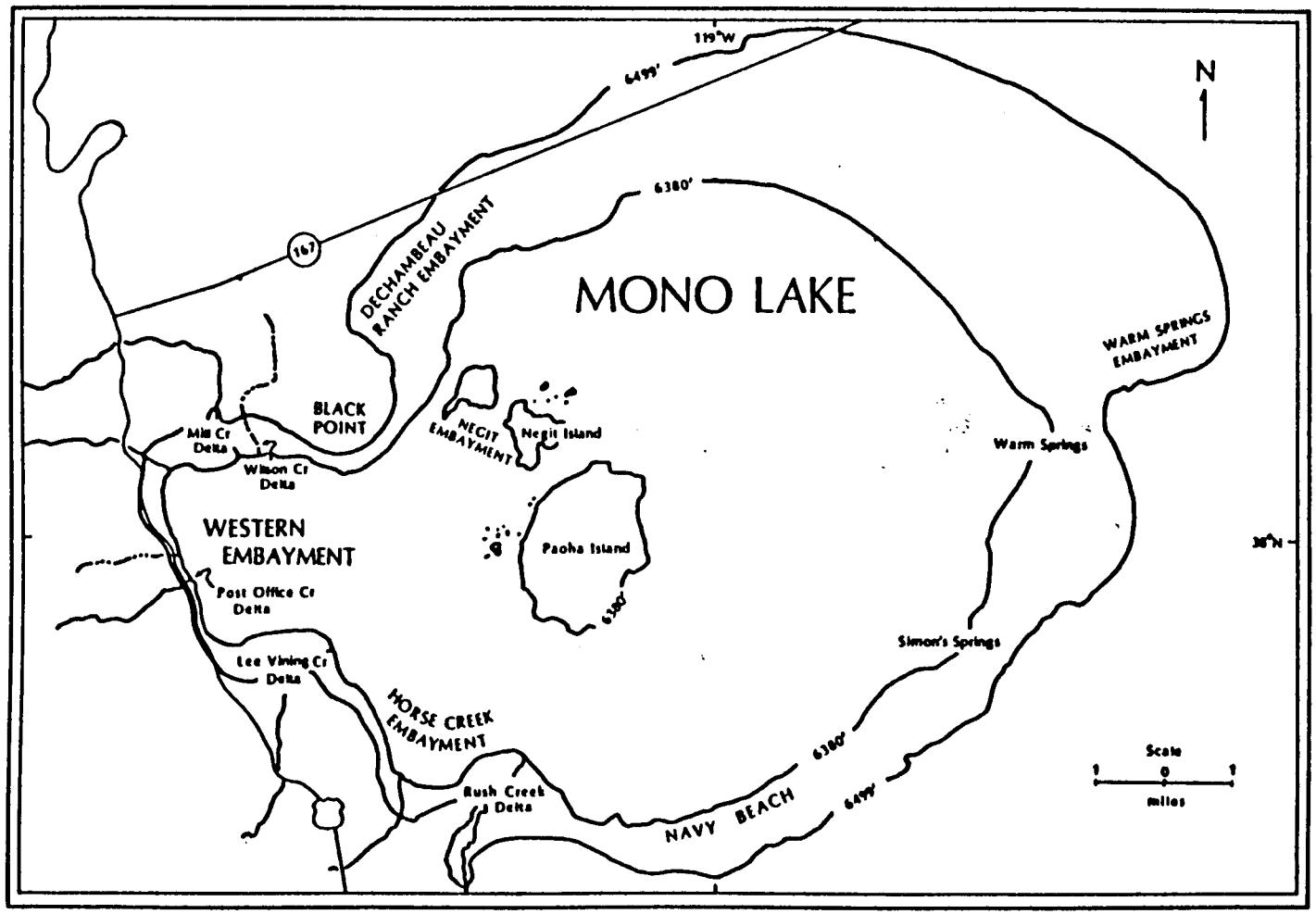


Figure 1b. Index map of the Mono Basin.

physiography, Mono is a potentially ideal terminal lake for deriving a quantitative index of Holocene climatic change.

The paleoclimatic potential of a terminal lake must be measured not only in terms of the lake's permanence, its hydrographic stability, and the "trueness" of its response to a climatic change, but also in its ability to yield an accurate record of the timing and magnitude of secular fluctuations in surface elevation. Here again Mono is distinctive among Great Basin terminal lakes. A wide variety of different types of evidence--botanic, geomorphic, sedimentologic, historic, radiometric, dendrochronologic, tephrochronologic, and tephrostratigraphic--can be used to adduce changes in Mono Lake's level.[4] Rarely can so many different types of evidence be brought to bear at a single terminal lake. This abundance of evidence makes it possible to produce a detailed, high resolution lake level curve that spans the past 4,000 years.

Scope of Work

This dissertation focuses on the surface fluctuations of Mono Lake that occurred during the past four millennia, a period referred to throughout the work as the "late Holocene". Chapter One attempts to clarify certain widely held misconceptions concerning the behavior of the lake during historic time, and provides a detailed fluctuation

curve spanning the past 13 decades. Chapter Two describes the various types of evidence that can be used to construct a lake level curve for the pre-historic period. The pre-historic fluctuation curve is constructed in Chapter 3, and is checked against the sedimentary record in Chapter 4. The history of the Mono Islands, and the degree to which late Holocene island building has modified the morphometry of the lake basin is the subject of Chapter 5, while Chapter 6 examines the paleoclimatic implications of the lake fluctuation curve. The record of climatic change derived from the lake curve is compared to that derived from other paleoclimatic indicators in Chapter 7, and Chapter 8 discusses the possible role of deVries-type solar variations in instigating the late Holocene fluctuations of Mono Lake.

Period of Study

Field work for this thesis was undertaken during the years 1980-1986. The importance of this period cannot be overstated. Indeed, the study could not have been carried out had it not been for the highly unusual and seemingly contradictory set of hydroclimatic circumstances that prevailed during those years: due to diversion of its tributary streams by the City of Los Angeles, Mono Lake stood at an exceptionally low elevation throughout most of this time (and in fact reached its Historic Low Stand of 6372.00

feet midway through the study period), a factor that permitted access to evidence that would have gone unseen and unappreciated had the lake been significantly higher. At the same time, discharge of the tributary streams was exceptionally high in five of the years. These high flows, in combination with the low-standing lake, caused the streams to incise their deltas, exposing sequences of riverine, littoral, lacustrine, aeolian, and volcanic sediments in the walls of the fresh stream cuts. These sedimentary sequences form the basis for the analysis of late Holocene fluctuations in lake level.

The first field season (summer, 1980) was spent in reconnoitering the Mono Basin, exploring the feasibility of developing a lake level curve, and examining the different types of evidence that might be used to construct such a curve. It was during this first season--a period of high stream flow--that the potential utility of the geomorphology and stratigraphy of the deltas became apparent.

During the 1981 field season little water flowed down the major streams to the lake. As a result, overburden accumulated against the walls of the stream channels, obscuring the sequences of sediments that proved to be of overriding importance to the study. Work during this field season thus focused on the late Holocene shorelands--the lands occupied by the margin of Mono Lake during the past

4,000 years.

The heavy precipitation of 1982 forced substantial releases of water down the major tributary streams. High flows freshened the exposures of deltaic sediments in the channel walls and permitted the cross sections drawn in 1980 to be checked and refined. By the end of the 1982 field season a generalized lake fluctuation curve had been produced.

The writer returned to the Mono Basin for final field-checking in late June of 1983. During the previous weeks stream flows far higher than those of 1980 and '82 had grossly altered the configuration of both Lee Vining and Mill Creeks, exposing sequences of lake-transgressive and lake-regressive sediments along perhaps a thousand meters of channel wall. It quickly became apparent that these new exposures could be used to improve the accuracy and detail of the lake level curve constructed between 1980 and 1982. The entire field season was thus spent in refining and correcting the fluctuation curve. Further refinement of the curve and study of the age and origin of the Mono islands were the foci of the 1984 field season. That year's field work culminated on October 13, when the writer had the honor of leading 280 professional earth scientists through the study area on the annual Friends of the Pleistocene field trip (Stine, 1984). Minor field checks were conducted during the summer of 1985,

and in late spring and summer of 1986.

Cartographic and Photographic Resources

A variety of maps and aerial photographs were used in the course of the study. Some of these--for instance, the USGS 15-minute topographic series--are well known and readily available. Others are more obscure. For convenience, these maps and aerial photos are listed in Table 1 below. Included are large-scale maps and photos to which reference is made in the text. Note that the "date" given for each of the topographic maps is the year of the aerial or ground survey on which the map is based, rather than the year that the map was issued.

Elevation Control

Elevations of hundreds of points on the Mono shorelands were measured using engineer's level and rod. Occasionally a USGS benchmark was used as elevation datum; more commonly, the surveys were started at the lake margin, where a precise elevation could be derived based on the lake level readings of the Los Angeles Department of Water and Power. For most purposes, elevations were considered sufficiently accurate if the survey closed within two feet. If a particular shoreline feature was critical to establishing the elevation of a lake high stand or low stand, the highest tolerable survey closure

Table 1

Photographic and Cartographic Resources

PHOTOGRAPHS

Source	Date	Stated scale	Calculated scale
Fairchild Aviation, LA	1929-30	1:12,000	1:17,360
United States Forest Service	1940	1:20,000	1:24,000
• United States Geological Survey	1956	1:24,000	--------
United States Geological Survey	1964	1:20,000	1:18,800
• United States Geological Survey	1972	--------	--------
United States Geological Survey	1973	1:64,000	1:71,000
United States Geological Survey	1975	1:24,000	1:24,000 (ortho-photos)
United States Forest Service	1979	1:30,000 (at nadir--optical bar photos)	1:30,600 (at islands)
United States Forest Service	1982	1:17,500	1:17,360
United States Forest Service	1986	1:12,000	1:13,287

TOPOGRAPHIC MAPS

United States Geological Survey		
Mono Craters Quadrangle	1953	1:62,500
Trench Canyon Quadrangle	1962	1:62,500
Cowtrack Mountain Quadrangle	1953	1:62,500
Bodie Hills Quadrangle	1958	1:62,500
United States Geological Survey		
Mono Craters NE Quadrangle	1986	1:24,000
Trench Canyon NW Quadrangle	1986	1:24,000
Cowtrack Mountain SW Quadrangle	1986	1:24,000
Bodie Hills SE Quadrangle	1986	1:24,000
Pacific Aerial Western Survey		
Mono Lake, 6430 - 6373 ft	1984	1:4,000

BATHYMETRIC CHARTS

Scholl and others	1962	1:62,500
Pelagos, Corp.	1986	various scales

error was one foot.

Choice of the Imperial System of Measurement

Virtually all of the hydrologic, topographic, and geologic work that has been conducted on Mono Lake to date has employed the Imperial system of measurement. Since fluctuations in lake level began to be monitered, elevation readings have been taken in feet; the cadastral survey system, which provides the means for assessing the fluctuations of the lake in early historic time, is based on units of acres and miles; all available topographic maps of the region (including the new 1:24,000-scale USGS topographic maps), and the two available bathymetric charts of the lake, show contours in feet rather than meters; all weather data, including wind (measured in miles per hour) and precipitation (measured in inches) are recorded in Imperial units; so too are streamflow (recorded in cubic feet per second) and lake inflow (recorded in acre-feet). Dependent as this study is on the cadastral survey system, streamflow and inflow records, weather data, and topographic and bathymetric maps, it was decided to maintain the convention of using Imperial units in discussions of hydroclimatic and lake-level data; the metric system will be used to express all other measurements.

Environmental Setting

Physiography. Mono Lake, at 38° north latitude, 119° west longitude, occupies the bottom of a roughly triangular, 1800 km^2 northeast-trending structural depression at the base of Sierra Nevada due east of Yosemite National Park (Figure 2, Photo 1). This elongate depression, variously called Mono Valley and the Mono Basin, is rimmed by the Bodie Hills on the north, by the Anchorite Hills and Cowtrack Mountain on the northeast and east, by the Glass Mountain-Bald Mountain ridge on the south, and by the bold escarpment of the Sierra Nevada on the southwest and west. The elevation of the lake surface (presently ~6,380 feet) is in marked contrast to that of the surrounding highlands, where summit elevations range from 8,800 feet in the Anchorite Hills to over 13,000 feet along the Sierran crest.

The Mono Sierra is made up of Paleozoic and Mesozoic meta-sediments and Mesozoic plutons, while the lower ranges on the north, east, and south are composed mainly of Late Tertiary and Quaternary volcanic rocks. Alluvial, lacustrine, and pyroclastic sediments of late Cenozoic age fill the Mono Basin to a depth of many thousands of feet (Pakiser, 1968, 1976; Christensen, et al, 1969),[5] forming an extensive (~650 km^2), gently sloping (<1° to 5°) central-basin area. Except for minor erosional and tectonic

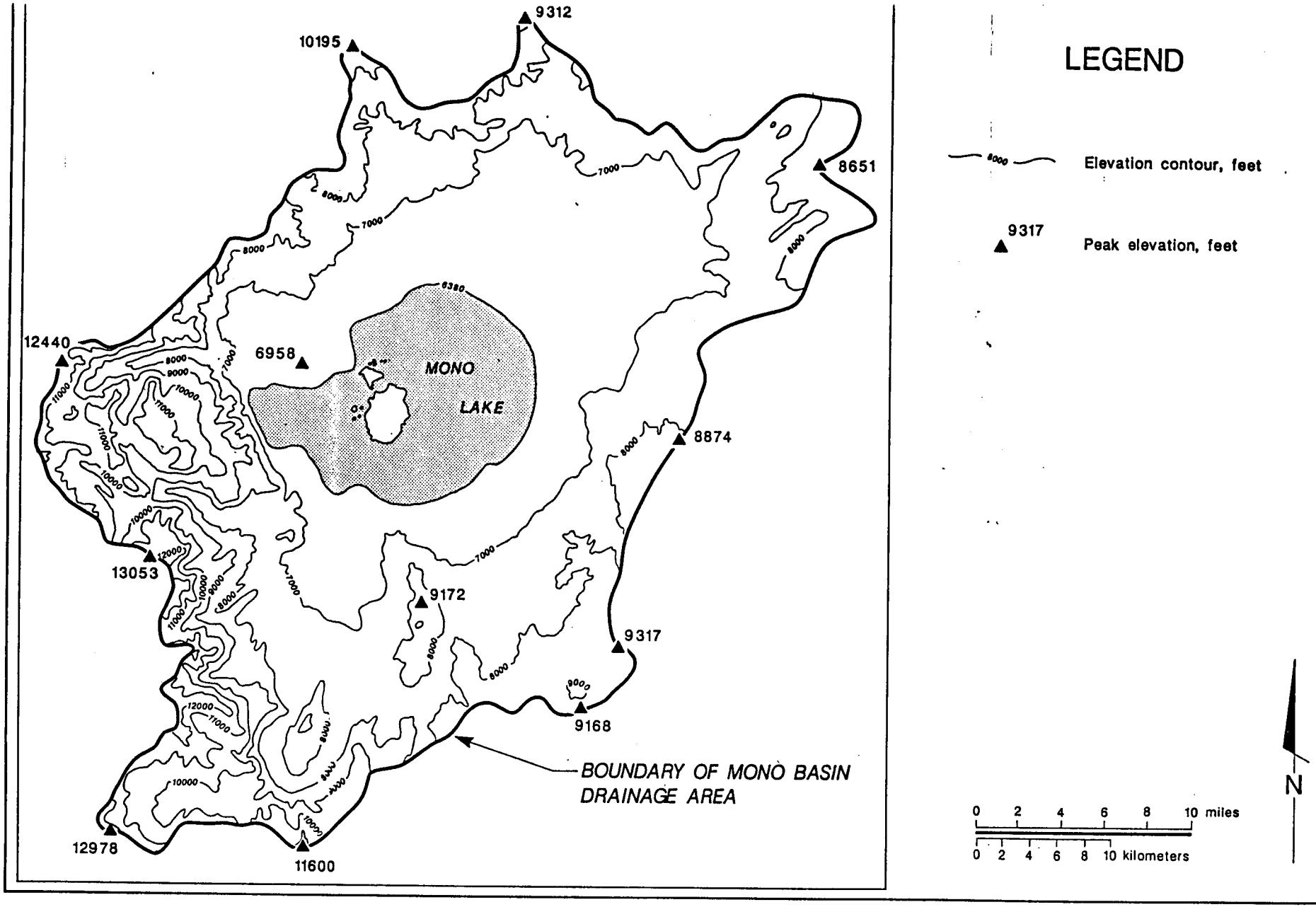


Figure 2. Topography of the Mono Basi

scarps at scattered locations on the valley fill, this central-basin area is characterized by substantial relief in only three places: around Black Point--a basaltic cinder cone of latest Pleistocene age in the basin's northwest quadrant (Christensen and Gilbert, 1964; Lajoie, 1968; Custer, 1973); around the Mono Craters--an arcuate chain of rhyolitic coulees, plug domes, and explosion pits of latest Quaternary age in the southwestern portion of the basin (Putnam, 1938; Wood, 1977; Sieh and Bursick, in press); and in the Aeolian Buttes--an outcrop of Bishop Tuff in the southern Mono Basin (Gilbert, 1938). Gradients on the valley fill increase gradually toward the highlands, reaching values of approximately 10° on the piedmont slope; where the piedmont gives way to the bedrock of the mountains, gradients typically mount abruptly to values sometimes exceeding 45°.

Climate. With the exception of the highlands to the west of the lake, which experience a microthermal climate with annual precipitation averaging as high as 50 inches, the Mono Basin is characterized by a cold steppe climate (Koppen's BSk). Because the basin floor lies within the rainshadow of the Sierra Nevada, precipitation is generally low. Average annual totals range from 14.5 inches at the "Mono Lake Station" on the lake's western margin, to approximately 5.5 inches at the Los Angeles Department of Water and Power (DWP) station northeast of the lake. Both

topography and distance from the Sierran crest exert a strong influence on the local distribution of precipitation, as illustrated on the isohyetal map constructed by Vorster (1985). Most precipitation falls as frontal snow during the winter half of the year, though convective rainstorms typically bring brief but intense downpours several times each spring and summer. Annual variability of precipitation is marked; at the Mono Lake station (elevation 6450 feet), with 37 years of record, it ranges from as high as 165% to as low as 49% of normal.

The temperature regime in the Mono Basin is continental, with mean daily summertime temperatures on the basin floor ranging from an average of 60°F at stations some distance from the lake, to 65°F near the lake shore, and mean daily wintertime temperatures dropping to below freezing at all stations. Diurnal temperature range is considerable in summer (typically between 40°F and 50°F), and somewhat less in winter (20°F to 30°F). Temperatures in excess of 90°F can be expected at stations on the basin floor for short periods virtually every summer, while temperatures below -10°F are encountered at these same stations for a few days nearly every winter. Throughout the year temperatures generally decrease with elevation (lapse rate = 3.2°F/1000 feet--Lee, 1969), so that sites at lower elevations are typically warmer than those in the surrounding mountains. During the winter

months, however, a shallow inversion settles on the basin floor, instigating a dense radiation fog locally called the "poconip".

Records from climate stations (Vorster, 1985), as well as geomorphological evidence (Mason, 1967) indicate the prevalence of southwesterly winds at most localities in the Mono Basin; the wind can, however, blow from all quadrants throughout the year. Monthly cumulative wind totals are typically highest in March and April; hourly totals are often high on summer afternoons (Mono Basin's "one o'clock wind"), when warming of the basin floor instigates surface winds through convection.

Vegetation. From the margin of Mono Lake to the crest of the Sierra Nevada, the Mono Basin spans five of Merriam's life zones--the Upper Sonoran, Transition, Canadian, Hudsonian, and Arctic-Alpine. As a result of the wide range of temperature and precipitation conditions in the basin, the flora is highly diverse, containing upwards of a thousand taxa (Taylor, 1981). Vegetation associated with the Upper Sonoran Zone is the most extensive areally as well as one of the simplest floristically. It is also of greatest interest to the present study since it covers most of the late Holocene shorelands and has been affected by fluctuations in lake level in such a way as to be a useful indicator of former shoreline position (see Chapter 2, section D). This

zone comprises the Pinyon-Juniper Woodland and the Sagebrush Scrub communities of Reveal (1965), whose list of indicator plants includes the following woody species:

Artemisia tridentata	Chrysothamnus nauseosus
Cercocarpus ledifolius	Ephedra viridis
Pinus monophylla	Juniperus osteosperma
Prunus andersonii	Salsola kali
Grayia spinosa	Purshia tridentata
Atriplex confertifolia	

These and other xeric species (most notably Sarcobatus vermiculatus) dominate the vegetation of the central basin area. Only at spring and stream sites, where a continuous supply of fresh water supports a dense stand of riparian vegetation, and on alkaline flats in the immediate vicinity of the lake, where Distichlis spicata forms the dominant cover, does the vegetation of the basin floor depart from an open patchwork of shrubs and low trees with intervening clumps of bunchgrass (most commonly Elymus cinereus and Oryzopsis hymenoides).

Mono Lake. According to Lajoie (personal communication, 1981) the log of a well drilled on Paoha Island in 1909 suggests that a lake has occupied the Mono Basin continuously since at least mid-Pleistocene time. Throughout this period the elevation of the lake surface has fluctuated widely in response to changes in climate. "Pluvial" hydroclimatic conditions as recently as 35,000-12,000 years BP (Lajoie et

al, 1983) forced the surface of Lake Russell--Mono's Pleistocene predecessor (Putnam, 1950)--to an elevation as much as 800 feet above that of the present day. Based on the altitudinal distribution of deltaic gravels and lacustrine silts of his Wilson Creek Formation, Lajoie (1968; Lajoie et al, 1983) constructed a fluctuation curve for this greatly expanded water body that includes high stands (at elevations ranging from 7000 to 7180 feet) between 36 ka - 34 ka, 28 ka - 24 ka, and 14 ka - 12 ka, with intermediate lake levels (6560 to 6800 feet) prevailing between 34 ka - 28 ka, and 24 ka - 14 ka. The onset of relatively xeric climatic conditions in very latest Pleistocene time forced a decline in lake level to elevations approximating those of the historic period. Lake fluctuations throughout the Holocene have been substantial, though of far lesser magnitude than during Wilson Creek time.

Over time, evaporation from the lake has concentrated soluble compounds into a dense, sodium carbonate-bicarbonate sodium chloride brine with high concentrations of sulfate, borate, and phosphate. In 1981, when the lake attained its lowest historic surface elevation and volume, salinity reached 91 parts per thousand, and pH approached 10 (Melack, 1983). Presently only calcium and magnesian carbonate precipitates from the lake waters, forming towers, domes, crusts, and pavements of tufa (low magnesian calcite,

aragonite, and high magnesian calcite--see Chapter 2, Section G).

The bitter waters of the lake support a simple but highly productive biota that includes bacteria, diatoms, green and blue-green algae, several protozoans, and a few zooplankton. Prominent among this latter group is a species of the brine shrimp Artemia. Melack (1983) quotes Clark and Bowen (1976) and Bowen et al (1978) to the effect that the Artemia of Mono Lake is probably distinct at the species level. The Artemia constitutes a major source of food for the hundreds of thousands of migratory waterfowl that annually flock to the lake to breed or fatten.

During the past 2,000 years volcanism on the floor of Mono Lake has given rise to rhyolitic-to-dacitic spires, domes, flows, and cones, and to up-arched blocks of lake-bottom sediments. Many of these volcanic features have protruded above the lake surface as islands during at least part of their existence. The islands of Mono Lake are conveniently divided into two groups on the basis of their distribution and composition. In the northwestern quadrant of the lake is the Negit Archipelago (Figure 1--see also Figure 19). The largest individual in this chain is Negit Island, a composite of two cratered-domes, a lava-filled cinder-breccia cone, and at least seven blocky lava flows.

Also included in the Negit group is a roughly-linear cluster of small spires and domes that stretches east and west from the northern tip of Negit Island. Historically, the Negit Archipelago has been an important rooking ground for the California Gull (Larus californicus).

South of the Negit Archipelago, near the center of the lake, lies Paoha Island, a large block of ancient lake-bottom sediment that was uplifted to its present position by the shallow intrusion of magma in immediately-pre-historic time. During the upheaval huge slabs of saturated lake sediment detached from the main island mass and slid westward, coming to rest in many tens of feet of water. Today, a portion of this chaotic jumble of slide debris protrudes above the lake surface as a constellation of small islets.

Scholl and his co-workers (1967) constructed a bathymetric chart of the lake in 1964.[6] The authors point out a prominent topographic linearity that trends southwest to northeast along the northwestern side of the lake, and relate the chaotic topography near the lake's center to disturbance associated with the emergence of Paoha Island. They draw attention to a sublacustrine terrace that encircles the lake at an elevation of approximately 6368 feet, and attribute it to a decline of the lake surface to near that level in pre-historic times. The deep of the lake is located along the eastern margin of Paoha Island, and presently lies

under approximately 156 feet of water. According to the hypsographic and volumetric curves derived from the bathymetry, today's mean area-depth is approximately 60 feet, while the mean volume-depth is around 52 feet. Present-day lake volume is approximately 2.4 million acre feet according to the stage/area/capacity curve derived by Vorster (1985) from the Scholl bathymetry. That curve is reproduced here as Appendix A.

Pelagos Corporation of San Diego produced a high resolution bathymetry of Mono Lake in 1986. In overall morphometric terms it differs little from the chart produced by Scholl. The high resolution of the Pelagos bathymetry, however, permits a detailed assessment of the topographic intricacies of the lake bottom (including the distribution of lineations, slumps, volcanic intrusions, boulders, etc.).

Under natural conditions three Sierran rivers--Rush Creek (average annual flow = 61,116 acre feet), Mill Creek (aaf = 22,103 acre feet), and Lee Vining Creek (aaf = 49,033 acre feet), and two small Sierran streams--Post Office Creek (aaf ≈ 400 acre feet) and Dechambeau Creek (aaf = 866 acre feet)--feed Mono Lake year-round (Figure 1). On average these drainages account for approximately 64% of the inflow to the groundwater basin. Several intermittent streams (including Wilson, Bridgeport, Rancheria, and Cottonwood creeks) carry relatively small amounts of water to the lake

from the Bodie Hills. These ephemeral creeks provide an average of roughly 3% of the lake's total inflow. Precipitation on the lake surface (estimated at ~17% of the total inflow) and recharge to the groundwater basin make up the remainder of the inflow (Vorster, 1985).

The lake's sole outflow component is evaporation. Data from test pans in and near the Mono Basin led Vorster (1985) to conclude that evaporation of fresh water from the lake averages 45 inches per year. Correction for lake salinity lowers this figure several inches. Evaporation is highly seasonal, with perhaps 80% of the total occurring during the six-month period from May to October.

Interannual variability in evaporation is slight. Pan data indicates that it has been as low as 5 inches below the mean (89% of normal) and as high as 5.8 inches above the mean (113% of normal). Inflow, on the other hand, varies greatly from year to year. During the period 1935-1985 the annual natural flow[7] of Rush, Mill, and Lee Vining creeks totaled as high as 288,000 acre feet, or 192% of normal (water year 1982-83), and as low as 62,000 acre feet, or 41% of normal (water year 1976-77). The major tributary streams exhibit a strong seasonal component in flow regime as well, brought about by the pronounced seasonality of precipitation and snowmelt in the Mono Basin. Typically, streamflow reaches an annual peak in June or early July, and declines to the yearly

minimum in January. This, together with the marked seasonality in evaporation from the lake surface, instigates an annual cycle of lake level fluctuations. Under natural conditions the lake surface usually attains its yearly high-water mark between May and July, then declines during the warm, dry months that follow. This annual cycle operates regardless of any long-term rising or falling trend of the lake surface. The lake thus "ratchets" upwards during relatively hydric periods, and "ratchets" downwards following the onset of relatively xeric climatic conditions, often crossing a single contour several times in the course of a rising or falling trend.

Because of the extreme density of Mono Lake water, the streams merge with the lake as a surface, or "hypopycnal", current.[8] The existence of hypopycnal conditions at Mono Lake is readily apparent near the mouths of the streams, where the stratum of freshwater (the "mixolimnion") can be seen as a lakeward-moving layer carrying mineral and organic detritus. This layer overrides lake water (the "monimolimnion") that often teems with brineshrimp, the movements of which are clearly unaffected by the overlying freshwater current. Indeed, the brineshrimp can normally be seen moving in a direction counter to that of the mixolimnion. This phenomenon was observed up to several hundred meters lakeward of the mouth of Lee Vining Creek

during times of high stream discharge in the spring and summer of 1982 and '83 (Photo 1). Despite the density difference between the stream and lake waters, the lake typically overturns once per year, thermally stratifying shortly after the vernal equinox and remaining inverted until November (Melack, p.224).[9]

In 1940, when the surface of Mono Lake stood at an elevation of 6,417 feet, the Los Angeles Department of Water and Power began to divert the flow of Rush and Lee Vining Creeks southward for municipal use. During the ensuing four decades the lake surface declined 45 vertical feet (to 6,372 feet in December, 1981, and January, 1982) as a result of these stream diversions. The abnormally high runoff of 1982 and '83 exceeded the diversion capacity of the Los Angeles aqueduct system, forcing the release of large amounts of water down the tributary streams, and occasioning a lake rise of nearly nine vertical feet. With the return of more normal runoff conditions in 1984 and '85 DWP resumed diversions, and the lake once again began to fall. Currently (June, 1986) the lake surface is again rising in response to abnormally high inflow, and presently stands at an elevation of around 6380 feet. Vorster (1985) estimates that, had diversions not occurred, the lake today would stand at approximately 6425-6430 feet.

At historic pre-diversion elevations the shoreline of

Mono Lake forms a smooth, sweeping curve along much of its length. The lake margin approximates an ellipse, with the major axis oriented at approximately 52 degrees to the right of the prevailing winds (Mason, 1967). Noteworthy negative deviations from the ideal ellipse are found where the streams have built deltas into the lake, and in the vicinity of Black Point; the only major positive deviation occurs along the southern shore, where a subdued embayment forms the region known as Navy Beach.[10] At lower lake levels, including those of the past two decades, a block of up-arched lacustrine sediments emerges from the lake, producing an island ("Sitnalta" of Lajoie, 1968; "Pancake" of Winkler, 1983); when the lake declines to elevations below 6,376 feet this block effectively connects Negit Island with the mainland, forming another major shoreline irregularity referred to as the "Negit landbridge".

The Negit landbridge is one of many points of contention in an ongoing land-use controversy that pits environmental organizations against the Los Angeles Department of Water and Power over the question of the artificial lowering of Mono Lake. With the emergence of the landbridge in 1977, coyotes made their way onto Negit Island, disrupting tens of thousands of nesting gulls and forcing a near-complete breeding failure by 1979. While the gulls have subsequently nested successfully on many of the lake's islets,

environmentalists argue that Negit Island may be essential to the long-term viability of the Mono gull colony. They warn that further decline in lake level and volume will concentrate the lake's dissolved solids, leading to conditions unsuitable to the continued existence of Artemia; this, they contend, would adversly affect the gulls, as well as several other species of birds that depend on the lake as a breeding or feeding site. The City of Los Angeles, which derives approximately 15% of its municipal water supply from the Mono Basin, and generates considerable hydroelectricity with Mono water, on the other hand, points to potential loss of water and power revenues. The agency questions the degree to which the Mono Basin environment will be impacted by future diversions, and advocates a "wait and see" policy. The controversy is currently awaiting resolution in the state and federal courts.

FOOTNOTES

[1] The fluctuations of several seemingly "terminal" lakes in northeastern California and southern Oregon have also been investigated (Davis and Pippin, 1979; Phillips and van Denburgh, 1971). J.O. Davis (pers. comm., March, 1986) reports that these water bodies (including Abert, Summer, Eagle and Fort Rock lakes) "leak"--that is, they lose water through subsurface seepage, and are therefore not truly "terminal".

[2] Winnemucca Lake has received large amounts of Truckee River water even in historic times. In 1867, for example, when Clarence King reached the mouth of the stream on his "Exploration of the 40th Parallel", he found that half the Truckee River water entered Pyramid Lake, while the other half flowed into Winnemucca Lake (King, 1878).

[3] On several occasions during late Holocene time eruptions of the Mono Craters in the southern portion of the Mono Basin resulted in the deposition of a considerable thickness of ash on the floor of the lake. The ejecta from each of these eruptions displaced enough lake water to force a rise in lake level of perhaps one foot. A somewhat more significant, though still minor (<6-foot), non-climatically-induced rise in lake level accompanied the emergence of Paoha Island in immediately pre-historic times (see Chapter 5).

[4] While not listed in the American Geological Institute's Glossary of Geology, the term "tephrostratigraphy" is being employed with increasing frequency in reference to the study of the stratigraphic intricacies of a tephra deposit (Davis, 1982; Smith and Street-Perrott, 1983).

[5] There has been considerable disagreement as to the thickness of Cenozoic fill in the Mono Basin. Pakiser (1968) originally proposed a depth-to-bedrock of up to 5.5 ($\pm$ 1-1.5) km near the center of the basin. This figure was considered excessive by Christensen, et al (1969), who estimated the thickness of fill to be on the order of 1-1.5 km. The controversy was the subject of a vigorous debate (see the Journal of Geophysical Research, v. 75 (20), pp.4077-4083

(1970)) that culminated in a reassessment by Pakiser (1976). In that work he presented evidence suggesting that the thickness of the valley fill is 2-2.5 km, a figure lying between the two extremes.

[6] The 20-foot drop in lake level that has occurred since 1964 has revealed only one significant inaccuracy in the bathymetry: the chart incorrectly shows a deep channel lying between Negit Island and the northern shore; thus, it does not predict the existence of a Negit landbridge.

[7] Annual natural flow is defined as the stream flow that would have occurred had there been no regulation by reservoirs in the Mono Basin.

[8] Bates (1953) notes that a stream can "merge" with a lake in three ways: as a bottom, or "hyperpycnal" current (when the stream water is denser than that of the lake); as a homopycnal current (when stream and lake water are of equal density); and as a surface, or "hypopycnal" current (when the stream water is less dense than that of the lake). Mono Lake represents an extreme case of the hypopycnal condition.

[9] The combination of high freshwater inflow and low lake volume that prevailed in 1982 and 1983 created a stratification so extreme that it could not be overcome by summer heating. The lake thus failed to overturn in 1983, '84, and '85 (Ormland, et al, unpub.).

[10] Mason (1967) believed that this embayment, as well as the cliff in the vicinity of Simon's Springs on the lake's southeastern margin, was carved by a return current running southward and southeastward at depth. Both of these features, however, are bounded by faults (see Appendix D), and are clearly structurally controlled.

CHAPTER 1

THE HISTORIC FLUCTUATIONS OF MONO LAKE

INTRODUCTION

It is essential at the outset to establish the fluctuations of Mono Lake that occurred during the years of historic record--the years since 1853 AD. Only in the context of this record is it possible to understand the pre-historic lake level curve, the lines of evidence used to construct that curve, and the nature of the climatic oscillations that controlled the late Holocene fluctuations in the size of Mono Lake.

Since 1912 actual lake level readings have been taken at daily to semi-monthly intervals. When corrected for obvious measurement errors, and for changes in elevation datum, these readings may be used to construct an accurate hydrograph for the period between 1912 and the present.

The surface fluctuations that occurred during the six decades prior to 1912 can be estimated based on historic accounts, cartographic evidence, and climatic records. This would be a simple task were it not for widely accepted misconceptions regarding the elevation of the lake in the

1850s, '60s and '70s. The purpose of this chapter is to correct this misinformation, and to provide an historic fluctuation curve for Mono Lake that can be utilized as a basis for the subsequent discussion of pre-historic changes in lake level.

Much of this information was presented in an earlier paper (Stine, 1981). The arguments and conclusions presented in that publication are further substantiated in the present work by the addition of newly discovered facts.

THE 1857 SURFACE ELEVATION OF MONO LAKE

Introduction

Between 1855 and 1857 Colonel Alexis Waldemer von Schmidt, under contract with the United States Land Office, conducted the first cadastral survey of the Mono Basin.[1] In addition to establishing the township, range, and standard lines over much of the basin, the Baltic-born engineer surveyed or "meandered"[2] almost the entire shoreline of Mono Lake.

Von Schmidt's survey notes and plats do not specify the surface elevation of Mono Lake as it existed at the time of the cadastral expeditions. During the past 50 years several workers have used those notes and plats in attempts to define

the 1857 lake level. These investigations have produced widely disparate conclusions, with the result that significant errors concerning the 1857 lake elevation have become entrenched in the scientific and legal literature. It will be shown here that the surface elevation of Mono Lake in 1857 was 31 vertical feet higher than the long-accepted figure, and that the lake shoreline in that year was as much as 7500 horizontal feet upslope from the position implied in much of the existing literature.

Previous Interpretations

The first attempts to determine the 1857 surface elevation of Mono Lake were undertaken by the City of Los Angeles during the early 1930's, when it moved to aquire water and property rights in the Mono Basin. E.A. Bayley of the Los Angeles Department of Water and Power calculated in 1931 that the lake surface in 1857 stood 6408 feet above sea level (Harding, 1962). The findings of an investigation begun two years later by Henry B. Lynch, then a consulting engineer for the Metropolitan Water District of Southern California, grossly contradict Bayley's conclusions. Most of Lynch's figures suggest that the lake stood at 6389 feet in 1857; one calculation, however, places the lake surface at 6376 feet in that year (Lynch, 1933; Harding, unpub.). In an article published in 1948, Lynch concludes that the lake

stood at 6376 feet in 1857 (Lynch, 1948).

The works of Lynch and Bayley were reviewed by engineer S.T. Harding in an unpublished manuscript of 1962 (Harding, unpub.). While he had concluded years earlier that the 1857 lake level was approximately 6388 feet (Harding, 1942), Harding accepted the lake elevation of 6376 feet postulated by Lynch, and attempted to corroborate that low lake level with relevant historic accounts. Since the publication of Harding's results in 1965 (Harding, 1965), the 6376-foot figure has been quoted often in the geologic, climatologic and legal literature. Bayley's unpublished figure of 6408 feet, on the other hand, has long been forgotten.

During the past four-and-a-half decades a number of other elevations for mid-nineteenth century Mono Lake have appeared in the scientific literature. While these have not been quoted as widely as the conclusions of Lynch and Harding, they have nevertheless added to the general confusion surrounding the record of historic lake fluctuations, and in several cases have reinforced the impression that the lake was exceptionally low during the 1850's, '60s, '70s and '80s. Antevs (1939), for instance, misquoted Harding (1935) to the effect that the lake stood at 6378 feet in 1857. In fact, Harding concluded in his 1935 article that in 1857 the lake stood somewhere between 6386

and 6393 feet. Without citing a reference, Keenan Lee (1969) cited an 1857 lake level of 6378 feet, presumably drawing upon Antevs. Scholl and Taft (1964) quoted I.C. Russell's estimate of 6380 feet for the 1883 lake level, apparently without considering the need to update Russell's figure to a modern elevation datum. Scholl et al (1967) wrote that the lake surface stood "close to 6385 feet" in 1850, but gave neither a source nor an explanation for this figure. Mason (1967) cited an elevation of 1954.8M (=6413.7 feet) for the year 1882 and attributed it to Russell; Russell conducted no leveling surveys in 1882, however, and mentioned no such elevation for that or any other year.

In 1975 the Los Angeles Department of Water and Power, which formerly accepted the 6376-foot figure of Lynch and Harding, published a report that put the 1857 surface elevation of Mono Lake at 6385.9 feet (LADWP, 1975). Under questioning by the writer in 1980 DWP hydrologists were unable to explain how such a figure was derived. The agency later retracted that elevation, and readopted the 6376-foot figure of Lynch and Harding.[3] In late 1981, after receiving a manuscript in which I asserted that the 1857 surface elevation of the Mono Lake was 6407 feet, and after reviewing that manuscript with Kenneth Lajoie of the United States Geological Survey,[4] representatives of DWP testified before

the California State Assembly Committee on Water, Parks and Wildlife that in 1857 Mono Lake stood at an elevation of 6407 feet (Assembly Record, November 16, 1981).

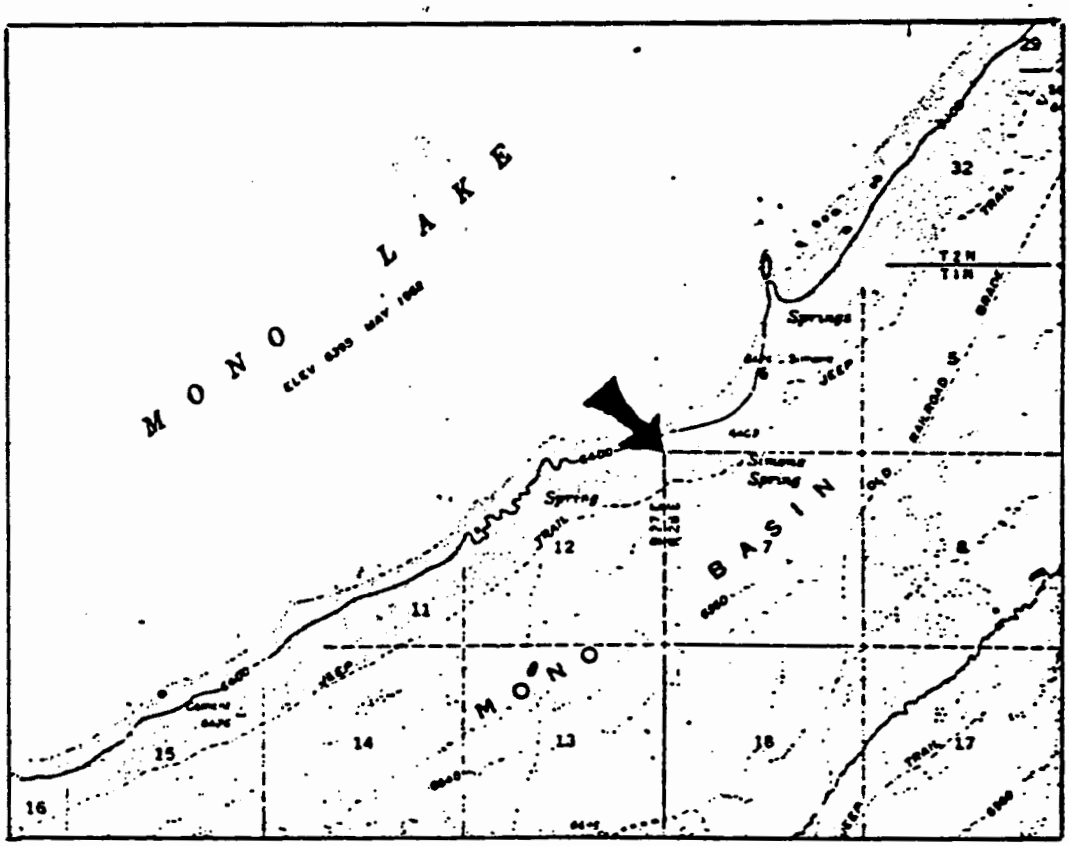
The Measurements of Bayley and Lynch

Bayley's postulated 1857 lake elevation of 6408 feet was derived in 1931 by locating the common corner of Sections 6, 7 and 12 in T1N R27 and 28E on the southeastern shorelands (Figure 3). Von Schmidt's survey notes place this point 1.50 chains (99 feet) south of the 1857 lake margin. Bayley measured 99 feet northward from the corner marker and determined the elevation of the newly found point--and thus of the 1857 lake shoreline--to be 6408 feet (Harding, unpub.).

In his unpublished notes, Harding dismisses the validity of Bayley's 1857 lake elevation for reasons that are unclear. His statement regarding Bayley's finding is vague: "This result does not check with current [date unknown] US Geological Survey map" (Harding, unpub.). In fact, however, this result does correspond precisely with the U.S. Geological Survey Cowtrack Mountain quadrangle (15 min. series) of 1962. This correspondence will be discussed subsequently.

To refute Bayley's conclusion, Harding resorted to an astonishingly imprecise and arbitrary procedure. Assuming

Figure 3.
A portion of the Cowtrack Mountain (1952) Quadrangle. The point at which Bayley derived an 1857 lake elevation of 6408 feet is designated with an arrow.



that von Schmidt had incorrectly located the previously mentioned common corner, Harding (unpub.) projected section lines from the USGS topographic quadrangle of the Mount Whitney region, over 50 miles to the southeast, onto W.D. Johnson's (Russell, 1889) 1883 bathymetric map of Mono Lake. He then located the "corrected" position of the common corner which, according to Johnson's map, would have been under 31 feet of water in 1883. Subtracting 31 from 6410 (the surface elevation of Mono Lake in 1883), Harding arrived at an 1857 surface elevation of 6379 feet, a figure more in keeping with the elevation of 6376 feet determined by Lynch, which he assumed to be correct (Harding, unpub.).

Section lines, of course, cannot be projected from one small-scale map to another with the degree of accuracy assumed by Harding. Johnson's bathymetric map shows only a highly generalized picture of the configuration of the lake bottom, and Harding's claim of 31 feet of water over the common corner clearly involved extrapolation and guesswork. Furthermore, because of the poleward convergence of meridians, section lines are reset at 24-mile intervals, and are not continuous from township to township. For this reason alone cadastral grid systems cannot be projected from a map of one area to that of another further to the northwest. Von Schmidt, an experienced surveyor, made his meander measurements from the cadastral system that he

established in the field, not from one transferred from a small-scale map of a different area 50 miles to the southeast.

In 1933 Lynch located 32 of the section corners placed by von Schmidt. From these points he measured to the 1857 meander line based on the directions and distances recorded in von Schmidt's survey notes. At each of the 32 points he calculated the slope of the land lying above the lake margin, which in 1933 stood at approximately 6418 feet. He then projected that slope as a line out into the lake. This, he believed, allowed him to determine the depth of water overlying von Schmidt's meander points. The average depth calculated in this manner was found to be approximately 29 feet which, when subtracted from the 1933 lake level, suggests an 1857 shoreline elevation of 6389 feet (Harding, unpub.).

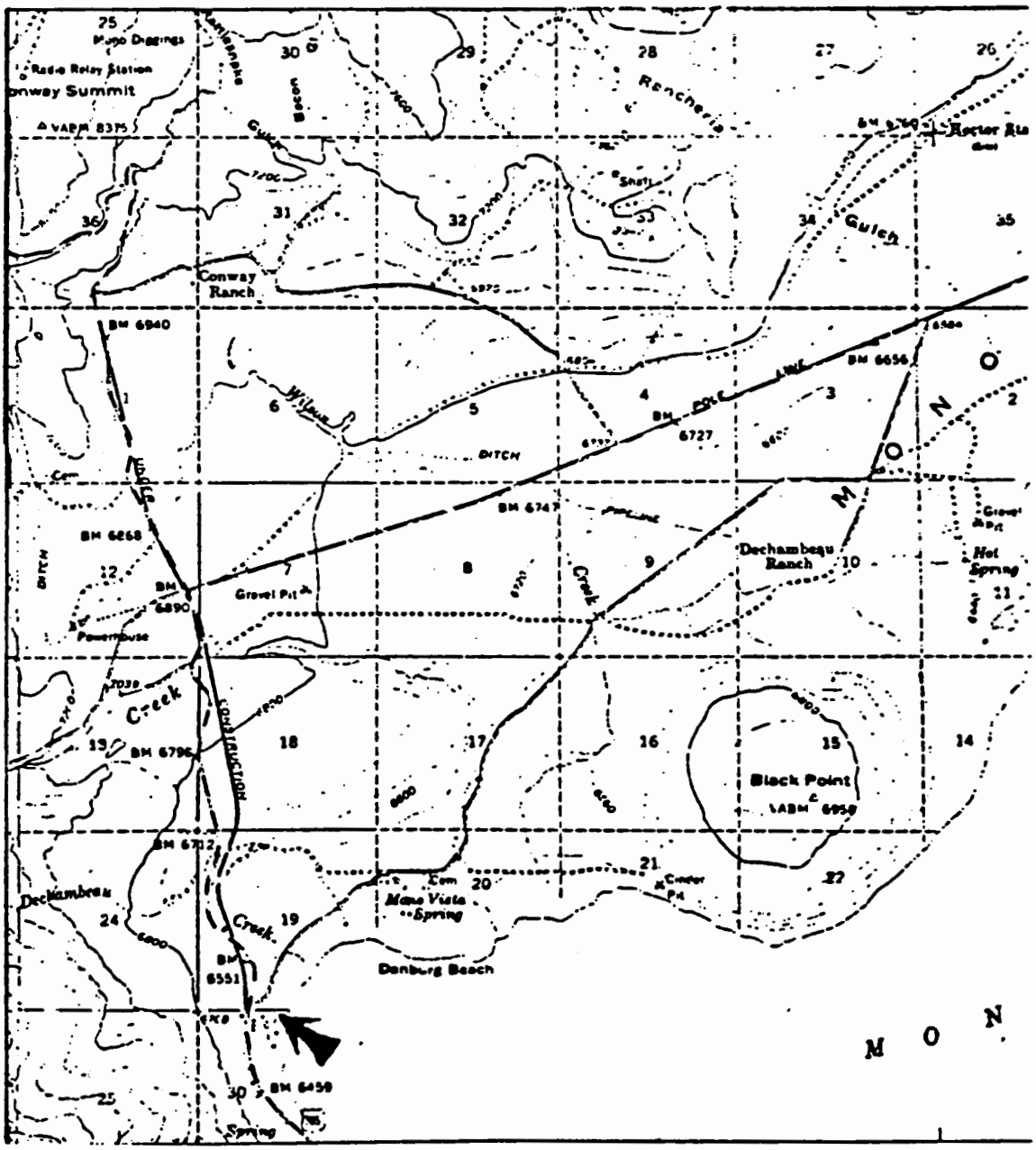
Lynch reported considerable variation in the individual results obtained by this method. Such variation may be due in part to small errors in von Schmidt's measurements. Minor mistakes have been found in the locations of many of his section corners (Harding, unpub.), and there is no reason to think that the measurements he made between section corners and meander points were completely error-free. But more importantly, Lynch assumed that the slope gradients found below lake level were the same as those existing above the

water surface. In virtually all areas of the Mono shorelands, however, there is a significant flattening of slope in the lakeward direction.[5] Lynch failed to take this flattening into account. Had he considered this factor he would have derived significantly higher values for the 1857 lake elevation.

Lynch's most notable measurement--indeed, the one that led to the widely accepted conclusion that the surface of Mono Lake stood at 6376 feet in 1857--was made along the southline of Section 19, T2N R26E, in the northwestern corner of the lake (Figure 4). Lynch noted that in 1857 von Schmidt recorded a distance of 60 chains (3,960 feet) between the southwestern corner of Section 19 and the shoreline directly east of that point. This section line was the southern extent of von Schmidt's survey in the western portion of Mono Lake. Lynch sounded the lake along the extended southline of Section 19 and found 42 feet of water overlying the supposed position of the 1857 meander corner. He then subtracted 42 from the 1933 elevation of the lake (6418 feet) and concluded that in 1857 the lake surface stood at an elevation of 6376 feet (Harding, unpub.).

Although all of Lynch's other calculations resulted in figures considerably higher than 6376 feet, it is that elevation which he accepted as being correct. Harding too,

Figure 4.
A portion of the Bodie (1958) Quadrangle showing the southline of Section 19 (designated with arrow) used by Lynch to derive an 1857 surface elevation of 6376 feet. Note that Dechambeau Creek enters Mono Lake just north of that line.



despite his own calculations suggesting a higher lake level (Harding, 1935; 1942), accepted the 6376-foot figure derived by Lynch along the southline of Section 19, T2N R26E. He reasoned thusly: "This line was the southern limit of sectionizing in 1857. It is probable that von Schmidt would have been more careful in locating and marking corners to which further surveys would be tied than he may have been for interior corners" (Harding, unpub.).

Harding's reasoning might be worthy of consideration if it held true for both end points of the meander survey. But it clearly does not. The other end point, located along the western edge of Section 4, T1N R26E, lies only slightly below an elevation of 6409 feet (see below).

There is sound evidence that the meander line in Section 19, which Lynch relied upon to derive his favored 1857 lake level, is not an accurate depiction of the shoreline as it existed in that year. Figure 5, which illustrates the relative positions of the 1857 meander line, the shoreline of 1958, and the 6376-foot contour in the vicinity of Section 19, T2N R26E, provides a graphic illustration of the inaccuracy. On that figure the 1857 meander line can be seen to lie upslope from the 1958 shoreline and the 6376-foot contour along almost its entire length. Only in Section 19

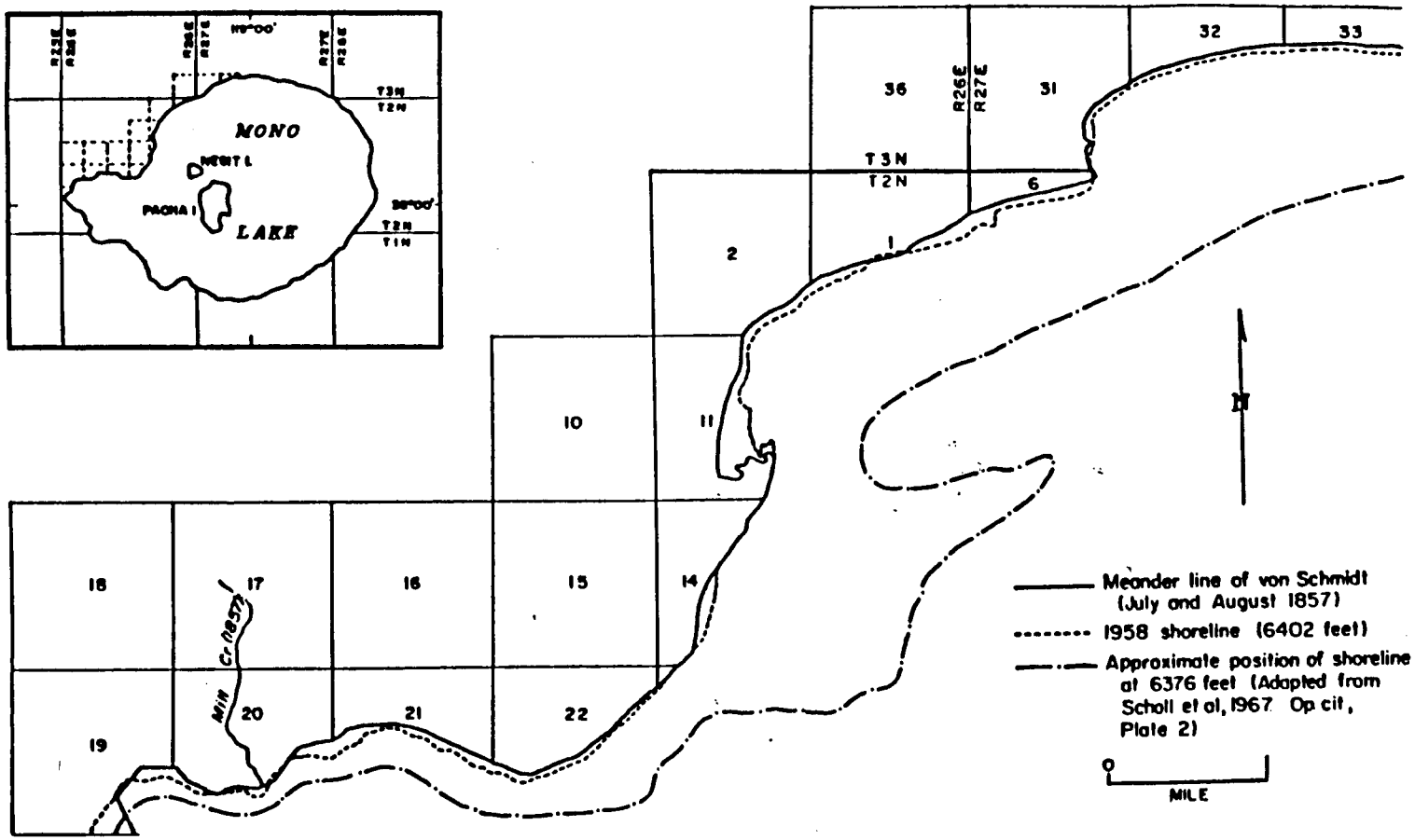


Figure 5. Relative positions of the 6376-foot contour, the 6402-foot contour, and the 1857 meander line, Bodie Hills Quandrangle.

does a gross exception exist. There, the 1857 meander line can be seen to cross both the 1958 shoreline and the 6376-foot contour almost perpendicularly. One possible explanation for this anomaly is that the shorelands in Section 19 underwent considerable geomorphic alteration after 1857. The writer examined the area for evidence of such alteration and found nothing that would suggest physical change on the scale necessary to explain the discrepancy.

The shape of the shoreline mapped by von Schmidt in Section 19 is also telling. Notice on Figure 5 that the distinctly angular configuration of that portion of the meander line is unlike the smooth, curving line that characterizes the rest of the 1857 meander (see also Figures 7, 9, and 10). Indeed, in comparison to the rest of the meander line the angular segment in Section 19 appears contrived. Furthermore, field investigation shows that the meander line mapped by von Schmidt in Section 19 bears no resemblance to any past or present shoreline lying between the elevations of 6372 feet and 6410 feet along that portion of the lakeshore.

One final observation suggests that the meander line in Section 19 is contrived. While surveying the lake, von Schmidt consistently recorded the precise position at which the meander line crossed the mouths of the tributary streams and springs (e.g. at the mouths of present-day Lee Vining,

Rush, Mill, Wilson and Bridgeport creeks). Yet his notes contain no mention of having crossed Dechambeau Creek (Figure 4) during his meander of Section 19 (see Figure 5). Had von Schmidt actually meandered the shoreline in Section 19 it seems likely that he would have mentioned crossing that stream mouth, and would have stated its exact position in his notes.

The atypical angularity of the meander line in Section 19; the dissimilarity between that line and any actual past or present shoreline in the area; the anomolous relationship between that portion of the meander line and the other two lines mapped on Figure 5; and his failure to mention the mouth of Dechambeau Creek in his survey notes, lead to the conclusion that von Schmidt either seriously erred in his survey within Section 19 or, more likely, that he "dubbed in" a shoreline in that section. In either case, it seems clear that calculation of the 1857 surface elevation of Mono Lake should not be based on measurements made within Section 19.

Climatic Implausibility Of An 1857 Surface Elevation Of 6376 Feet

Before attempting to demonstrate the actual 1857 shoreline elevation of Mono Lake it is instructive to consider the severity of the climatic conditions that would be required to force a drop in lake level to 6376 feet. It

is assumed in this discussion that significant fluctuations in lake level during late pre-historic and early historic times were caused primarily by changes in the rate of inflow, rather than by changes in the rate of evaporation from the lake surface; justification for this assumption is discussed on pg. 359.

Between 1924 and 1934 central California, and indeed much of western North America, experienced the most severe and prolonged drought in the 136 years (1849-1985) of record. That eleven years of aridity shows up as a marked perturbation in the rings of drought-sensitive trees in the Mono Basin.[6] According to Harding, the inflow to Mono Lake during these years of the mid-continent Dust Bowl averaged only about 70% of normal (Harding, 1965, Table 24). Harding also calculated that approximately that same amount of inflow would be required to sustain Mono Lake at a level of 6376 feet. By Harding's own reckoning, then, the persistence of drought such as occurred during the period 1924-1934 would eventually result in the stabilization of Mono Lake at about 6376 feet.[7]

How long would such drought conditions have to persist to reduce the level of Mono Lake to that elevation? This, of course, depends on the level of the lake at the onset of the drought. In 1924, when the drought began, the lake stood at

an elevation of 6424.1 feet. By 1934 it had dropped approximately 8.3 feet, to an elevation of 6415.8 feet. Assuming a rate of decline of 8.3 feet per eleven years (= 0.75 feet per year), then, it may be ventured as a first approximation that to draw Mono Lake to 6376 feet from its 1924 elevation would require about 63 years of a hydroclimatic regime similar to the drought period of the 1920s and '30s. It must be remembered, however, that as the level of the lake falls, several factors, including an increase in salinity and a decrease in surface area (both of which reduce evaporative loss), act to slow the rate of lake decline. Thus, based on this simple assessment, it is safe to say that if such a climatic regime had persisted from 1925 to the present, and no water diversions had occurred, the lake today (1987) would still be higher than 6376 feet. Perhaps another decade or more of Dust Bowl-like conditions would be necessary to force the lake to that elevation.

The point of this discussion is not that a particular number of years of severe drought is required to draw the surface of the lake to 6376 feet; it is, rather, that if the lake was as low in 1857 as Lynch and Harding contend, the causal drought must have been of sufficient severity and duration to be evident in the historic and the dendroclimatologic record. The lack of evidence for such a severe and prolonged drought underlines the implausibility of

an 1857 surface elevation of 6376 feet.

Appendix B includes graphic and tabular data demonstrating the relationship between San Francisco precipitation[8] and the measured flow of Sierran streams into Mono Lake[9] for the period 1935-1964. (The latter variable is a direct function of precipitation on the Sierran slope of the Mono Basin.) The reasonably high correlation (r= .84) is to be expected, since both San Francisco and the eastern slope of the central Sierra Nevada receive the great bulk of their precipitation from the passage of the same frontal disturbances. (This correlation, in fact, probably underestimates the utility of San Francisco precipitation as an indicator of Sierran inflow to the lake, since groundwater recharge and discharge tend to moderate the extremes in inflow that would be expected in years of particularly high or low precipitation.) The San Francisco precipitation record can therefore be used as a surrogate to estimate in a general and qualitative way the annual inflow to Mono Lake.

It can be seen in Appendix B that the average annual precipitation in San Francisco during the years 1849-1857 (22.92 in.) is greater than "normal" (1935-1964 = 20.66 in.) for that station. It is safe to assume, therefore, that Sierran runoff into Mono Lake during that period must have been more than the amount required to sustain the lake at

6376 feet. Thus, if the lake did stand at 6376 feet in 1857, it must have risen to that elevation from an even lower level in 1849--a level which, if it existed, must have been brought about by a decades-long drought even more severe than that which characterized the Dust Bowl years. There is an important point to be seen in this argument: the further back in time one unsuccessfully seeks evidence of Lynch and Harding's putative causal drought, the more severe and prolonged that drought must be to account for their proposed 1857 surface elevation of 6376 feet.

No official precipitation records were kept in California prior to 1849. The historic record, however, makes it possible to characterize in a general way the climate of the previous decade. William Heath Davis (1967) wrote that the winter of 1839-40 was "a severe one in California . . . [Rain] poured down for forty days and forty nights with but little cessation . . . The whole country was flooded". Pioneer John Sutter described the Sacramento Valley during that winter as "one vast expanse of water [with] deer, elk and other animals crowded together in large numbers on every little prominence that appeared above the water" (Davis, ibid).

Many accounts indicate that the winter of 1840-41 was extremely dry (Burcham, 1957). The following winter, however, was again "severe" in its wetness, according to

Davis (op cit). John Bidwell (1877; 1894), whose diary includes a valuable account of the climatic conditions of the 1840's, noted that it was "one of the wettest winters . . . fully equal to the winter of 1849-50." (The 1849-50 season saw over 160% of normal precipitation fall in San Francisco; see Appendix B.)

The winter of 1842-43 brought "a moderate rainfall", according to Bidwell, while 1843-44 was "almost rainless. . . with the exception of one good rain in November or early December and a light rain in March".[10]

Bidwell (ibid.) noted that the winter of 1844-45 brought "considerable rain" to central California. Moses Schallenberger, a member of the Elisha Stevens Overland Party of 1844, became separated from his fellow-immigrants and was forced to spend that stormy season in the Sierra Nevada. His diary tells of days on end of unceasing snowfall (Schallenberger and Stewart, 1953). The winter of 1845-46 was said by Bidwell (op cit.) to be "very wet", with "floods and inundations". The season brought "an immense quantity of snow", according to Sutter (1932).

The following winter (1846-47) may rank among the wettest in California history. The lowlands, according to Bidwell (op cit.), received "copious rains". Early snows in the Sierra Nevada trapped the Donner Party near the crest of the range. Over four months of unrelenting precipitation

foiled all rescue attempts and led to the deaths of 47 of the party's 87 members (Stewart, 1936).

Edwin Bryant (1848) wrote of the many heavy storms that drenched central California during the winter of 1847-48. Bidwell's account tells of "some early rains . . . and some good rains in March". The winter of 1848-49 was said by him to be "very snowy" with "considerable rain" (Bidwell, op cit.).

These historic accounts suggest that during the period 1839-40 to 1948-49 two winters ('40-'41 and '43-'44) were very dry, two winters ('42-'43 and '47-'48) were perhaps moderately wet, and the precipitation was "considerable" to "extreme" in six of the winters. While these accounts are admittedly subjective, qualitative, and only indirectly applicable to the eastern side of the central Sierra Nevada, they strongly suggest that the inflow to Mono Lake during the late 1830s, and the 1840s was greater than that required to sustain the lake surface at an elevation of 6376 feet. Thus, if Mono Lake did stand at 6376 feet in 1857, as Lynch and Harding contend, it must have risen to that elevation from a considerably lower level in 1839. This would require that prior to 1839 central California would have experienced a decades-long drought far drier than that which characterized the Dust Bowl years. To the contrary, the tree-ring record reveals that the Mono Basin did not experience a drought as

severe and prolonged as that of 1925-1934 for at least 150 years prior to 1857.[11] It must be concluded, therefore, that a drought of the intensity and duration necessary to account for an 1857 surface elevation of 6376 feet did not occur between the years 1700 and 1857, and that the 1857 lake level postulated by Lynch and Harding is climatically implausible.

Cartographic Evidence for an 1857 Surface Elevation of 6407 (±1) Feet

Suggestions from early maps. The earliest known cartographic depiction of Mono Lake and its islands appears on Eddy's "Official Map of the State of California", published in 1854.[12] A portion of that map can be seen on Figure 6a. That same crude view of the lake was perpetuated on Mitchell's map of 1856 (Figure 6b) (Wheat, 1960, p.49). Mono Lake was drawn somewhat more accurately on Goddard's "California State Map of 1857" (Figure 6c) (ibid.). Further refinement is evident on the 1860 "Map of the Washoe Mining District" by Evans (Figure 6d) (ibid.), and on Clayton's 1861 "Map of Esmeralda and Mono" (Figure 6e). The latter projection can be considered the first accurate depiction of the entire lake shore; it includes the western portion of the shoreline that von Schmidt did not meander, and shows the precise locations of all the major tributary streams.

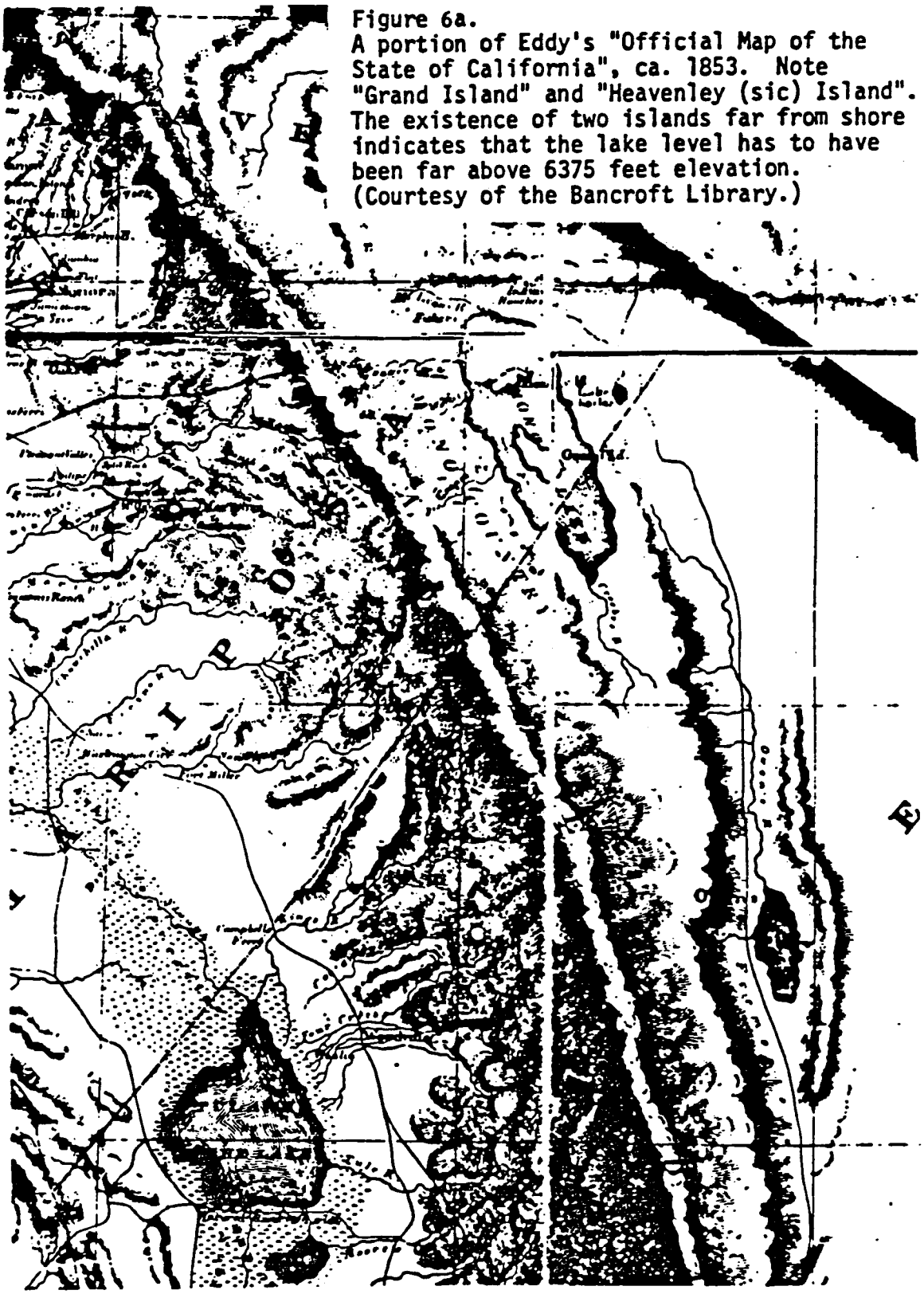


Figure 6a.
A portion of Eddy's "Official Map of the State of California", ca. 1853. Note "Grand Island" and "Heavenley (sic) Island". The existence of two islands far from shore indicates that the lake level has to have been far above 6375 feet elevation. (Courtesy of the Bancroft Library.)

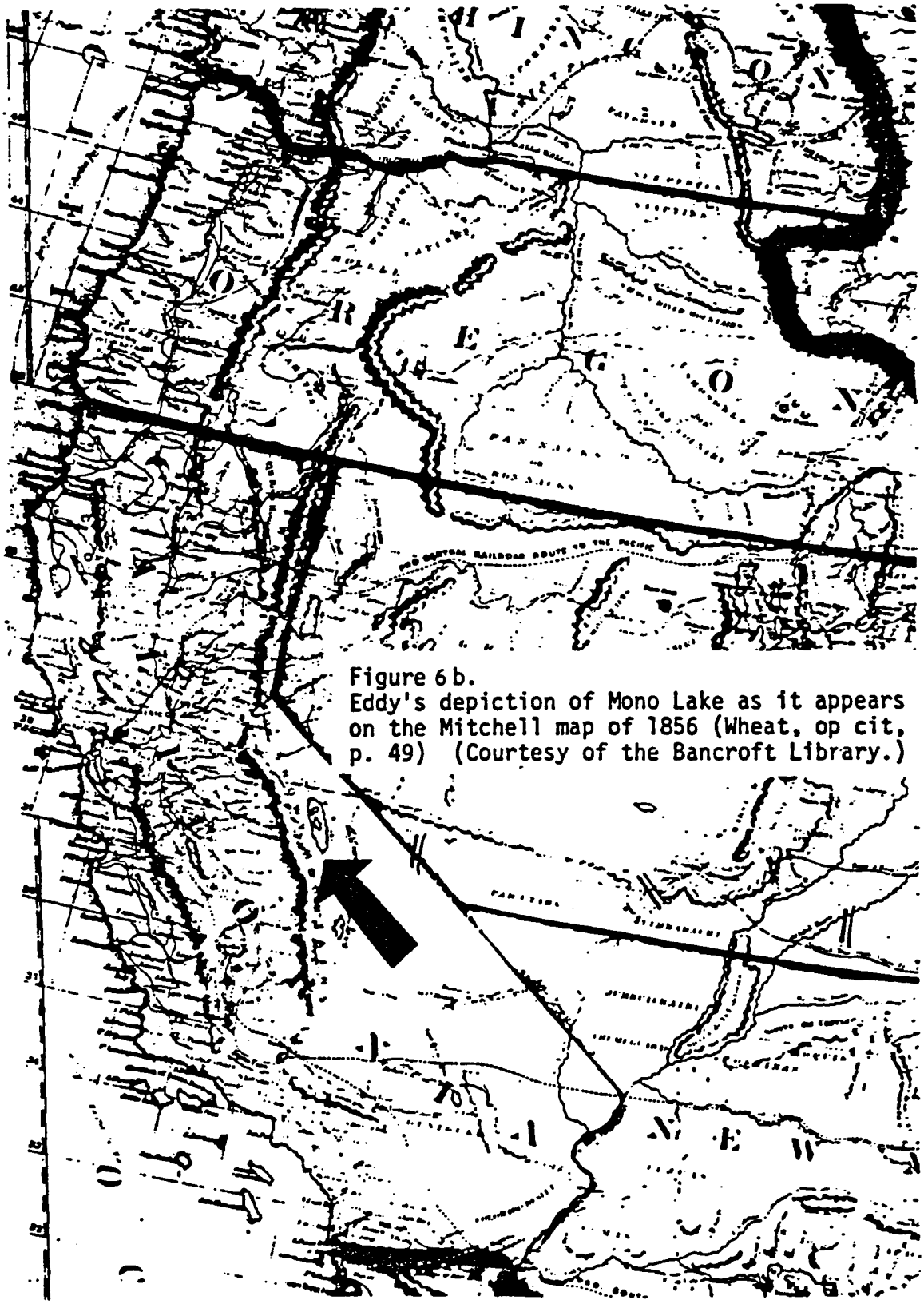


Figure 6 b.
Eddy's depiction of Mono Lake as it appears on the Mitchell map of 1856 (Wheat, op cit, p. 49) (Courtesy of the Bancroft Library.)

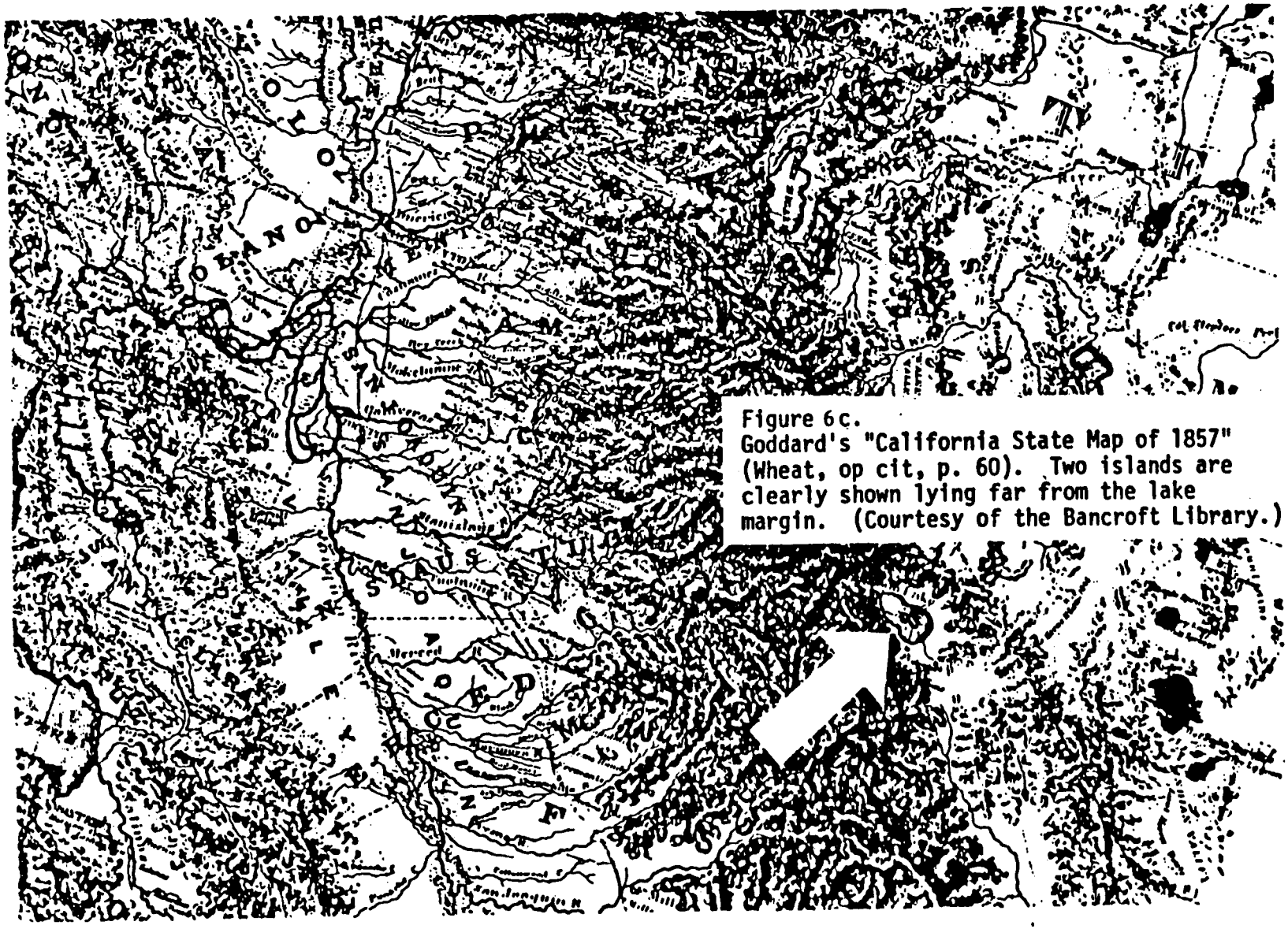


Figure 6c.
Goddard's "California State Map of 1857" (Wheat, op cit, p. 60). Two islands are clearly shown lying far from the lake margin. (Courtesy of the Bancroft Library.)

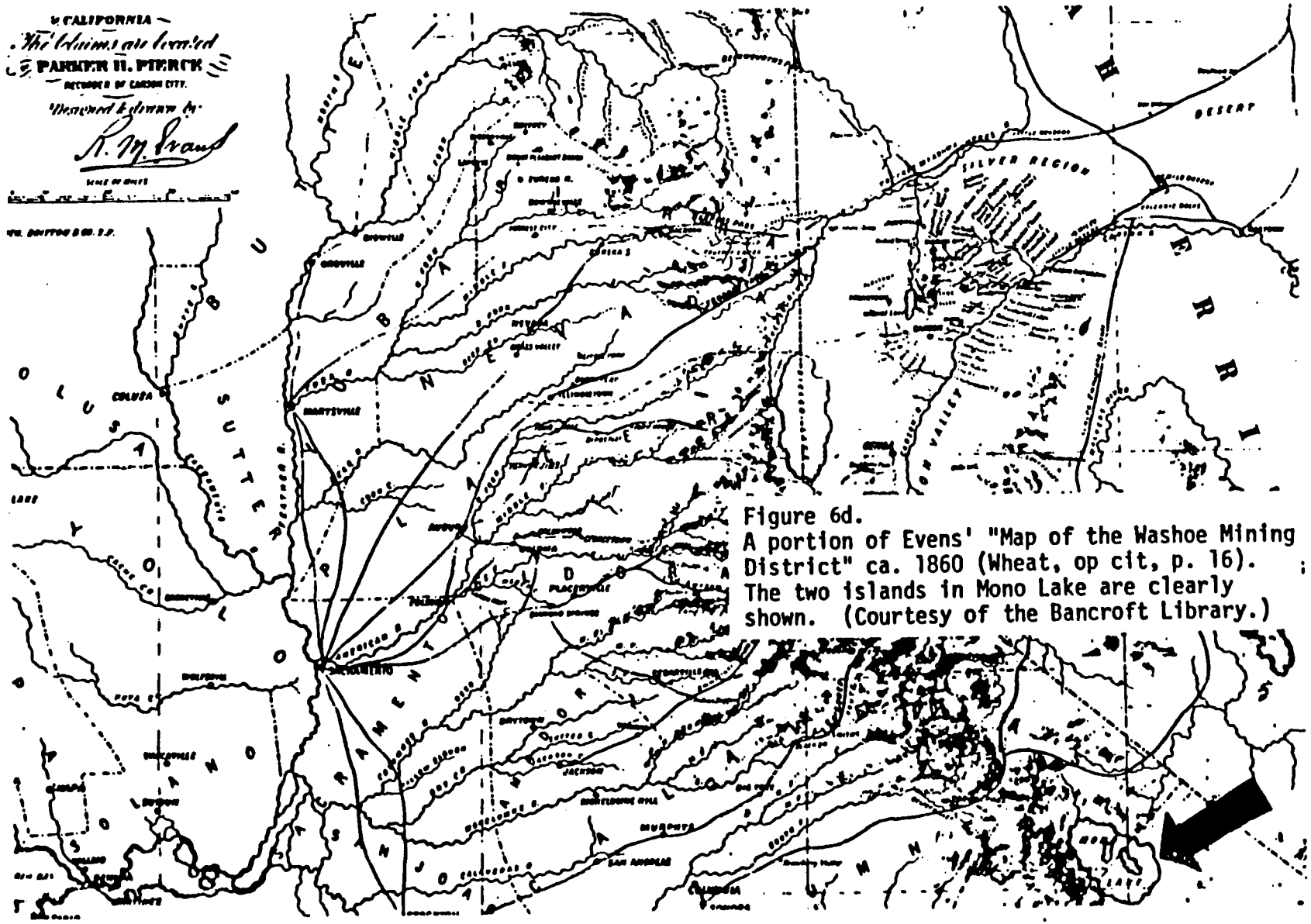


Figure 6d.
A portion of Evens' "Map of the Washoe Mining District" ca. 1860 (Wheat, op cit, p. 16). The two islands in Mono Lake are clearly shown. (Courtesy of the Bancroft Library.)

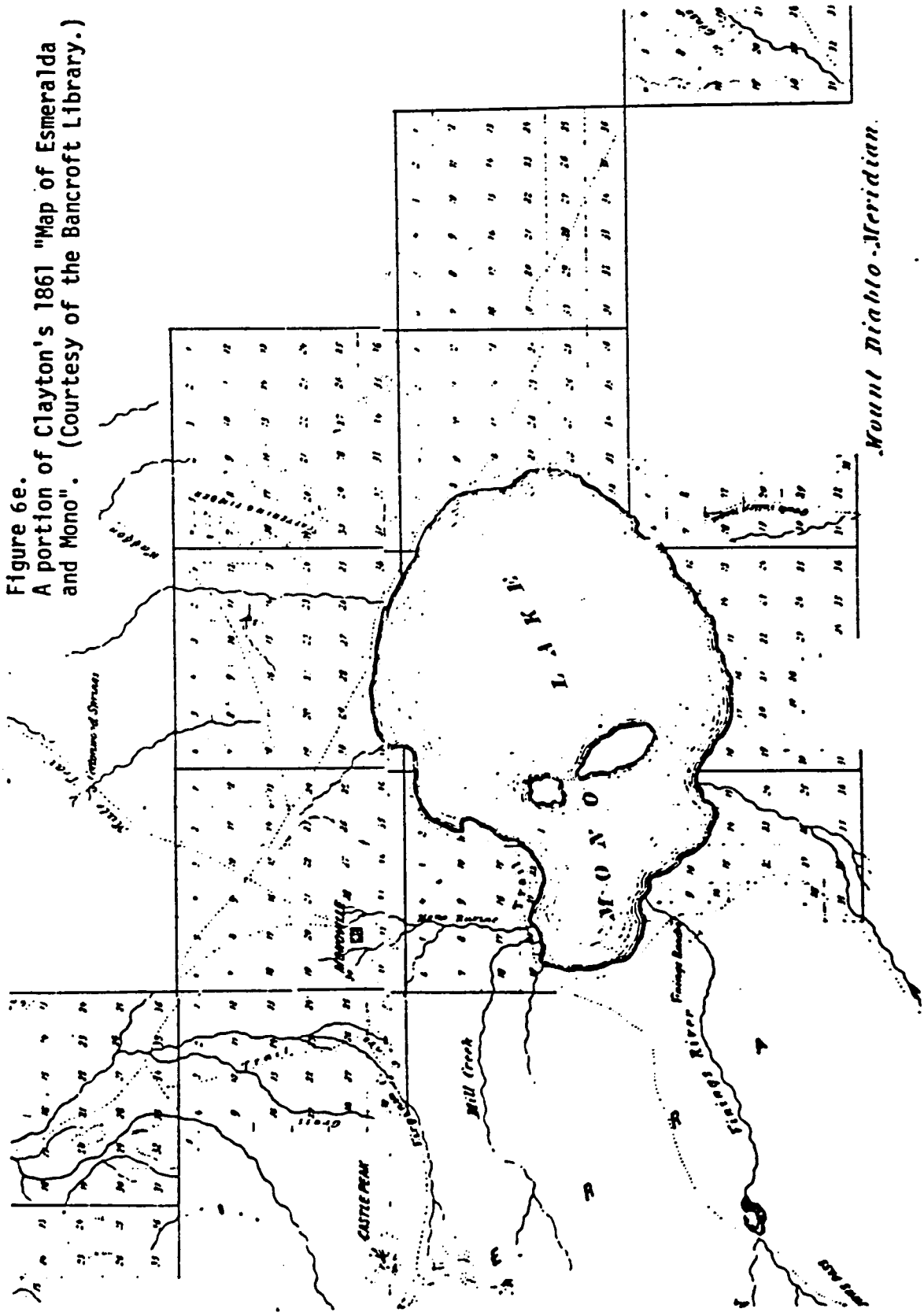


Figure 6e.
A portion of Clayton's 1861 "Map of Esmeralda and Mono". (Courtesy of the Bancroft Library.)

The significance of these four different maps of Mono Lake, and of others too numerous to include here[13], is that they all show that two islands existed in the lake during the years prior to, coinciding with, and immediately following the von Schmidt survey. The maps also indicate that the islands were far from the lake shore. Written accounts of the Mono Basin from the 1850s also describe the lake's two islands.[14] Indeed, von Schmidt himself wrote glowingly of the islands in 1855, and referred to them frequently in his notes of 1856 and '57.[15]

When the surface of Mono Lake reaches 6376 feet Negit Island becomes connected to the mainland by an isthmus, leaving Mono Lake with only one major island. The fact that two large islands existed during the 1850s, and that these islands were distant from the shoreline, can be taken as evidence that the surface of Mono Lake was far above the 6376-foot elevation postulated by Lynch and Harding. Indeed, the following analysis comparing more recent maps with the von Schmidt survey plats indicates that the lake was fully 30 feet higher than the Lynch-Harding figure.

Evidence from the Cowtrack Mountain (1962) Quadrangle. Because of the gentle gradients of the shorelands surrounding much of Mono Lake, a relatively slight rise or fall in surface elevation translates to a considerable horizontal

displacement of the shoreline. In many locations within the elevation range 6400 to 6410 feet, a mere five-foot drop in lake level brings about a horizontal shoreline migration of a thousand feet or more. Shoreline position is thus a sensitive indicator of lake level; it can be used with considerable precision to determine the 1857 surface elevation of the lake.

Figure 7 illustrates the relative positions of von Schmidt's 1857 meander line and the shoreline shown on the Cowtrack Mountain (1962) Quadrangle. The meander line and the section grid were traced from portions of the appropriate survey plats, while the shoreline of 1962 was plotted by using a Focalmatic Desk Projector to enlarge the Cowtrack Mountain Quadrangle to the scale of the plats. I believe the shoreline and meander positions depicted on Figure 7, as well as on Figures 5, 9 and 10, are planimetrically accurate to within approximately 150 feet. Confidence in this method is reinforced by information obtainable from the topographic maps themselves. Note on Figures 3, 4, and 8 that the section lines on the USGS Bodie, Cowtrack Mountain, and Mono Craters quadrangles typically do not extend precisely to the lake margin, but rather stop short of, or extend beyond, the water's edge. This is because the section lines, which were established by von Schmidt in 1856-57, terminate where they intersect the shoreline that he meandered during those years.

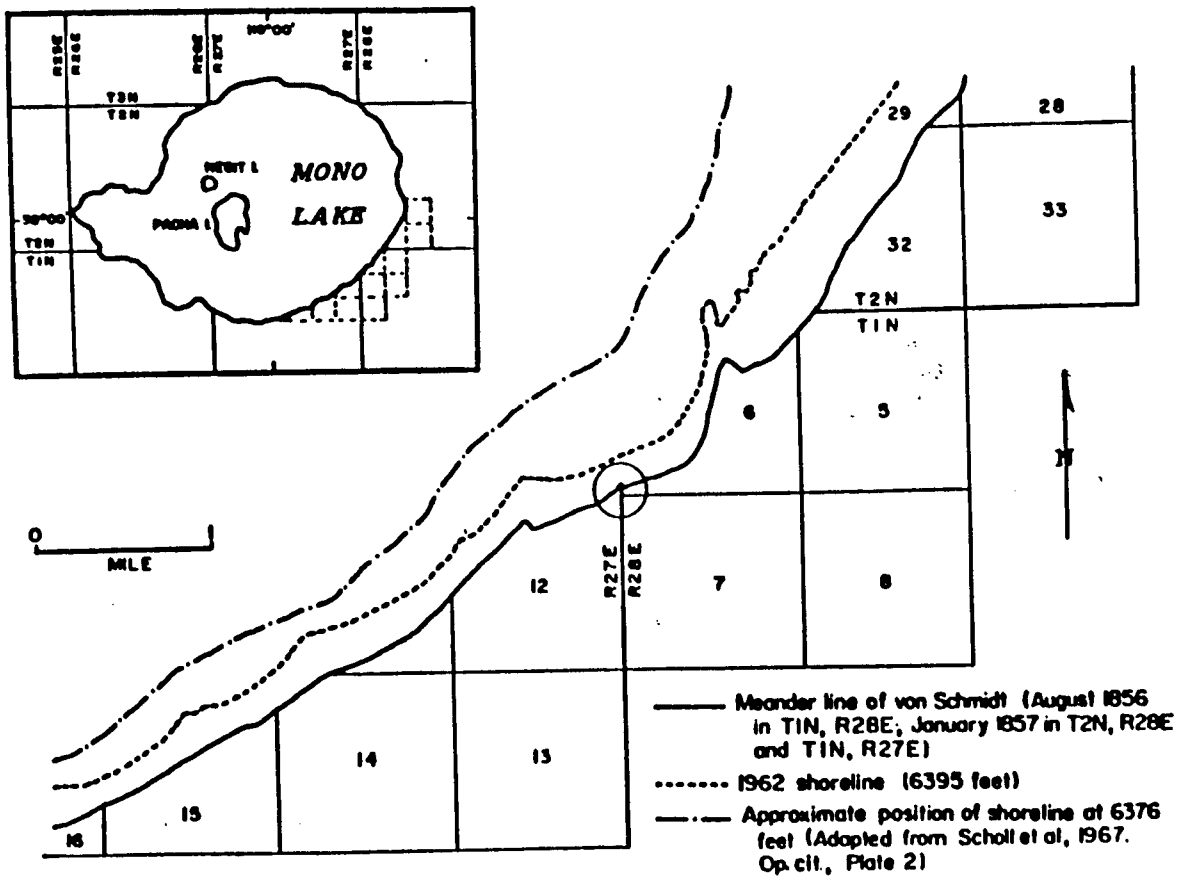


Figure 7. Relative positions of the 6376-foot contour, the 6402-foot contour, and the 1857 meander line, Cowtrack Mountain Quadrangle.

Figure 8. A portion of the USGS Mono Craters Quadrangle of 1953 (lake level 6409 feet). Note that the section lines terminate at, or slightly beyond, the shoreline, suggesting that Mono Lake stood at, or slightly below, 6409 feet at the time of the cadastral survey.

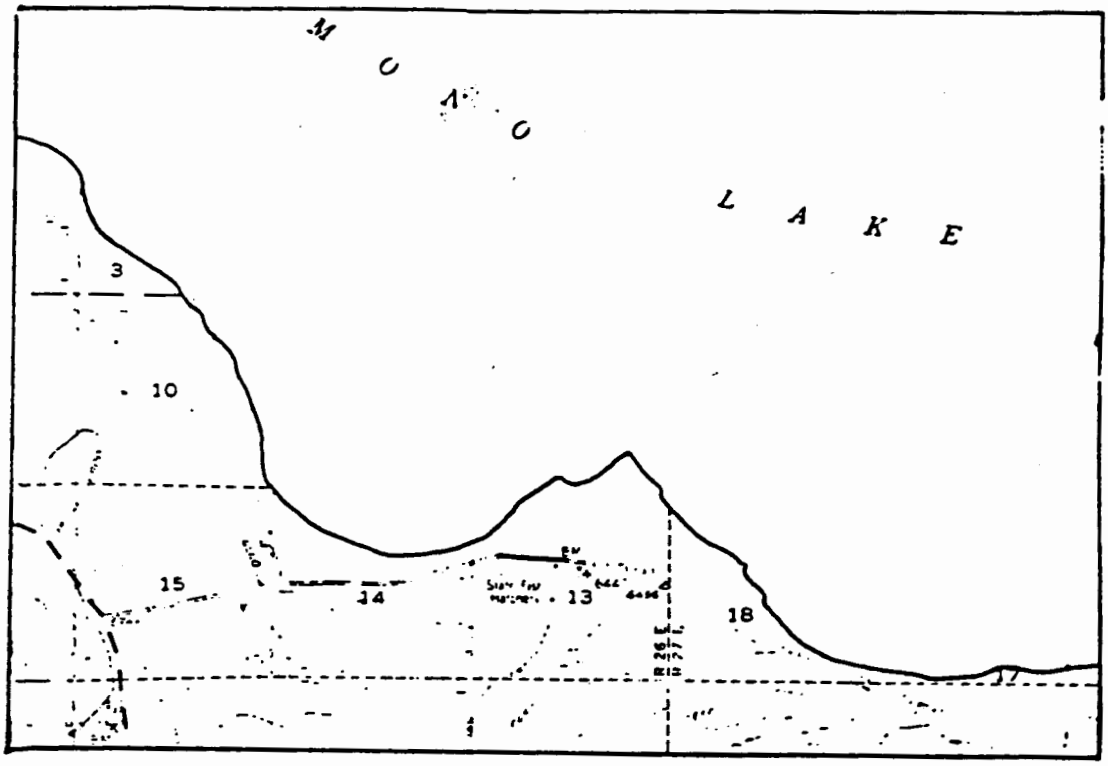


Figure 7 shows clearly that the 1857 meander line stands as much as 2100 feet landward of the 1962 lake margin. (This same conclusion can be drawn by exaimining the termination points of the section lines shown on the Cowtrack Mountain Quadrangle itself--see Figure 3.) The elevation of the lake in 1962 was 6395 feet. Based on this evidence it may be tentatively concluded that the shoreline elevation of Mono Lake in 1857 was higher than 6395 feet.

This conclusion can be considered correct only if the meander line mapped by von Schmidt closely coincided with the actual 1857 shoreline--that is, the conclusion is correct only if von Schmidt surveyed the actual shoreline, rather than some arbitrary line farther upslope. In fact, there is reason to believe that any discrepancies between the actual and the mapped shorelines of 1857 are minor. Von Schmidt's notes consistently refer to "setting charred meander posts *on the edge* of Mono Lake" (emphasis added). The shoreline detail evident on the plats (e.g. see Figure 5, Section 31, T3N R27E, and Sections 2, 11, 20 and 21 of T2N R26E) indicates that von Schmidt did indeed meander the lake's edge, rather than some more generalized line farther upslope. It is also interesting to note that along the western boundary of T1N R27E, von Schmidt found it necessary to set the meander post two chains (132 feet) short of the actual shoreline, and that along the eastern boundary of that same

township he placed the meander post one chain, fifty links (99 feet) from shore. In both cases he stated the deviations in his notes. It may therefore be conservatively assumed that when von Schmidt set his meander posts farther than 98 feet from edgewater he so indicated in his notes. This 98 feet seems insignificant when it is considered that in places there is a 7,500-foot difference between the position of the 1857 meander line and the position of the shoreline corresponding to the lake level postulated by Lynch and Harding. Given the shoreline detail that von Schmidt mapped, the explicit wording of his notes, and his statements concerning minor deviations from the lake margin, it cannot be accepted that von Schmidt meandered an imaginary line over 7,500 feet from the actual water's edge. There can be little doubt, then, that the lake elevation in 1857 was over 6395 feet.

Evidence from the Trench Canyon (1958) Quadrangle. Following the procedure described above, the shoreline shown on the Trench Canyon (1958) Quadrangle was plotted onto a trace of portions of the appropriate survey plats (Figure 9). The elevation of the lake in 1958 was 6,402 feet. While the agreement between the two lines is close, the 1857 meander occupies a position upslope from the 1958 lake margin at 6402 feet along almost its entire length. Only in portions of Sections 7 and 8 in T2N R28E, and over parts of

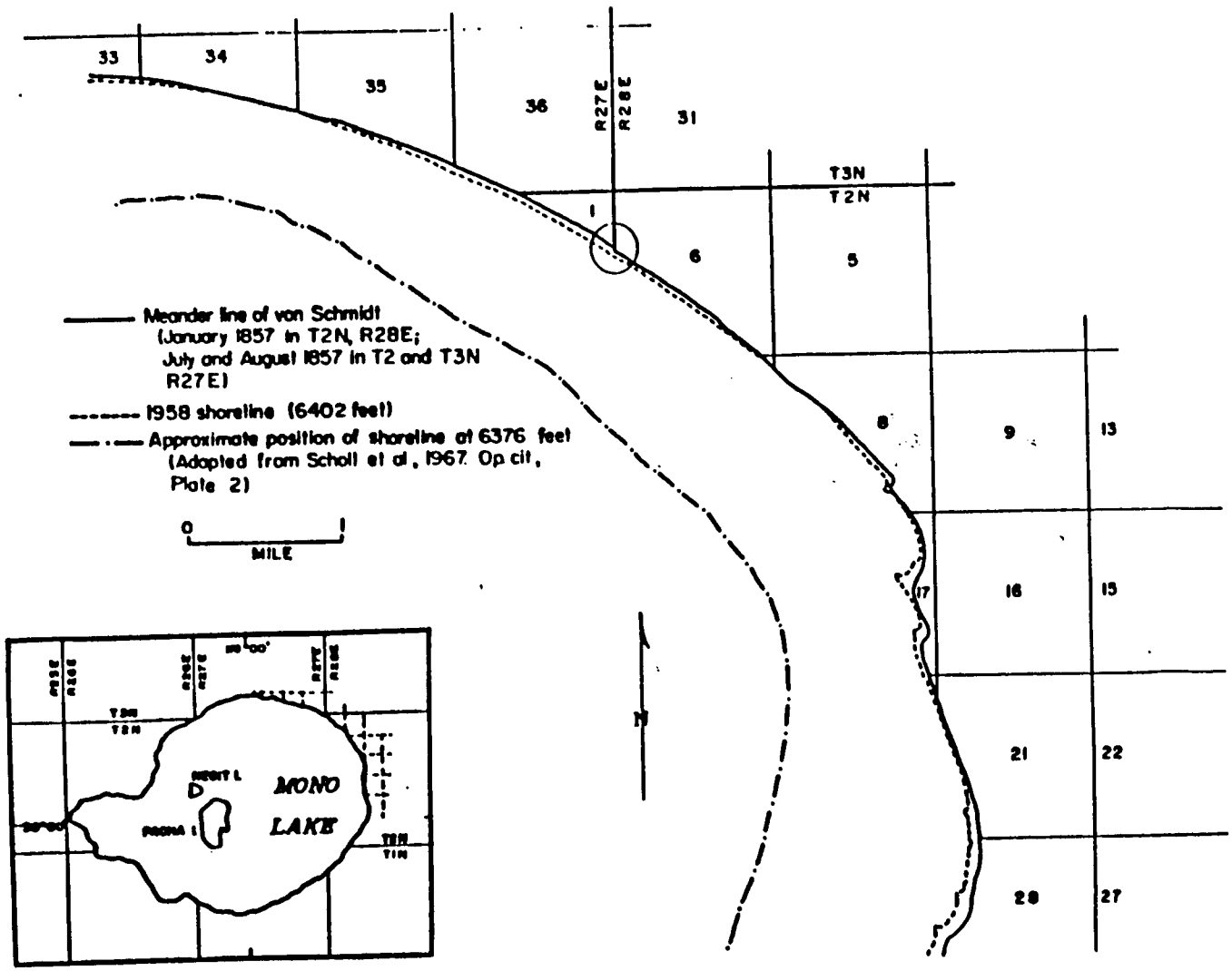


Figure 9. Relative positions of the 6378-foot contour, the 6402-foot contour, and the 1857 meander line. Trench Canyon Quadrangle.

Sections 34 and 35 in T3N R27E, is the opposite true. These local anomalies may reasonably be attributed to minor changes in the configuration of the lakeshore due to wind and wave action between 1857 and 1958. Evidence from the Trench Canyon Quadrangle thus indicates that the lake elevation in 1857 was above 6402 feet.

Evidence from the Bodie (1958) Quadrangle. As previously described, Figure 5 illustrates the relative positions of the 1857 meander line and the 6402-foot shoreline depicted on the Bodie (1958) Quadrangle. The superposition of the 1857 shoreline is apparent along almost its entire length. (This superposition is also evident from the termination points of the section lines on the Bodie Quadrangle--see Figure 4.) The minor exceptions that exist in Sections 1, 6, 14 and 23 of T2N R26E are believed to be due to wave-induced modification of the unconsolidated beach sediments. The slight deviation in Section 20 is the result of progradation of Mill Creek. The gross anomaly in Section 19 was discussed previously: the marked departure between the 1958 shoreline and the 1857 meander line in that section is believed to be the result of a fabrication by von Schmidt.

A small firth and an adjacent pond can be seen on the Bodie Quadrangle northeast of Black Point in Section 11, T2N R26E (Figure 4). Notice on Figure 4 that in 1958, when the lake surface stood at 6402 feet, the pond was separated from

the firth by a low bar. Von Schmidt's survey plats indicate that in 1857 the bar either did not exist, or was submerged, and that the pond composed a small embayment in the shoreline of Mono Lake.

Harding (unpub.) discussed the fact that von Schmidt's meander line encircled the pond in Section 11, but he ignored the obvious implications and chose instead to accept Lynch's postulated lake elevation of 6376 feet. At that elevation the lake margin would have stood more than one mile from the pond in Section 11 (see Figure 5). Surely it is unreasonable to assume that von Schmidt would have painstakingly meandered the intricate detail of the embayment in Section 11 if the water's edge had stood well over 5000 feet away.

The relationship between the meander line and the shoreline in the area covered by the Bodie (1958) Quadrangle substantiates the conclusion drawn from the Trench Canyon (1958) Quadrangle that the 1857 surface elevation of Mono Lake was greater than 6402 feet.

Evidence from the Mono Craters (1953) Quadrangle.

Similar plots were drawn for that portion of the lake covered by the Mono Craters (1953) Quadrangle (Figure 10). The elevation of the lake surface in 1953 was 6409 feet. A close correspondence can be seen between the position of the 1857 meander line and the lake margin of 1953. The 1857 meander line lies downslope from the 1953 shoreline along most of its

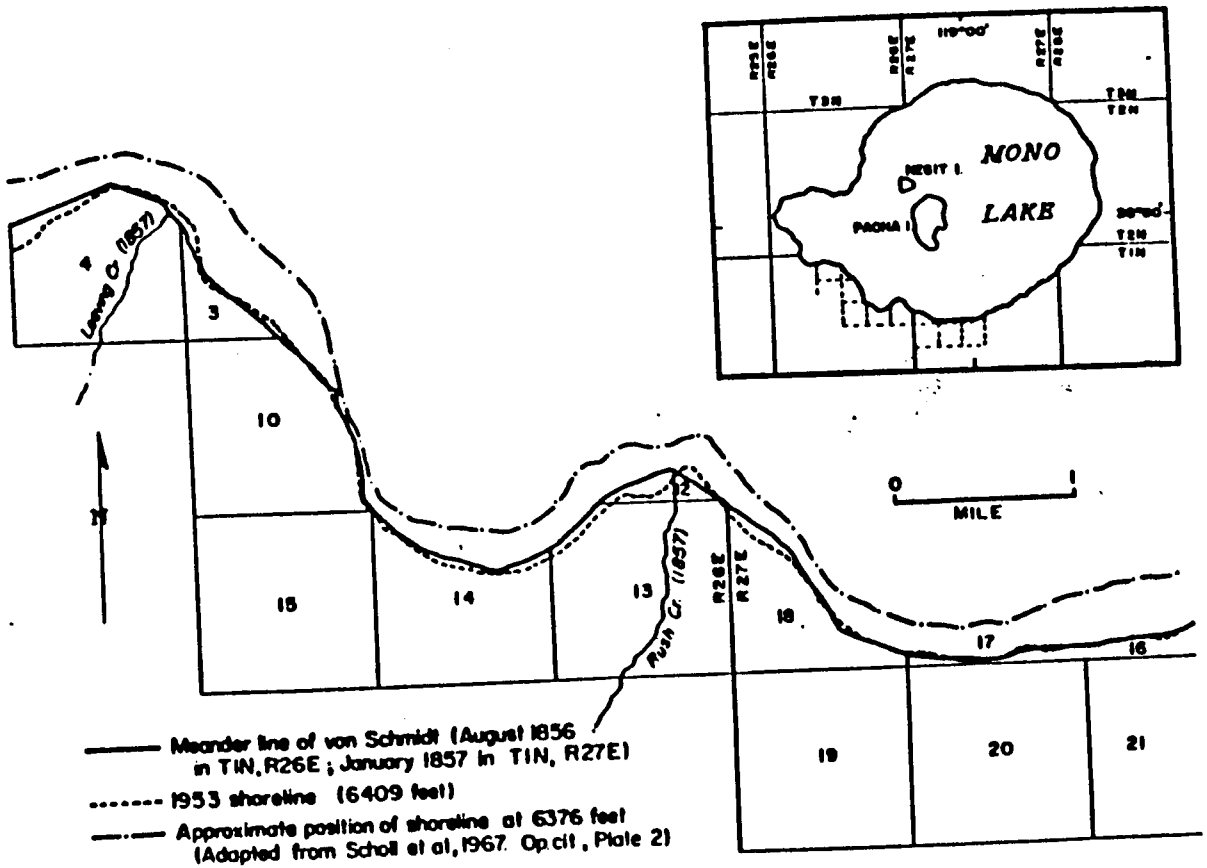


Figure 10. Relative positions of the 6376-foot contour, the 6402-foot contour, and the 1857 meander line, Mono Craters Quadrangle.

length. Only in Sections 3, 4, and 12 of T2N R26E do notable exceptions exist. These departures are due to progradation of the deltas at the mouths of Rush and Lee Vining creeks. From this evidence it is clear that the elevation of Mono Lake in 1857 was less than 6409 feet.

Summary of cartographic evidence. In light of the cartographic evidence cited above there can be little doubt that in 1857 the shoreline of Mono Lake stood somewhere between 6402 feet and 6409 feet in elevation. Three lines of reasoning lead this writer to conclude that the 1857 surface elevation of the lake was 6407 (± 1) feet.

First, in comparing Figures 4, 8 and 9 it is apparent that in 1857 the shoreline stood closer to 6409 feet than to 6402 feet. In other words, the 1857 shoreline elevation stood between 6405.5 feet (the midpoint between 6402 and 6409) and 6409 feet. This allows an estimate of 6407.25 (±.75) feet.

Secondly, in 1933 Lynch calculated the area lying within the von Schmidt meander line to be approximately 81.8 square miles. Based on modern stage/area relationships, a surface area of 81.8 square miles corresponds to a surface elevation of 6407 feet (see Appendix A).

Thirdly, an elevation survey was conducted on July 21, 1979. On that day the writer leveled from Benchmark 6656 (Section 3, T2N R26E; see Figure 3) to the area of the

previously described lagoon in Section 11 of the same township. The meander configuration around the lagoon and bar as depicted on the von Schmidt plat was matched in the field with the local topography. It was found that the meander line in that area stands at approximately 6407 feet.. Allowing one foot for error, it is concluded that in 1857 the elevation of Mono Lake was 6407 (±1) feet above sea level.

THE FLUCTUATIONS OF MONO LAKE--1857-1883

Fluctuations in lake level, 1857-1866

Not until 1883 can a surface elevation for Mono Lake be established with absolute surety. On November 5th of that year W.D. Johnson, topographer for Israel Cook Russell, chiseled an inverted T at waterline on the southwestern tip of Negit Island. That mark was later located and found to lie at an elevation of 6410.38 feet (Harding, unpub.).[16]

Using the San Francisco precipitation record and the written accounts of scientists and other observers as guidelines, Lynch and Harding speculated on the rate of lake rise from their postulated 1857 level of 6376 feet to the known 1883 lake elevation.[17] Figure 11 is a hydrograph illustrating the fluctuations in lake level proposed by Lynch and Harding for the period 1857-1883.

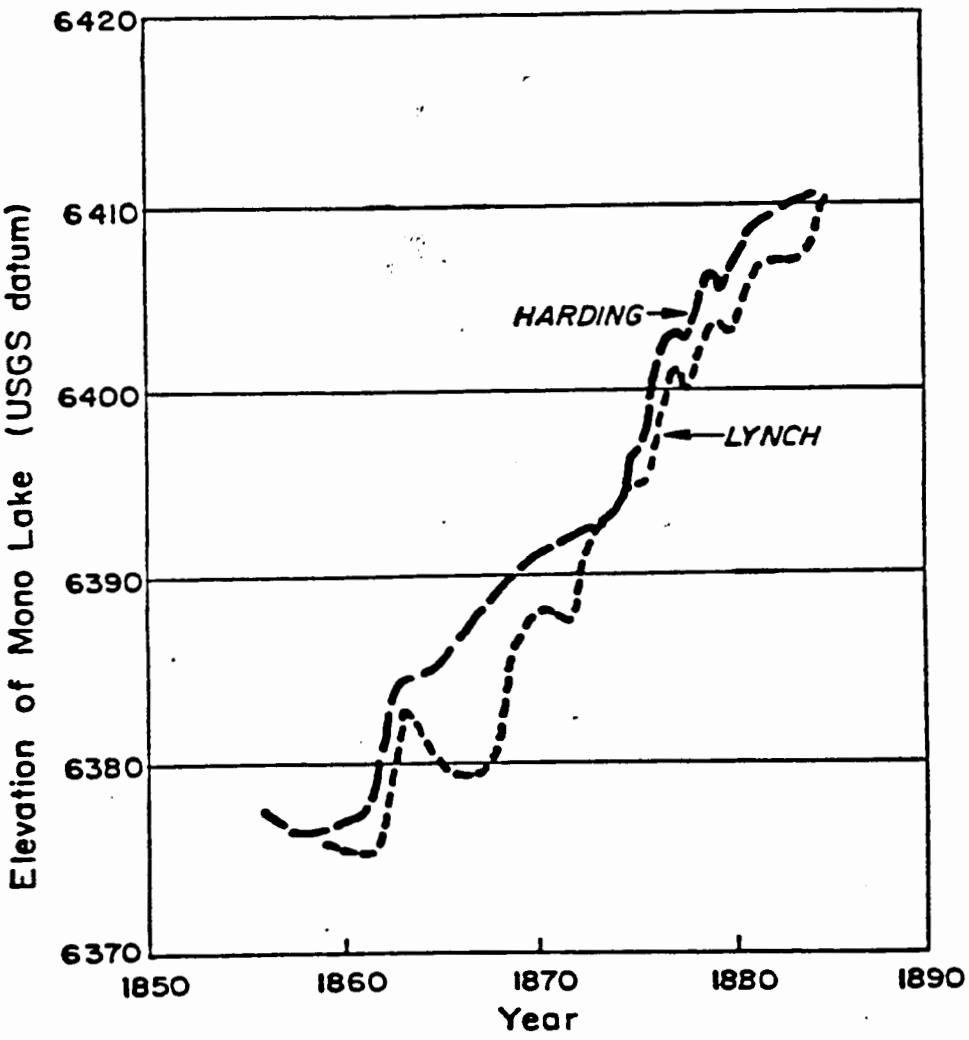


Figure 11. Lake fluctuations of Lynch and Harding, 1857-1883.

None of the historical accounts cited by Lynch and Harding directly addresses the question of the 1857 surface elevation of Mono Lake. The apparent effect of noting such accounts, however, is to add credence to their postulated 1857 lake level. In actuality, the historical record is consistent with an 1857 surface elevation of 6407 (±1) feet, and grossly contradicts the 6376-foot figure of Lynch and Harding.

The purpose of the paragraphs that follow is to point up the ways in which Lynch and Harding misinterpreted the historic record to corroborate their proposed 1857 lake elevation, and, in light of the corrected 1857 lake level, to reevaluate the lake fluctuations that occurred between that year and 1883. It is readily admitted that, in the absence of actual inflow and evaporation data, it is impossible to know the precise pattern of lake behavior during these years. It is safe to assume, however, that the lake rose in years of abnormally high runoff (determined from the San Francisco precipitation record), and that it dropped when runoff was abnormally low.[18] This information, in combination with historical accounts, can be used to produce a reasonable interpolation of the fluctuations in lake level that occurred between 1857 and 1883.

Several accounts cast light on the nature of the changes in lake level that occurred between 1857 and 1866. These,

together with the extremes of the San Francisco precipitation record, suggest the following sequence of events: a drop in lake level between 1857 and 1861; a marked rise in 1862; and a lake decline in 1863-66.

Two lines of evidence can be cited in support of the proposed decline in lake level between 1857 and 1861. The first is a brief account written by an anonymous correspondent from the mining town of Monoville in October of 1859. He noted that "those who have known this body of water [Mono Lake] for a few years past have observed its gradual decline. . ." (Lynch, 1933). Secondly, a stone foundation believed to be the remains of a cabin built on the northern side of Negit Island in 1861 (Russell, 1889) was found to have a basal elevation of 6406 feet, indicating that the lake stood below that elevation at the time of construction.[19] San Francisco received approximately average precipitation (normal period = 1935-1964) between 1857 and 1861, a fact that argues against a radical drop in lake level during those years. It is not unreasonable to suppose that between 1857 and 1861 the lake declined approximately 3 feet, to an elevation of around 6404 feet.

The 1861-62 season is the wettest on record in central California. San Francisco received more than twice its average precipitation. Intense and prolonged flooding occurred in the Central Valley as well as in the mining

districts east of the Sierra Nevada (Stine, unpub.). Owens Lake, 100 miles south of the Mono Basin, is said to have risen 12 feet (Lynch, 1933). Mono Lake undoubtedly rose as well, perhaps more than six feet. A reasonable estimate of the 1862 lake elevation might be 6410-6411 feet (see discussion below).

During the following two seasons (1862-63 and 1863-64) central California experienced drought conditions severe enough to help put an end to the booming California cattle industry (Cleland, 1951). San Francisco recieved 66% of normal precipitation in the first of these dry years, and only 49% in the second. Mono Lake undoubtedly declined during these two years, perhaps reaching an elevation of around 6409 feet in 1863, and 6408 feet by the late summer of 1864.

Accounts written by Josiah Whitney, chief of the Geological Survey of California, and his botanist William Henry Brewer, corroborate within broad limits the lake elevation of 6410 feet proposed here for the year 1863, and grossly contradict the 1863 elevation postulated by Lynch and Harding. Whitney reported that in early July of that year, when the party visited Mono Lake, they measured "a very distinct terrace 385 feet above the water", and that they found "the highest well defined one 680 feet above the present surface of the lake" (Whitney, 1865). Brewer

likewise reported the latter figure. These measurements were taken along the northern shore of the lake, between Black Point and Trench Canyon (Farquhar, 1949). When Russell studied the lake in 1883 he found the high terrace in that vicinity to lie between 670 and 685 feet above lake level (Russell, op cit.), the variation being a result of tectonic warping. The surface elevation of the lake in 1883 is known to have been 6410 feet. It follows that at the time of the Whitney-Brewer visit the lake surface stood between 6405 feet and 6420 feet, an elevation range well in keeping with the 6410-foot figure proposed here. It goes without saying that in the six years following 1857 the lake could not have risen from the level proposed by Lynch and Harding (6376 feet) to even the lowest of those elevations.

Harding, in attempting to demonstrate an 1863 lake elevation of about 6384 feet (see Figure 11), plays down the significance of the Whitney-Brewer accounts. His statement in that regard is baseless: "Whitney's report supports a conclusion that Mono Lake was not above 6410 feet in the early 1860's, but does not define how much lower it may have been" (Harding, 1965).

Further corroboration for an 1863 lake level of around 6410 feet is found in the Appendix to the California Legislative Journal (1863-64), written by State Surveyor General John Kidder. During his visit to Negit Island in

1863, Kidder found a "water line . . . marked at about 22 feet above the lake". Twenty years later Israel Russell would likewise describe a "water line" on Negit Island:

> "A thin coating of calcareous tufa occurs about [the island's] base, and sheaths the rocks up to a height of about twenty feet above the present lake surface." (Note that this same line persists today on Negit Island at an elevation of approximately 6430 feet.)

While the nature of the Kidder's "water line" is not made clear in his account, it is reasonable to assume that it is the same line described by Russell. Thus, Kidder's account, too, suggests that the elevation of the Mono shoreline in 1863 was close to that of 1883 (6410 feet).

The 1864-65 season was slightly wetter than normal in San Francisco. It is probable, however, that because of groundwater recharge related to the marked drought of the previous two years the lake continued its downward trend. This judgment is based on known data from the years 1932-35, when the occurrence of an above-normal runoff year (1935) failed to halt the decline in lake level brought about by the preceding dry years. The 1865-66 season brought average precipitation to San Francisco, perhaps stablizing the lake surface. It is suggested that by the late summer of 1866 the surface of Mono Lake stood at approximately 6407 feet.

The lake fluctuations proposed here for the period 1857-1866 are graphed as a line labled Segment A on Figure 12. The 1857 lake level may be considered accurate to within

±1 foot. The line itself should be considered less accurate, perhaps to within ±2 feet.

Fluctuations in lake level--1867-1870

In March of 1867, prior to the runoff season, a United States Survey Corps headed by Clarence King passed through the Mono Basin en route to its now-renowned "Exploration of the Fortieth Parallel" (King, 1878). Among the members of the corps was veteran Civil War photographer Timothy O'Sullivan, who took photographs of Paoha Island and Panum Dome (northernmost of the Mono "Craters"). This latter photo encompasses a view of the southwestern margin of the lake stretching from Horse Creek Embayment to the Lee Vining Creek delta. It is included here as Photo 3. A similar photograph, taken by Israel Russell in 1883 when the lake stood at an elevation of 6410 feet, is shown on Photo 4. While the resolution of the Russell and O'Sullivan photographs is less than perfect, and while the distance between the camera and the lake margin is such that a precise assessment of lake elevation is precluded, it can be seen that the shoreline in the vicinity of the Horse Creek Embayment and the Lee Vining Creek delta appears to stand at virtually the same position in both views. Comparison of these two photos with others taken in January of 1986 (Photos 5a,b,c), when the lake stood at 6378 feet, reveals a striking difference in the position

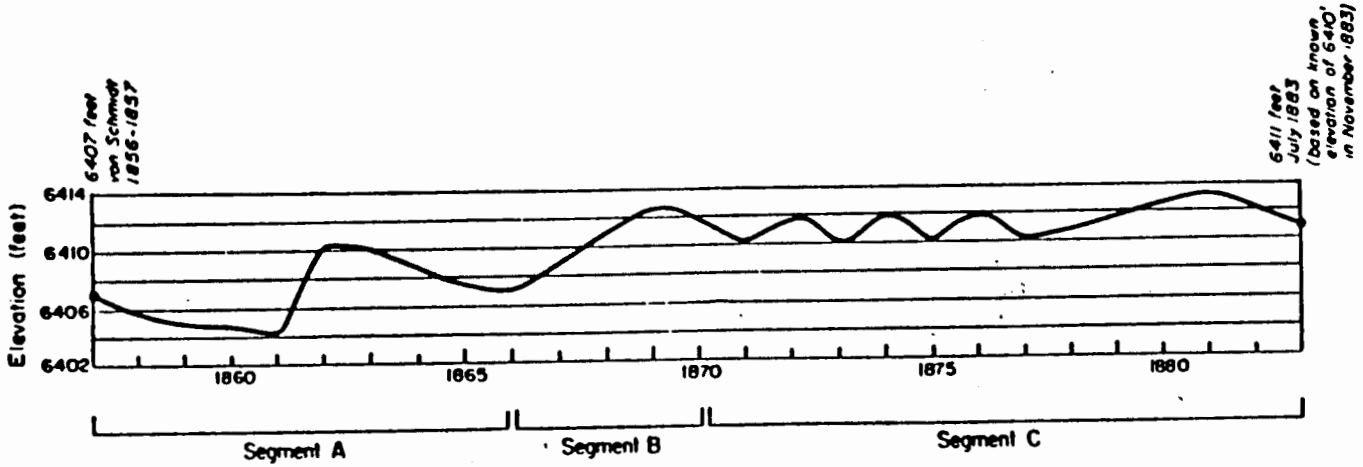


Figure 12. Lake fluctuations proposed for the period 1857-1883. End points are believed accurate to within ±1 foot. Line should be considered accurate to within perhaps ±2 feet.

of the lake margin. The 6378-foot figure is of importance because it is that elevation which Lynch assigns to the lake for 1867, the year in which O'Sullivan took the photograph. This photo comparison indicates that in 1867 the lake was far higher than the level proposed by Lynch, and suggests that it stood at, or at least close to, the 1883 lake elevation of 6410 feet.

San Francisco received 167% of normal precipitation during the 1866-67 season, suggesting that during the months following King's tour of the Mono Basin the lake rose markedly. The rise likely continued in 1867-68, a year in which San Francisco received 188% of normal rainfall, and perhaps in 1868-69, when San Francisco precipitation was slightly greater than normal. It is suggested here that between 1866 and 1869 the lake rose six feet, to an elevation of approximately 6413 feet.

This six-foot rise in lake level proposed here is attested in the Proceedings of the California Academy of Sciences (1873, p. 89). According to that document Professor Henry Nicholas Bolander addressed the Academy in December of 1869 on the subject of "the recent rise of 6 feet in the level of Mono Lake, said to be accompanied by a freshening of the waters and the disappearance of the dense clouds of flies, of which the larve were formerly abundant in the lake." Eighteen seventy was a year of slightly below-normal

precipitation in San Francisco, and the lake may have fallen slightly, perhaps to an elevation of 6412 feet. The fluctuations in lake level proposed here for the period 1867-1870 are graphed as Segment B on Figure 12.

Fluctuations in lake level--1871-1883

Beginning in 1871 San Francisco experienced eight years in which annual rainfall alternated from drier, to wetter, than normal. (Indeed, with the exception of 1875, this series of years was characterized by conditions significantly drier or wetter than normal.) With little historical guidance available, I suggest that the lake fluctuated between elevations of roughly 6410 feet and 6412 feet during this eight-year period.

It is interesting to compare the lake fluctuations proposed here for the early and mid-1870s (see Figure 12) with those postulated by Lynch and Harding (Figure 11). Both Lynch and Harding show the lake rising steeply during the early and mid-1870s, a conclusion they drew from the writings of geologist Joseph LeConte. While studying the volcanic features of the Mono Basin in 1875 LeConte (1879) noted that "residents about the lake state that the waters have risen ten to twelve feet in ten or fifteen years". Israel Russell (op cit.) warned of taking such hearsay evidence literally, considering it to be "of little more than qualitative value".

It might be added that word-of-mouth evidence is particularly suspect when it concerns a transgression of Mono Lake, since a rise in the lake surface not only submerges reference marks used to judge changes in elevation, but results in gross shifts in shoreline position (over a thousand feet per five-foot rise, in many places), thus making accurate determination of lake fluctuations extremely difficult in the absence of an actual elevation survey. Russell (op cit.) questioned the claims of the residents, and concluded that the available physical evidence suggested that between the early 1860's and 1883 a rise in lake level on the order of five or six feet had taken place (Russell, op cit.). Lynch and Harding either overlooked or disregarded Russell's caution, as well as his assessment of lake level change during the decades preceding 1883.

During his stay in the Mono Basin LeConte also reported finding "old fences of sheep corrals and old trails submerged many feet deep. While visiting [Paoha] island I found the vegetation. . . Artemisia tridentata and . . . Sarcobatus vermiculatus submerged in five feet of water and of course killed." Based on this passage Lynch (1948) placed a line ("LeConte's sagebrush line") at elevation 6390 feet on his lake level curve. The presence of this line has the effect of adding credence to his curve, leading many workers (including Harding) to conclude that Lynch plotted his lake

levels for the early and mid-1870s in relation to a reference line of known elevation. In fact, however, the opposite is true: Lynch plotted the elevation of the sagebrush line in relation to lake levels that he assumed to be correct. That line adds nothing to his lake level curve but a false sense of verisimilitude. Circular reasoning such as this pervades the Lynch and Harding assessments of the early historic fluctuations of Mono Lake.

The criticisms of Lynch and Harding mentioned above must not be construed as outright rejection of the qualitative value of LeConte's account. It is reasonable that during the "ten or fifteen years" mentioned by LeConte the lake did rise as much as eight feet--from around 6404 feet in 1861, to 6412 feet by 1874. This eight-foot rise in lake level would have caused a shift in shoreline position of well over 1000 feet in places. Corrals and fences built far from the water's edge in the late 1850s and early 1860s would have been inundated by the lake beginning in 1862.

The years 1878, '79, '80, and '81 were all significantly wetter than normal in San Francisco, suggesting that Mono Lake rose during that period, perhaps to an elevation of around 6413 feet. The following two years were relatively dry, forcing a decline of the lake surface to 6410.38 feet in November of 1883, when Johnson marked the water line on Negit Island.

The fluctuations in lake level proposed here for the period 1871-1883 are graphed as Segment C on Figure 12. It should be stressed again that, because of a lack of accurate inflow and evaporation data, the actual changes in lake level that occurred between 1858 and 1882 cannot be objectively estimated; the line shown on Figure 11 is simply an estimate based on the historic record, and on rainfall data from San Francisco.

Inconsistencies and Contradictions in the Lynch and Harding Curves

In light of the discussion above it is well to consider the climatic plausibility of the lake fluctuations proposed by Lynch and Harding for the period 1857-1883. The rises and falls in Lynch's curve (Figure 13) generally agree in trend but not in magnitude with those proposed in this report. Lynch's line reflects the drops in lake level that, based on the historic and precipitation records, must be expected to have occurred during the years 1857-61, 1863 and '64, and 1871. Yet in allowing for these lake recessions, it was necessary for him to compensate by proposing rises that are impossibly steep. His 8-foot rise shown for the single wet year of 1869, for instance, represents a jump even more extreme than that proposed for the considerably wetter year of 1861-62. Lynch shows several similarly unjustifiable

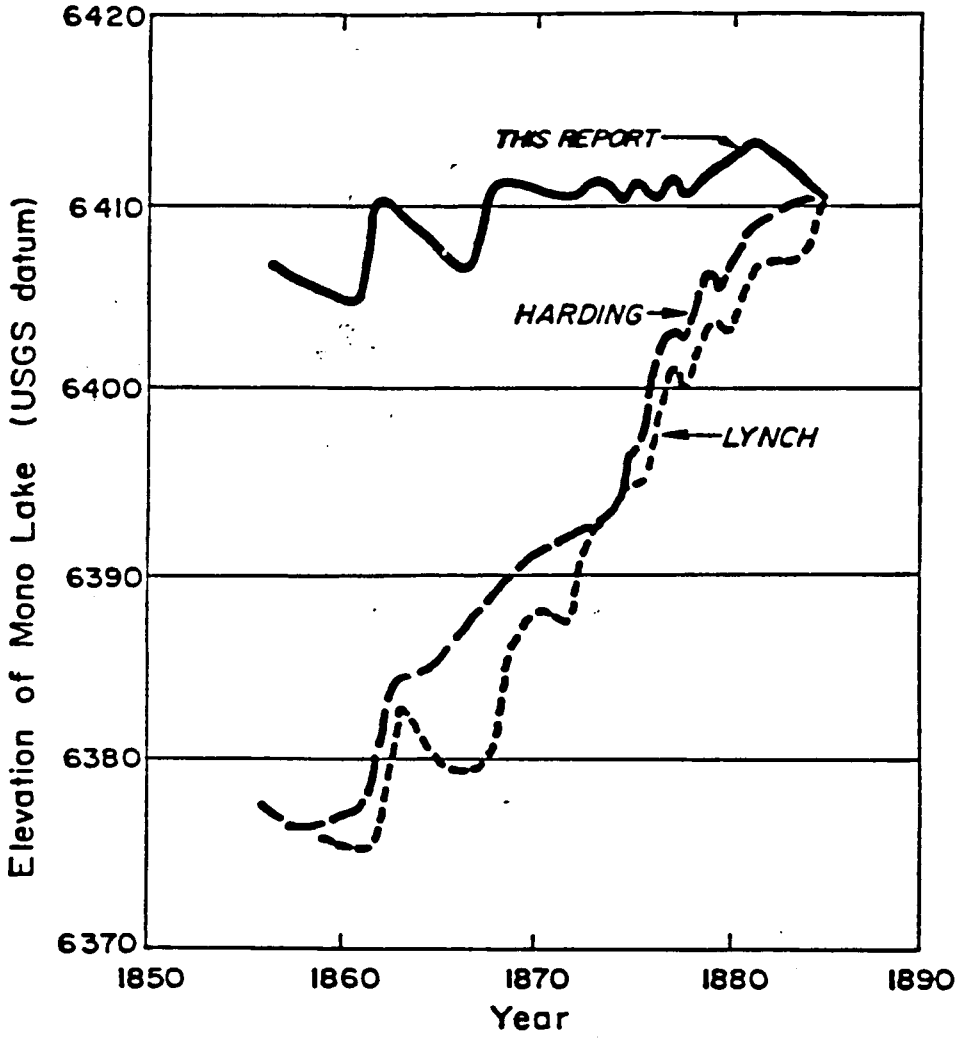


Figure 13. Lake fluctuations proposed here compared with those of Lynch and Harding.

rises between 1871 and 1880.

Perhaps realizing the discordance between the steep rises in Lynch's curve and the available climatic data, Harding flattened the rises in his own curve by not allowing for the declines in lake level that must be expected to have occurred during the relatively dry years. He actually shows a substantial rise in lake level in 1862-64 and 1877--years in which San Francisco measured only about half of its long-term average precipitation--as well as in 1871, '73, '82, and '83, when precipitation in San Francisco was below 78% of normal. In short, any attempt to connect an 1857 lake elevation of 6376 feet with the known 1883 elevation of 6410 feet requires either that the rises be untenably steep, or that the expected declines be ignored. A 34-foot net rise in lake level between 1857 and 1883 simply cannot be reconciled with the available climatic and historic records.

THE SURFACE FLUCTUATIONS OF MONO LAKE--1883-1912

Any effort to estimate the surface fluctuations of Mono Lake for the period 1883-1912 is hindered by the same absence of inflow and evaporation data that characterizes the period 1857-1883. It is known that the lake surface rose from 6410 feet in 1883 to 6417 feet in 1898 (Harding, unpub.), and that it stood at 6423.77 feet on June 15, 1912, when lake level

fluctuations began to be monitored. Based primarily on precipitation data from central California, Lynch and Harding estimated the fluctuations in lake level that occurred between these points of known elevation.

With no controversy surrounding the elevation of the end-points of this segment of the curve, and with no new historic information to bring to bear on the lake fluctuations that occurred during this period of time, it seems pointless to try to improve on the post-1883 interpolations of these two workers. For the purposes of this report Harding's line is considered the more trustworty--not because of any characteristic of the line itself, but because he was relatively explicit in defining his methodology. Harding's lake levels for the period 1883-1912, therefore, are included on the hydrograph of historic fluctuations of Mono Lake shown on Plate 1.

THE SURFACE FLUCTUATIONS OF MONO LAKE--1912-1986

In 1912 the United States Forest Service began to monitor changes in the level of Mono Lake. For the next 22 years elevation readings were taken at irregular intervals from a staff gauge located along the western shore near the Post Office Creek Delta. The City of Los Angeles, which started recording lake elevations from this same gauge [20] in

December of 1925, relieved the Forest Service of the task in 1934. Since that time DWP has taken lake level readings at approximately weekly intervals and, like the Forest Service before them, has reported these readings to the United States Geological Survey for publication in the USGS Water Supply Papers (since 1966 called Water Resources Data for California).

In general the accuracy of this record is high. In addition to the period between May, 1915 and June, 1916, which, according to USGS Water Supply Paper 765 is "obviously in error", only five of the nearly 3000 lake level readings should be considered suspect.[21]

One other source of confusion clouds the record. In 1932 the United States Geological Survey adjusted the elevation net in the Mono Basin to conform to the United States Coast and Geodetic Survey datum change of 1929. This involved a correction of +0.37 feet. The City of Los Angeles never made this adjustment, and continues to report uncorrected figures to the USGS. For decades the USGS corrected the DWP lake elevations (that is, USGS added 0.37 feet to the DWP figures) before publishing them in the Water Supply Papers. In September of 1976, however, following a personnel change and a move of the Water Resources Division to their Laguna-Niguel office, the USGS stopped making the correction, and began to publish unadjusted DWP figures.

This practice has continued to the present day.[22]

Plate 1 illustrates graphically the surface fluctuations of Mono Lake that occurred between 1857 and 1986. All elevations on the graph and throughout this dissertation conform to the National Geodetic Vertical Datum of 1929.

It can be seen on Plate 1 that following the shoreline fluctuations described above for the period 1857-1883 the lake began a marked rise that culminated on July 18, 1919 at an elevation of 6428.07 feet. In the sections that follow, this point on the lake level curve is referred to as the "Historic High Stand". The lake remained close to the Historic High Stand until 1924, when it began to decline in response to the onset of Dust Bowl conditions. The climatic amelioration of the mid-1930s halted this decline, and the abnormally wet conditions of 1938 forced a minor rise in lake level.

The City of Los Angeles began to divert Mono Lake's tributary streams in 1940. For the next 7 years these diversions were relatively small; this, and the high precipitation of the early and middle portions of the decade combined to essentially stabilize the lake at elevations between 6416 and 6418 feet. With an increase in stream diversions and a return to a more normal precipitation regime in 1947, the lake surface began to drop dramatically. With few exceptions (i.e. the abnormally wet years of 1952, 1958,

1967, 1969, and 1980) that drop continued until December 30, 1981, when the lake reached its "Historic Low Stand" of 6372.00 feet. Record-breaking runoff from the Mono Sierra in 1982 and 1983 exceeded DWP's diversion capabilities, forcing the release of massive amounts of water into the lake and instigating a rapid lake-level rise to an elevation close to 6381 feet in early April of 1984. Over the next 20 months the lake experienced a minor decline; at the time of writing (June, 1986) the lake surface is once again rising, and lies at approximately 6380 feet above sea level.

In portions of the chapter that follows the historic lake fluctuations will be mentioned often. With this in mind the reader will want to keep Plate 1 close at hand.

FOOTNOTES

[1] Von Schmidt was a Californian of some distinction. His life as an engineer and his exploits as a surveyor are the subject of a Master's Thesis by George Reimer (1961). Von Schmidt's survey notes and plats are available at the Office of the Bureau of Land Management, Sacramento.

[2] The verb "meander" is used by engineers to denote the surveying of a lake margin. "Meander points" are those points set as reference marks around the lake margin. A "meander line" is a line connecting two adjacent meander points, or, more generally, a line connecting several or all meander points along the periphery of a lake.

[3] Personal communication with Messrs. Dave Evens and Mel Blevins, Los Angeles Department of Water and Power. August, 1979, May, 1980.

[4] Personal communication with Dr. Kenneth Lajoie, United States Geological Survey, Menlo Park, California. November, 1981.

[5] The 5-foot contour maps of Mono Lake prepared for Federal Litigation Civil No. S-80-696, U.S.D.C., E.D. Cal. by Pacific Western Aerial Surveys (available at Water Resource Archives, University of California, Berkeley) clearly indicate the marked lakeward flattening of the Mono shorelands. In the vicinity of South Tufa on the southern shore of the lake the ground slope in the elevation interval 6415'-6420', where Lynch made his slope measurements, is approximately 55.6' per mile. The gradient declines to approximately 25' per mile in the elevation interval 6395'-6400', and reaches 11.7' per mile in the elevation interval 6372'-6375'. On the eastern side of the lake, in the vicinity of Warm Springs, the gradient drops from 41.7' per mile in the elevation interval 6415'-6420', to 15.6' per mile in the elevation interval 6395'-6400', and to 11.7 feet per mile in the elevation interval 6372'-6375'. These same elevation intervals on the western side of the lake near the Mono County Marina are characterized by slopes of 250', 125', and 23.3' per mile, respectively, while on the northern shore near Bridgeport Creek they display slopes of 13.9', 11.6', and 6.47' per mile, respectively.

[6] Personal communication with Mr. Joel Michaelsen, Department of Geography, University of California, Berkeley, March,

1980. Present address: Department of Geography, University of California, Santa Barbara.

[7] Recent work by Vorster (1985) verifies Harding's conclusion in this regard.

[8] Prior to 1857 only three California stations--San Francisco, Stockton and Sacramento--kept reliable precipitation records. Of the three, San Francisco provides what is by far the best index of inflow to Mono Lake.

[9] Data on measured inflow available from the Los Angeles Department of Water and Power.

[10] John C. Fremont crossed the Sierra Nevada during the winter of 1843-44. While the crossing could not have been accomplished in a year of high precipitation, his account does indicate that the winter may have been somewhat wetter than described by Bidwell. Fremont recorded snowstorms in the central Sierra on January 13th, 19th, 20th, 30th and 31st, and wrote that cold, rainy conditions prevailed on the 26th, 27th and 28th of that month. Snow fell "thickly" on February 1st, and snowstorms on the 9th, 10th and 11th resulted in a deep snow-lie on February 12th. He also wrote of falling snow on the 21st and 22nd of February, and of heavy rainfall on the 26th of that month (Jackson and Spence, 1970, pp. 601-644).

[11] Personal Communication with Joel Michaelsen, op cit.

[12] Eddy's map is available at The Bancroft Library, University of California, Berkeley. One earlier map (Trask's 1853 "Map of the State of California"--see Fletcher, 1982) depicts Mono Lake. This map, however, does not show any of the islands, an omission that renders it useless in assessing the lake elevation of 1853.

[13] See, for instance, DeGroot's 1863 Map of the Nevada Territory (in Wheat, op cit. v. 5, p. 67); and Browning's 1861 map of California, New Mexico and Utah (ibid., p. 11).

[14] E.g. the Sacramento Daily Union, November 23, 1859.

[15] Von Schmidt first viewed the Mono Basin from the crest of the Sierra Nevada in 1855. He described the panorama thusly: "From this point the view of the country is magnificant. Mono Lake, *with its two islands* lying to the northeast, looks beautiful--and in short, take the view all together, is the most beautiful I ever saw" (emphisis added).

[16] According to Harding (1962), the inverted T was discovered on September 30, 1950 by a survey party headed by R.V. Phillips of the LADWP. The mark was leveled on that day, and was found to lie 0.29 feet above the lake surface. Phillips reported a September 30th lake level of 6409.72 feet, "USGS Datum", and concluded that the bench mark (and thus the lake level of November, 1883) stood 6410.01 feet above sea level, "USGS Datum". This figure is the one cited by Harding.

The datum used by Phillips in his determination of the bench mark elevation, however, is not the National Geodetic Vertical Datum (NGVD) of 1929 (the datum used by USGS since 1932). USGS lists the lake elevation of September 30, 1950 as 6410.09 feet, 0.37 feet above that cited by Phillips. It is concluded therefore that the Johnson bench mark lies at an elevation of 6410.38 feet, NGVD of 1929. The discrepancy between the NGVD of 1929 and the datum used by the LADWP is discussed in detail on page 86-87.

[17] Lynch, working as he was during the years prior to 1950, when W.D. Johnson's bench mark was discovered, was unaware of the precise 1883 elevation of Mono Lake. He estimated from Russell's photographs that the lake elevation in that year was 6408 feet. Thus, while Harding sought to interpolate changes in lake level between 6376 feet (for 1857 AD) and 6410 feet (for 1883 AD), Lynch interpolated between 6376 feet and 6408 feet.

[18] Any attempt to quantitativly evaluate the behavior of Mono Lake during the period 1857-1883 is hampered by a lack of accurate inflow and evaporation data. The correlation between San Francisco precipitation and Mono Basin stream flow, while reasonably high ($r = 0.84$), provides the basis for only a rough estimate of Mono Lake inflow. At the 80% confidence interval, for instance, it can be said that a year of normal precipitation in San Francisco brought somewhere between 75% and 122% of normal stream flow to the Mono Basin, a distressingly wide range of values that, at the extremes, could have forced either a substantial rise, or a marked decline, in lake level. Based on the San Francisco precipitation record, in fact, an annual net rise in Mono Lake can be retrodicted at the 80% confidence interval only for those years in which the city received over approximately 130% of normal rainfall; similarly, an annual net drop in Mono Lake can be retrodicted with 80% surety only in those years in which San Francisco precipitation was less than approximately 70% of normal.

Indices of Mono Basin runoff for years after 1870 have been derived by the State of California (1923). These

indices, however, are of highly questionable value. They are based on a "wetness" index derived from only occasional measurements of streams far from the Mono Basin, and on an assumed runoff "normal" which is far too high.

[19] This crude structure lies within the narrow and highly protected declivity that separates the Western- and Central-Negit coulees (Figure 19). It is approximately square, measuring nine feet on a side. The rock foundation is hidden by a dilapidated wooden platform that was built in the 1950s to accomodate the movie crews filming "Fair Winds to Java". The side of the foundation that faces lakeward has collapsed downslope, making it impossible to determine precisely its original setting.

[20] The staff gauge from which lake level readings are taken was originally attached to a "willow tree" near Hammon's Store in Lot 6, the SE 1/4 of the NE 1/4 of Section 31, T2N R26E, "about two miles south of the Mono Lake post office". On September 16, 1916, the gauge was mounted to the support of a boathouse located approximately 300 feet northwest of its former position. Zero on the gauge installed in 1916 was 10.0 feet higher than that on the original gauge.

The description of the gauge location was revised in 1933 to read thusly: "SE 1/4 of the NE 1/4 of Section 31, T2N R26E, *about a mile south of the Mono Lake post office* " (emphasis added). This did not involve a change in the location of the gauge.

Sometime between 1960 and 1964 DWP moved the staff gauge to its present location at the Mono County Marina in the SE 1/4 of the NW 1/4 of Section 5, T2N R26E. See USGS Water Supply Papers 250, 330, 530, 750, 765, and 1927.

[21] Five lake levels reported by DWP to USGS should be considered incorrect. All five (reported for 1/11/44, 11/22/68, 9/15/78, 4/27/79, and 5/1/79) involve putative rises that occurred in the middle of a general falling trend; in all three cases, the difference between the questionable lake level and the subsequent reading is so great that it would require an untenably rapid drop in lake level. Consider, for example, the lake elevation reported for September 15, 1978 (recorded here in the context of the preceding and subsequent lake level readings, as listed in United States Geological Survey Water Resources Data for California, v.1, p.222, 1978):

7/6 /78 6375.34
7/13/78 6375.31

7/20/78	6375.30
8/3 /78	6375.24
8/17/78	6375.23
9/15/78	**6375.29**
9/18/78	6374.69
9/25/78	6374.65

Note that the reading for 9/15/78 represents a departure from the general falling trend of the previous weeks, and that, if the reading were correct, the lake would have to have dropped 0.6 feet in the three days following September 15. This alleged rate of lake decline is almost seven times as fast as any other recorded for Mono Lake during the 74 years of record.

[22] The writer brought this oversight to the attention of the USGS in March of 1984. The agency subsequently acknowledged the error (see Appendix C) and plans to publish an updated and corrected synthesis of the Mono Lake record in the next volume of Water Resources Data for California.

CHAPTER 2

MEANS OF TRACING THE PRE-HISTORIC SURFACE FLUCTUATIONS OF MONO LAKE

The surface fluctuations of Mono Lake described in the previous chapter were deciphered using maps, climatic data, early historic accounts, and for the past seven decades, actual lake level records. No such information is available for the period preceding 1853 AD. Fluctuations in the elevation of the lake surface that occurred prior to that year must be inferred from sedimentologic, geomorphic, paleobotanic, tephrochronologic, and radiometric evidence. While no single line of evidence provides a perfect record of lake behavior, the sum of the information permits construction of an accurate, high-resolution curve that spans the past four millennia.

This chapter discusses each of the various types of evidence in the context of the Mono Lake environment. Included here are seven sections, each of which explores a different line of evidence. The sequence of topics is as follows: a) deltaic sedimentation at late Holocene Mono Lake; b) littoral and lake bottom sedimentation at late Holocene Mono Lake; c) geomorphology of the Mono shorelands;

d) vegetation as an indicator of lake level fluctuations; e) the volcanic record and its bearing on the lake fluctuation curve; f) radiometric control of the lake level curve; g) tufa and its bearing on the lake fluctuation curve.

A. THE DELTAS OF MONO LAKE AND THEIR BEARING ON THE PRE-HISTORIC LAKE LEVEL CURVE

Introduction

Between 1941, when the City of Los Angeles began to divert water from the Mono Basin, and 1982, when a series of abnormally wet winters temporarily curtailed stream diversions, the surface of Mono Lake fell 45 feet--from an elevation of 6417 feet to 6372 feet (Plate 1). In response to this drop in base level the major tributary streams incised their deltas to depths ranging from 5 to 30 feet. Exposed in the walls of these fresh stream cuts are sequences of riverine, littoral, lacustrine, aeolian and volcanic sediments. These sedimentary sequences, and the deltaic landforms they compose, are the most important source of evidence for past fluctuations in the level of Mono Lake. It is therefore appropriate to begin this chapter with a discussion of deltas of closed lakes and the ways they can be used to construct a lake fluctuation curve.

The existing literature on this subject is disappointingly meager. Several studies of closed lakes have focused on the delta as a means of tracing past changes in lake level, but these analyses have largely ignored the processes that create deltas in widely fluctuating water

bodies, as well as the basic geomorphic forms and sedimentary structures and sequences that result from those processes. In what follows, concepts and terminology relating to Gilbert-type deltaic sedimentation in a widely fluctuating saline lake are introduced. This simple model is conceived with hypersaline Mono Lake and its tributary streams in mind, though it may have application to all deltas built into terminal lakes by small, high-gradient streams carrying both suspended and traction loads. The model is intended to provide a working vocabulary, and to serve as a rational basis for interpreting the late Holocene deltaic forms and sedimentary sequences exposed on Rush, Mill, and Lee Vining creeks.

The Gilbert Model

In his monograph of 1883 on the history of Pleistocene Lake Bonneville, G.K. Gilbert provided the first comprehensive discussion of the formation and sedimentary structures of lacustrine deltas. He reasoned that a stream, in merging with the relatively still water of a lake,[1] undergoes a decrease in current velocity that diminishes its ability to transport sediment. Upon entering the lake, the suspended fraction of the sediment load rides the diffuse remnants of the stream current basinward for some distance before settling out. This fine debris builds up on the lake

floor as bottomset beds. The coarse fraction of the stream load, on the other hand, drops out immediately after entering the lake and accumulates at the stream mouth as foreset beds.

Deposition at the mouth of the stream causes a lengthening, and consequently an initial flattening, of the channel. This flattening reduces stream velocity and competence, causing deposition of some bed load, which, according to equilibrium principles, will maintain a gradient steep enough to transport its subsequent load. Thus, a prograding stream must aggrade.[2] Coarse sediment is deposited on the channel floor, first at the newly prograded mouth, then progressively headward for some distance upstream. The deposit so formed comprises a delta topset bed.

Continued deposition of topset and foreset beds results in growth of the delta. Growth occurs both in the lakeward direction, due to stream progradation, and in the landward direction, as topset beds backfill to higher and higher levels upstream. Gilbert did not entertain the possibility that the stream might enter the lake by way of a canyon, and that backfilling in response to stream progradation might bring about the deposition of topset beds within such a canyon. With this case in mind, subsequent workers have recognized both "inner" and "outer" portions of a delta: The

inner portion (here called the confined delta), lies within the confines of the trunk stream canyon; it is composed of topset beds that overlie non-deltaic alluvium. The outer portion (here called the unconfined delta) protrudes lakeward from the mouth of the trunk stream canyon. It is tripartite in structure: steeply dipping foreset beds overlie fine-grained bottomset beds and in turn support topset beds of riverine cobbles and gravels. Since no canyon walls exist to restrict the lateral development of the unconfined delta, it grows lakeward in all possible directions, taking on a shape that, in plan view, resembles an alluvial fan.

The trunk stream distributes its flow over the surface of the delta (the delta plain) among a number of channels. These channels--the distributaries--are built on, rather than incised into, the delta plain. They are, to use Gilbert's term, "sluiceways", contained only by their own natural levees. Over time each distributary builds its own small delta (here called a distributary delta) at its mouth, instigating aggradation headward. In this way the prograding distributary channels become increasingly elevated above the general surface of the delta plain. This situation is highly unstable: Any water that finds its way over a levee brink encounters a relatively steep interlevee path to the lake shore. Should the overflow erode a notch in the levee, water will flow preferentially through the breach, resulting in the

abandonment, or partial abandonment, of the sluiceway. Fugitive flow freed during the avulsion follows the shortest, steepest available route to the lake margin, building natural levees enroute, and there begins anew the process of distributary deltification.[3]

Gilbert described an abrupt change in gradient at the point where the trunk stream meets the delta, the slope of the trunk stream being steeper than that of the delta plain.[4] Uncharacteristically, Gilbert did not provide an explanation for this phenomenon, which must lie at least partly in the following principle: The trunk stream must move a coarse load and therefore requires a relatively steep gradient. The delta plain, on the other hand, is an area of deposition for relatively fine-grained sediment that can be carried through low-gradient distributary channels. The extension of the delta continually lengthens the stream and flattens its gradient, precluding transport of coarse load far onto the delta itself. The slope of the distributaries, and thus of the delta plain, is therefore less than that of the trunk stream.

The Gilbert-type delta--environments and lithofacies. Classification of the different depositional environments associated with Gilbert-type deltas has been undertaken in a number of recent studies. The simple scheme devised by Born

(1972) for the Truckee River Delta at Pyramid Lake in western Nevada is well suited to the deltas at Mono Lake. Born recognizes four distinct depositional environments: The pro-delta environment, composed of the bottomset beds of Gilbert; the delta-slope environment, made up of Gilbert's foreset beds; the on-delta environment, constructed of topset beds; and the delta-front-platform environment, situated in the near vicinity of the shoreline and composed of stream debris reworked by waves and littoral currents.

While the different lithofacies associated with each of these depositional environments can be expected to vary from lake to lake and from stream to stream, certain generalizations regarding the nature and character of the deposits can be made. On-delta lithofacies include channel deposits, flood basin sediments, levee deposits, and alluvial islands. Lithofacies commonly associated with the delta-front-platform environment include high- and low-energy beach deposits. Fine, laminated sediments typically characterize the pro-delta environment. The foreset sediments of the delta-slope environment are highly variable in grain size, reflecting seasonal and areal vicissitudes in distributary flow, proximity to the distributary mouth, and other factors. Facies on the delta slope thus include well- to poorly-sorted foreset beds of coarse to fine debris; slump structures may be common.

A Conceptual Model of Deltaic Sedimentation in a Widely Fluctuating Lake

There has been surprisingly little discussion of the complications to Gilbert's model that might result from significant fluctuations in the elevation of the lake surface. Gilbert himself recognized that the deltas of Lake Bonneville are composed of stream sediments deposited at three different lake levels (his Provo, Intermediate, and Bonneville stages), but he stopped short of a detailed analysis of the relationships between these different deposits, yielding to the "general confusion" of such an undertaking. Other workers have warned of the complicated onset and inset relationships that characterize deltas built into widely fluctuating lakes (Davis, 1982; Morrison, 1964), but a systematic treatment of these relationships is still wanting. Such a treatment is the intent of the paragraphs that follow.

The response to a drop in lake level: The "parent delta", "delta trench", and "subsidiary delta". Starting hypothetically with a Gilbert-type delta built into a previously non-fluctuating lake, it is apparent that a drop in lake level will instigate incision of the delta plain. During the initial stages of the lake regression many or all of the distributaries may incise. Quickly, however,

streamflow is abstracted by a dominant distributary. Incision thus becomes concentrated along a single stream, which cuts a defile, here called a "delta trench". With streamflow now confined to the delta trench, the delta plain is said to be "abandoned".

At lakes like Mono, which are characterized by marked intra- and interannual variability in inflow and evaporation, the decline in surface elevation will proceed at a variable rate, with periods of relatively rapid recession alternating with stillstands or short-lived rises. The stream responds to each drop in base level by deepening the delta trench, and to each rise or pause by cutting laterally, thereby widening the trench floor. The delta trench thus evolves in stages, each stage marked by an erosional stream terrace, and each terrace graded to a lower level of the falling lake.

As long as the stream is incised deeply enough to prevent the spread of fluvial debris onto the abandoned delta plain, deposition on the plain surface is limited to aeolian and perhaps paludal sediments. Vegetation may establish itself on the abandoned plain, leading to the development of an organic-rich soil horizon, and on the banks, terraces, and floor of the delta trench as well, forming a riparian woodland.

Sediment transported by the stream during and after incision of the delta is deposited in the lake at the mouth

of the trench, where it accumulates as foreset and bottomset beds. Continued deposition leads to progradation of the incised stream channel, instigating construction of topset beds, as described above. A new Gilbert-type delta graded to the lower lake level thus forms adjacent to the distal margin of the old, incised delta. The incised feature is here called the "parent delta", while the younger form is designated the "subsidiary delta".

The subsidiary delta undergoes a multistaged evolution similar, and closely linked, to that of the delta trench. The initial episode of incision of the parent delta generates a flush of sediment, redeposition of which forms the initial stage of the subsidiary delta. Any ensuing drop in base level not only instigates renewed downcutting of the delta trench, but also strands, and forces incision of, this seminal subsidiary feature. The newly eroded sediment comes to rest adjacent to the distal margin of the stage-one subsidiary delta, giving rise to a second-stage subsidiary delta. This process continues through numerous stages as the lake staggers to lower elevation.

The subsidiary delta thus grows lakeward in a descending series of steps, each succeeding step continuous with a lower terrace of the delta trench. The analogy of an arcuate staircase protruding from the front of the parent delta suggests itself; this ideal form is seldom realized,

however, since the stranded "steps" from early stages of subsidiary deltification are readily removed by incision and lateral stream erosion during later stages. At any given moment during the lake regression, then, the subsidiary delta will consist of an active stage, with small remnants of stranded subsidiary deltas from earlier stages perhaps persisting along its lateral fringes.

Examples of subsidiary deltas and delta trenches can be found today on all the major tributary streams of Mono Lake. Photos 6a, b, and c show various views of the Rush Creek delta. Note there that a deep trench bisects the parent delta to depths of up to 10 m. The great bulk of this incision occurred in just three years--1967, 1969, and 1980. In the first of those years the lake stood at 6390 feet; the stream thus incised to that elevation, depositing the excavated debris at the mouth of the trench to form a stage-1 subsidiary delta. By 1980 the lake surface had declined to 6374 feet. The release of massive amounts of water by the DWP in that year instigated further downcutting. This incision stranded the trench floor of 1967-69, creating a trench terrace; it also stranded the stage-1 subsidiary delta, and prompted the deposition of a stage-2 subsidiary delta. The trenches and subsidiary deltas on Lee Vining and Mill Creeks will be discussed subsequently.

<u>The response to a rise in lake level: transgressional</u>

sedimentary sequences: the "inset", "onset", and "confined-onset" deltas. Suppose now that the lake rises from the hypothetical low stand described above, ultimately attaining a level high enough to submerge the unconfined portion of the parent delta and drown the lower reaches of the trunk-stream canyon. The rising lake first inundates the subsidiary delta. There, on the gently inclined subsidiary-delta plain, lake waves and littoral currents rework the topset sediments. Coarse alluvium transported to the edge of the rising lake by way of the delta trench no longer falls off the distal margin of the subsidiary delta into deep water. Instead, the debris comes to rest on the surface of the newly inundated plain, where waves and littoral currents may stack it into shoreline embankments.

Deepening water gradually brings an end to wave activity on the plain of the subsidiary delta, and permits only progressively finer stream sediment to reach the newly-submerged surface. The lake transgression thus produces an upwardly-fining sequence of sediments--from high-energy beach debris, to shallow-water sands, to silts of deeper water--on the inundated plain of the subsidiary delta.

The rising lake next engulfs the delta trench, forming an elongate embayment protected from vigorous waves and shoreline currents. Bay-mouth bars composed of sediment eroded from the front of the parent delta may be deposited

across the mouth of the embayment, further isolating the ria from the open water of the lake. Stream sediment reaching the floor of the newly-flooded trench grows finer as the lake attains greater depth. In the trench, then, as on the plain of the subsidiary delta, the lake transgression produces a sequence of sediments that fines upwards--from riverine cobbles and gravels, to sand, and finally to silt. Illustrations of the early stages in the drowning of the delta trench on Rush Creek are shown on Photos 7a and b.

The character of the transgressive sequence of sediments on the surface of the subsidiary delta and on the floor of the delta trench is related to the nature of the lake transgression: If the lake rises steadily (an unlikely senario at a lake that experiences seasonal and annual variations in inflow and evaporation), the result is a simple, upwardly-fining progression of sediments. If the lake rise is punctuated with pauses and minor declines, the product will be an interfingered succession of coarse and fine debris that, overall, grades into sands or silts.

Eventually the transgressing lake overtops the plain of the parent delta, flooding and killing the incumbent vegetation. Waves and shoreline currents rework any loose, unbound sediment, as the zone of littoral agitation moves to higher and higher levels on the parent-delta plain.

Deposition of sediment on the plain of the parent delta

during the early stages of inundation is meager, since the main source of debris--the stream itself--remains confined to the delta trench. Coarse alluvium continues to be dumped into the trench at the head of the embayment, and is thus prevented from reaching the plain of the parent delta. Only very fine stream-borne sediment may find its way onto the inundated plain. Transport and deposition of this fine debris at hypersaline lakes is made possible by the hypopycnal stratification that occurs as the fresh water of the stream flows outward over the heavy, saline water of the embayment. A portion of the fine stream sediment remains entrained in the surface current, and thus escapes the confines of the drowned trench. As the stratum of fresh water, with its suspended sediment, debouches from the trench, it spreads laterally over the lake surface. The sediment settles out through the relatively still water of the lake, a portion of it coming to rest on the plain of the parent delta.

In like manner and for similar reasons, the surfaces of highstanding trench terraces are also deprived of coarse stream sediment during a rise in lake level. Thus, by the time the shoreline has overtopped a given point on the surface of a highstanding terrace surface, the junction of the stream and the lake--and, correspondingly, the point of deposition for all but the finest fraction of the stream

load--has migrated far uptrench. Only fine detritus entrained in the hypopycnal stratum of stream water can find its way onto the terrace surface. A distinction, then, must be made between a lake-transgressive deposit of the trench *floor*, which typically fines upward through an interfingered sequence of coarse and fine debris, and a lake-transgressive deposit of a trench *terrace*, which consists of very fine sediment that unconformably overlies stream cobbles and gravels. Only after sediment fills the trench to the level of a terrace do deposits of the trench floor and the trench terrace become essentially one and the same.

Lake-transgressive deposits of the delta trench are also peculiar in that they may include large quantities of plant detritus--the remains of riparian vegetation killed by the rise in lake level. Here again a distinction must be made between the nature of this organic deposit as it occurs on the trench floor, and its character on the trench terraces. On the high-energy environment of the trench floor the plant remains are incorporated helter-sketer into a primarily-clastic stream deposit. In the still-water conditions that prevail on inundated surfaces of trench terraces, in contrast, remains of the dead vegetation may collect as a thick (from 3 to 12 cm thick on Mill and Lee Vining creeks), fibrous mat that includes only small amounts of clastic sediment.

As long as the stream occupies the delta trench, the trench acts as a trap for all but the finest stream sediment. A continued rise in lake level, or a prolonged period of relative lake stability, however, may allow the stream to fill the trench with sediment and aggrade onto the plain of the parent delta. Should this occur, the entire stream load can be dispersed onto the delta plain. Coarse sediment comes to rest on the gently-sloping plain near the stream mouth, where waves and littoral currents may sweep it into shoreline embankments. The finer detritus moves farther lakeward, onto or beyond the submerged delta plain.

With the stream no longer confined to the delta trench, the ongoing rise in lake level affects sedimentation on the upper reaches of the parent-delta plain much as it did on the plain of the subsidiary delta. Deepening water thus permits only progessively finer debris to be deposited at any one point. The result is a succession of sediments that fines vertically upward.

Under the ideal conditions described above, then, a lake transgression can be expected to produce an upwardly-fining sequence of sediments on the subsidiary delta, on the floor of the delta trench, and, if the stream aggrades out of the delta trench, on the upper reaches of the parent-delta plain. The transgressional progression of sediments deposited on the lower reaches of the parent-delta plain and on highstanding

trench terrraces, on the other hand, is marked by an abrupt change--from vegetated topset sediments, to silts brought to the newly-inundated surface by hypopycnal stream flow.

It is likely that minor stream progradation (i.e. deltaic sedimentation) will occur periodically during a lake transgression. Three distinctive ancillary deltaic forms result: When progradation occurs while the stream still occupies the delta trench the product is an "inset delta", so called because of its relationship to the parent delta. Lateral development of the inset delta is restricted by the walls of the trench; it therefore never assumes the broad, arcuate form, nor does it develop the widely branching system of distributaries, typical of Gilbert's normal delta. A single lake transgression may produce an entire flight of these ancillary features in the delta trench, each individual inset delta marking the approximate elevation of the lake surface at a time of high sediment delivery--a time most likely coincident with an annual peak in stream inflow. When short-term sediment yield is high, or when the lake stabilizes, allowing deltaic sedimentation to proceed at one elevation for a prolonged period of time, an inset delta may prograde substantially. It is at these times that the stream is most likely to fill a portion of the delta trench with sediment and prograde onto the plain of the parent delta. An inset delta that formed within the delta trench on Rush Creek

in 1982-84 is shown on Photo 7a.

If, during a lake transgression or stillstand, stream progradation occurs on the surface of the parent-delta plain, the result is an "onset delta". Unconstrained by trench walls, the onset delta, under ideal conditions, assumes a broad, arcuate form that crowns the plain of the parent delta. Streamflow is spread over the surface of the prograding onset delta among a network of distributaries. This ideal form is seldom attained, however; unlike the inset delta, which forms in an environment protected from waves and shoreline currents, the onset delta may be modified--in most cases even prevented from forming--by waves and littoral currents.

Should the lake rise high enough to submerge the entire plain of the unconfined parent delta and flood a portion of the trunk-stream canyon, stream progradation might occur on the confined portion of the parent delta. Under these circumstances the stream produces a "confined-onset delta"--simply, an onset delta built within the confines of the trunk stream canyon. The confined-onset delta is identical in form to the inset delta; only their positions relative to the parent delta distinguish the two features. Built as it is within the slackwater environment of the trunk stream canyon, the confined-onset delta is a relatively persistant feature, protected from modification or

destruction by waves and littoral currents. A confined-onset delta is shown on Photo 6a.

The response to a second lake recession: regressive sedimentary sequences. Imagine now that the lake withdraws from the trunk-stream canyon and returns to a level approximating that of the low stand described above. Retreat of the lake forces the stream to incise the confined-onset delta, creating erosional terraces that extend some distance up the trunk stream canyon. If the confined-onset delta lies only a short distance up the canyon the debris excavated during its incision is washed out onto the unconfined plain of the parent delta, where it is dispersed by waves and longshore currents. If the confined-onset delta lies far up the canyon, on the other hand, the product of its incision may accumulate in the lower reaches of the cut as one or more fills that become terraced with continued stream incision. Examples of such "inset regressive fill terraces" can be found on all the major streams at Mono Lake (see pg. 297).

Presently, the declining lake margin reoccupies the plain of the parent delta. The course that the stream follows as the lake recedes across the plain is contingent on the presence or absence of a delta trench. If the trench produced during the previous lowstand remains unfilled during the lake recession, the stream is likely to reoccupy the existing defile. In such a case the drop in lake level may

bring about reexcavation of the old delta trench and reoccupation of the old subsidiary delta. If the trench has been filled with sediment, on the other hand, the stream assumes a course across the surface of the delta plain. When the lake falls below the brink of the plain, the stream cuts a new delta trench and deposits a new subsidiary delta.

Examples of both cases can be seen at Mono Lake. It will be demonstrated that on both Lee Vining and Mill creeks, the present-day delta trench occupies virtually the same position that it did during other late Holocene low stands. On the Rush Creek delta, in contrast, the stream followed a course roughly 1 km west of its present-day path until shortly after 600 years ago (see discussion, pg. 265). Remnants of the paleo-trench and the paleo-subsidiary delta from this time are pictured on Photo 6a.

Because the stream is prone to incise during a lake recession, and is therefore typically laden with detritus, channel progradation (i.e. deltaic sedimentation) may occur often as the lake recedes from its high stand. Thus, onset deltas and confined-onset deltas, (and, if the stream reoccupies a delta trench, inset deltas) will likely form in the course of the lake recession. A drop in lake level may bring about the deposition of a chain of these ancillary forms, each one composed in part of sediment derived from the incision of its antecedents.

Whether or not it results in actual stream progradation, deposition of alluvium at the margin of the shrinking lake effectively raises the elevation and flattens the gradient of the channel bottom immediately lakeward of the stream mouth. Ongoing recession, then, continually exposes a fresh deposit through which the stream must cut. In this way the stream becomes "locked" in its own deposits during a lake regression. As long as the lake continues to recede toward the brink of the parent delta plain, then, bifurcation of the stream into a widely-branching system of distributaries is prevented.

Deposition of coarse fluvial debris on the delta during the lake recession is thus confined to the general vicinity of a single trunk stream. This area of fluvial activity is designated the "active" portion of the delta. While alluvium may reach other areas of the delta surface through the agency of littoral currents, these areas are not undergoing deltaic sedimentation, and therefore are considered the "passive" portions of the delta. A cross section through an idealized lake-regressive sequence of sediments on the active portion of the delta would reveal an upward coarsening of debris--from fine lacustrine detritus, to riverine sands and gravels, and finally to coarse alluvium; a similarly ideal section through the passive portion would display lacustrine sediments coarsening upward into littoral detritus.

The Endoreic Delta-Complex

As time progresses the delta becomes a complex of principle (i.e. parent) and ancillary (e.g. onset, inset, subsidiary, and confined-onset) components, reflecting multiple cycles of lake rise and fall. The sum of these components is here called an "endoreic delta complex". If used without a qualifying adjective, this phrase is intended to include all components of a delta, regardless of age. In some instances it may be desirable to restrict discussion to a particular portion of the endoreic delta-complex. In such cases it will be necessary to apply an appropriate adjective (e.g. a "Holocene endoreic delta-complex").

A Conceptual Model of Deltaic Sedimentation in a Widely Fluctuating Lake--Summary and Conclusions

The model outlined above seeks to describe in general terms the basic geomorphic forms and the sedimentary structures and sequences that characterize Gilbert-type deltas built into widely fluctuating saline lakes. It identifies different ancillary deltaic features, and names them on the basis of their relationship to the primary component--the so-called "parent delta". These ancillary components include the following:

--The *delta trench* is a channel incised into the parent delta by the trunk stream. It is produced in response to a drop in lake level to below the elevation of the parent-delta plain. Since it forms in stages as the lake seasonally staggers to lower elevations, its banks may be lined with erosional "trench terraces", each individual terrace graded to a lower level of the lake. Until it refills with sediment, the delta trench profoundly influences stream deposition, acting as a catchment for all but the finest alluvium, and thus preventing the spread of coarse sediment onto the plain of the parent delta.

--*The subsidiary delta* abuts the front of the parent delta at the mouth of the delta trench. It is composed in large part of debris excavated during the cutting of the trench. Like the delta trench, it forms in stages, each successive stage continuous with a lower trench-terrace.

As a practical matter, an individual delta can be both parent and subsidiary. At Mono Lake, for instance, the Holocene deltas on Rush, Mill, and Lee Vining creeks are at the same time the subsidiaries of the larger, higher, late Pleistocene deltas, and the parents of the lower, smaller, presently-active subsidiary deltas.

--The *inset delta* forms within the confines of the delta trench. During times of lake stability and/or high stream discharge, an inset delta may prograde out of the

trench to form an onset delta (see below).

--The *onset delta* forms on the plain of the parent delta during a lake transgression or stillstand. It is characterized by a widely-branching system of distributaries. Unlike the ancillary deltaic features deposited within the confines of the delta trench and the trunk stream canyon, the onset delta is subject to modification, and even obliteration, by littoral processes.

--The *confined-onset delta* is a feature of the trunk stream canyon. Like the inset delta, it is protected from waves and shoreline currents, and is therefore a relatively persistent feature.

--The *inset regressive fill terrace* forms in the canyon of the trunk stream as the lake retreats from a confined-onset delta. It is composed of alluvium excavated by the incising stream during the recession.

In discussing inset, onset, and confined-onset deltas, the term "delta" is used advisedly. Because each of these features is built onto a gently sloping surface, it must prograde for some distance before developing a steep front against which foreset beds may accumulate. The lake surface may not spend sufficient time at one elevation for this to occur. A tripartite structure--the diagnostic trait of a Gilbert-type delta--then, is not necessarily a characteristic of the onset, inset, or confined-onset deltas; it can,

however, be taken as a sign of prolonged development of each of these features.

The model invokes a hypothetical sequence of lake recessions and transgressions to describe the evolution of an idealized "endoreic delta-complex". Variations in the rate, timing, magnitude and progression of actual lake level fluctuations will bring about deviations from the stated pattern of delta evolution.[5] Tremendous variety in the degree of development of, and the interrelationships between, the different geomorphic and sedimentary components of an endoreic delta-complex is thus to be expected. This variety is made evident in the following description of the Holocene endoreic delta-complexes on Rush, Mill and Lee Vining creeks.

Geomorphology of the Mono Lake Deltas

Introduction. Throughout Late Pleistocene (Wilson Creek) time, when Lake Russell stood many hundreds of feet higher than the lake surface of today, glaciofluvial sediments accumulated at the mouths of the major tributary streams, forming massive deltas up to thousands of hectares in extent. The advent of relatively xeric climatic conditions some 12,000 years ago forced a rapid recession of the lake. In response to the drop in base level the tributary streams incised these highstanding deltas, redepositing the alluvium at the receding shoreline as a

descending flight of subsidiary deltas. Several of the early-stage subsidiary features persist today on Rush, Mill, and Lee Vining creeks. All three streams display subsidiary deltas graded to lake elevations of approximately 6685 feet, 6580 feet, and 6505 feet; both Lee Vining and Mill Creeks show an additional early-stage subsidiary delta graded to a lake elevation of about 6615 feet. Erosional stream terraces associated with each of these subsidiary deposits line the walls of the early Holocene delta trenches, further marking pauses in the lake recession of early Holocene time[6] (Photos 6a, 8a and b, and 9a).

Trenching of the late Pleistocene deltas on Rush, Mill, and Lee Vining creeks culminated in the deposition of the prominent Holocene deltas that protrude into Mono Lake today (Figure 2). These "Mono Lake deltas"[7] are subsidiary features with respect to their late Pleistocene (Lake Russell) antecedents. Because they have been the foci of deltaic sedimentation in Holocene time, however, they are properly considered the parent deltas of Mono Lake.

Since their deposition perhaps 10,000 years ago the parent deltas of Mono Lake have undergone repeated episodes of trenching and inundation. Deltaic landforms that might be used to illuminate the lake fluctuations of early and middle Holocene time have been either buried, or destroyed by

erosion. Only those features of the past 4000 years are accessible today.

The Holocene endoreic delta complex of Rush Creek. The unconfined portion of the Holocene parent delta on Rush Creek forms a roughly arcuate deposit of approximately 110 ha that radiates northward from an ill-defined apex at an elevation of around 6450 feet (see index map, Plate 2). The parent delta-plain descends lakeward at an average gradient of about 1%. At an elevation of approximately 6400 feet the delta plain gives way to the relatively steeply sloping (~15-20%) delta front.

While the Holocene parent deltas on Lee Vining and Mill creeks are composed almost exclusively of alluvium derived from the Sierra Nevada, the Rush Creek delta contains substantial amounts of detritus eroded from pyroclastic deposits ejected from the Mono Craters. Particularly during the past 600 years, Rush Creek has carried large amounts of light, easily erodible pumice sand, cobbles, and boulders to its delta, accounting for a sedimentation rate many times that seen on Mill and Lee Vining creeks.

The major ancillary features of this delta--the largest of the Mono Lake deltas--were described and illustrated above in the discussion of deltaic sedimentation. These include a delta trench with trench terraces, a subsidiary delta, an inset delta, and a confined-onset delta, as well as a

paleo-subsidiary delta and a paleo-trench. In addition to these major ancillary forms are several minor features that can be related to the lake fluctuations of historic time. The highest of these minor features is an onset delta that lies at an elevation of approximately 6426 feet. This small delta, which has been largely destroyed by stream planation and incision, was deposited during the five-year period of relative lake stability immediately following 1919, the year of the Historic High Stand.

The decade of rapidly declining lake levels that began in 1925 coincided with (indeed, was brought about by) a period of low discharge on all the tributary streams. The small quantity of alluvium deposited at the mouth of Rush Creek during this period was overwhelmed by longshore currents. The lake recession of the 1920s and '30s is thus marked only by small littoral embankments on the Rush Creek delta.[8]

The high stream flows of 1938 forced a rise in lake level sufficient to obliterate the shoreline embankments deposited during the previous six years. For the next decade streamflow remained substantial, stablizing the lake and permitting alluvium to accumulate at an elevation of approximately 6417 feet. This debris persists today as a prominent embankment on the plain of the Rush Creek delta.

Between 1948 and 1966 the Los Angeles Department of Water and Power diverted virtually the entire flow of Rush Creek in all but two years--1952 (lake elevation = 6408 feet) and 1958 (lake elevation = 6402 feet). On both occasions deposition of alluvium at the mouth of the stream resulted in the construction of onset deltas. Remnants of these onset deltas persist today despite littoral and fluvial modification. The continued drop in lake level, coupled with the releases of water in 1967, 1969, and 1980, instigated the cutting of the delta trench and the deposition of the subsidiary delta, as described above and illustrated on Photos 6a-c.

Stratigraphy of the Holocene delta on Rush Creek is illustrated on Plate 2 and discussed in Chapters 3 and 4.

The Holocene endoreic delta-complex on Lee Vining Creek. The unconfined parent delta on Lee Vining Creek (see index map, Plate 3) covers approximately 70 ha. Except for its smaller size, and the absence of alluvium derived from the Mono Craters, the Lee Vining Creek delta is similar to its counterpart on Rush Creek. Its plain slopes gently (~2.5%) lakeward, dropping off to the steeper delta front (~15% gradient) at an elevation of around 6398 feet. The history of flow along Lee Vining Creek since 1919 is similar to that of Rush Creek. The elevations of bars and onset deltas deposited on Lee Vining Creek since 1919 are therefore

analagous to those on the Rush Creek delta.

Like the Holocene Rush Creek delta, the Lee Vining delta is bisected by a trench that was carved in 1967, 1969, and 1980, as Mono Lake declined due to water diversions. This trench, the trench terrace of 1967-69, and the active and abandoned late Holocene subsidiary deltas of Lee Vining Creek are shown on Photo 8c.

In addition to these historic ancillary deltaic features on Lee Vining Creek are two pre-historic confined-onset deltas and associated fill-terraces. The lowest of these features was deposited when the lake stood at an elevation of 6456 feet; the higher one is graded to a lake surface of 6499 feet. The importance of these features in constructing a prehistoric lake fluctuation curve is discussed subsequently.

Plate 3 illustrates the stratigraphy of various sections exposed along the walls of the delta trench on Lee Vining Creek. These sections are discussed in Chapters 4 and 5.

The Holocene endoreic delta complex of Mill Creek. The smallest of the Gilbert-type deltas of Mono Lake lies at the mouth of Mill Creek (Photos 9a and b; see also index map, Plate 4). The plain of this fan-shaped deposit slopes lakeward at a gradient of approximately 2.5%. At an elevation of 6390 feet the gradient increases abruptly to

around 8%.

The nature and history of the major ancillary features associated with this ~50 ha delta are similar to those on Rush and Lee Vining creeks, though, unlike the these larger features, the Mill Creek delta is cut by two trenches. The easternmost of these is considered the "normal" channel of the stream; the western trench represents the avulsion channel that was cut in 1969, when high flows backed up behind the culvert at the "Cemetery Road" crossing, forcing the stream to hop its banks. The same sequence of events led to the reoccupation of the avulsion channel in 1980 and 1986. Photos 9a and b illustrate the delta trench that was cut during those years, and the subsidiary delta that formed at the mouth of the trench.

As on the other streams, a sequence of lake-recessional berms and onset deltas on Mill Creek records the decline in lake level from the Historic High Stand. These features are more numerous on the Mill Creek delta than on the other streams, however, owing to the fact that water has flowed down Mill Creek in virtually every year since 1919.[9]

The stratigraphy exposed in the Mill Creek delta trenches is illustrated on Plate 4 and discussed in Chapters

4 and 5.

B. LITTORAL AND LAKE BOTTOM SEDIMENTATION

Introduction

Away from the deltas, along open stretches of the late Holocene shorelands, sedimentation during the past 4000 years has been dominated alternately by longshore and deep-water processes. Sequences of littoral and lacustrine sediments encountered in dozens of shallow excavations and in one 10-meter core have been used to corroborate, and in some cases clarify, the lake level fluctuations inferred from other lines of evidence. The nature of littoral and lacustrine sediments at Mono Lake, the processes that lead to their deposition, and the use of alternating sequences of these sediments in constructing a lake level curve, are the subjects of this section.

Lake-Bottom Sedimentation at Mono Lake

During latest Pleistocene time, when tongues of ice last filled the canyons of the Mono Sierra, lake bottom sedimentation at pluvial Mono Lake (Lake Russell) was dominated by glacio-lacustrine processes. Cold, proglacial streams carried outwash to the lake margin. There, each stream dropped the coarse fraction of its load, then flowed on along the lake bottom as a silt-laden hyperpycnal current.

The glacial silt accumulated on the floor of Lake Russell to a thickness of between 20 and 50 feet, forming the Wilson Creek Formation of Lajoie (1968).

The climatic amelioration of early Holocene time brought significant changes in the mode of lacustrine deposition at Mono Lake. Warmer temperatures wasted the Sierran glaciers, thus eliminating the major supply of silt to the lake's tributary streams, and forced a drop in lake level, concentrating the lake salts into an increasingly bitter brine. The demise of the glaciers and the shrinkage of the lake combined to reverse the fluid densities that had permitted the hyperpycnal dispersion of silt along the lake floor. Since early Holocene time, when the surface of Mono Lake neared elevations approximating those of the historic period, the tributary streams have entered the lake as hypopycnal (surface) currents, dumping their now-meager loads of silt in close proximity to the stream mouth. By perhaps 10,000 years ago, glacial silt was no longer an important component of lake-bottom deposition at Mono Lake.

With the onset of Holocene hydroclimatic conditions, a highly flocculated, biogenic ooze became the dominant deposit of the deep-lake floor. Microscopic examination of this biogenic mud, or seston, shows the frustules of diatoms to be abundant. No taxonomic work was conducted on the diatoms that compose these profundal muds, though Lovejoy and Dana

(1976) have listed the species that currently inhabit the lake.[10]

The Holocene bottom mud is typically black to olive-green when unoxidized. It oxidizes rapidly to light grey or white. Temporal as well as small-scale spatial factors apparently influence bedding, since in some areas of the lake the mud may be laminated while a contemporary deposit not far away appears massive. Where present, the laminations sometimes suggest varving, though the "varves", if real, are not continuous enough either spatially or temporally to be of use in dating the fluctuations in lake level inferred here.

The profundal muds that have accumulated during Holocene time are composed primarily of clay. Coarser sediments, however, have found their way onto the lake floor. These sediments are of four types:

1) *Tephra deposits from eruptions of the Mono Craters and the Mono islands.* On numerous occasions during late Holocene time volcanic eruptions have spread tephra onto the lake floor. This material ranges in size from silty ash to blocks with dimensions measured in meters. Tephra units encountered in late Holocene sediments are discussed in greater detail in Section E of this chapter.

2) *Deposits of sand and gravel that result from avalanches and debris flows down canyons tributary to the*

lake. During torrential rain storms in the Mono Sierra, debris flows move down the steep canyons of the intermittent streams tributary to Mono Lake's Western Embayment. Sediment mobilized during these events typically accumulates as an alluvial fan at the mouth of each canyon.

These course sediments occasionally reach the lake margin, then flow into deeper water as a turbidity current. Such sediment may reach the lake bottom more readily during times of high lake levels, wnen the shore impinges on the canyon mouths or the attendant fans, than when the lake is low and far from the source of debris. The resulting deposits take the form of clayey sands, sandy clays, or gravels and sands, in otherwise-clayey deposits of the lake bottom. In this same manner sediment carried from the Sierran escarpment by snow avalances might make its way into the deep water of the lake.

3) *Granitic and metamorphic boulders deposited by rockfalls off the Sierran escarpment*. Boulders of Sierran origin dot the shorelands of the Western Embayment, and are occasionally encountered in excavations along this shore. These clasts owe their existence to rockfalls off the steep eastern escarpment of the Sierra Nevada.

4) *Silts deposited by winds during times of low lake levels*. During periods of atmospheric turbulance, large plumes of deflated silts are carried over and deposited into

the lake. These dust storms are undoubtedly most common at times of low lake levels, when lake-bottom sediments are exposed and subject to wind erosion. Wind-blown silts may find their way into deep water of the lake.

5) *Gravels and sands deposited in shallow water by littoral processes.* Waves and longshore currents instigated by winds transport drift along the littoral zone of Mono Lake. These shallow-lake deposits are the subject of the paragraphs that follow.

Littoral Sedimentation at Late Holocene Mono Lake

Longshore currents. The winds of the Mono Basin propel longshore currents that entrain sediment and distribute it along the lake margin as embankments and sheets of littoral drift. The distribution and provenence of drift, together with information obtained from aerial photographs, were used to trace the direction of prevailing currents around the shores of Mono Lake. Major features of the current system, as discussed below, are illustrated on Figure 14.

Perhaps the most easily traceable of the prevailing littoral currents occurs along the lake's sweeping northern shore. There, berms and spits composed primarily of cinder eroded from the flanks of Black Point can be traced eastward from the cone for up to 10 km, attesting to the clockwise movement of littoral waters in this section of the lake.

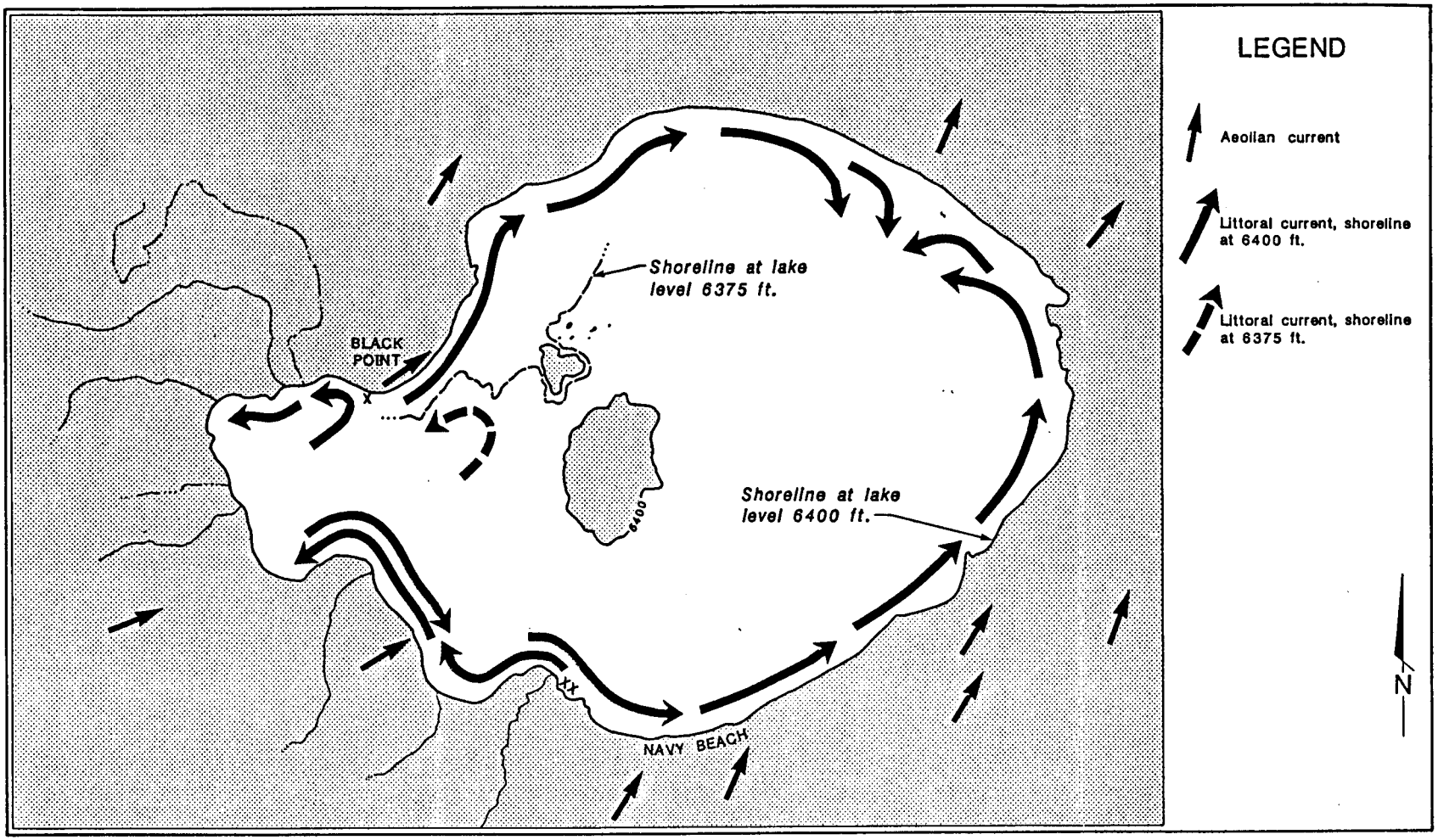


Figure 14. Prevailing littoral and aeolian currents of the Mono Basin.

On the southern margin of Black Point is a pronounced inflection in the shoreline (labeled "x" on Figure 14) that represents a point of diverging littoral flow. East of this point the currents move in the manner described above. To the west of point "x" a counterclockwise backset eddy, apparently induced by onshore flow of wind against the steep southwestern flank of the volcano, has built small embankments of basaltic cinder that can be followed westward into the Western Embayment. This backset eddy, illustrated on Photos 10a and b, may disappear when a drop in lake level causes the shoreline to withdraw some critical distance from the flank of Black Point.

A similar backset eddy forms off the southeastern shore of Black Point when the lake surface drops below an elevation of approximately 6390 feet. At this level portions of the "Negit landbridge" begin to project above the lake surface, inducing the eddy by deflecting the usual northeastward flow of surface waters.

Prominent berms and bars composed of riverine detritus reworked from Rush Creek, and of pumice sand eroded from the bulky deposit of Mono Craters tephra just east of that stream (point "xx" on Fig. 14) project westward into the Horse Creek Embayment. These same clockwise currents transport riverine cobbles, gravels and sand from Lee Vining Creek into the Western Embayment--an area of generally feeble longshore

flow.

Along the southeastern margin of the lake the prevailing currents flow counterclockwise, carrying rhyolitic pumice sand and gravel eroded from deposits of Mono Craters tephra. Bars and berms of this pumiceous drift extend north and eastward from Navy Beach for a distance of over 15 km.

A swift current sweeps from southwest to northeast through the Negit-Paoha straits. This current is strong enough to build berms of volcanic boulders and cobbles on the northern end of the larger island.

The longshore currents of Mono Lake, like the winds that stir them, are variable. Evidence of occasional reversals in current direction are found in many areas. Subdued bars and berms composed of riverine sediment can be traced a short distance southward from both Lee Vining and Rush creeks, for instance, indicating the existence of an occasional counterclockwise current in this region of the lake.

Sources of longshore drift. In addition to the major sources of littoral drift previously mentioned (i.e. Black Point, the major tributary streams, and the prominent deposits of Mono Craters tephra) are several minor sources. These include the intermittent tributary streams that drain the andesitic Bodie Hills, and deposits of unconsolidated sediments against which the lake margin occasionally impinges (e.g. cliffs of Wilson Creek Formation along the eastern

shorelands). Many of these sources of littoral drift, like several of the littoral currents discussed above, are affected by changes in lake level. A rise or fall in surface elevation may increase the supply of sediment to currents along one shore while decreasing it elsewhere. When the surface of the lake declines to below 6401 feet, for example, the regressing shoreline loses contact with the flanks of Black Point, cutting off the supply of basaltic cinder to the current system. When the surface elevation of the lake exceeds approximately 6435 feet the shoreline takes a sharp northerly bend just east of Black Point, creating an embayment (the Dechambeau Ranch Embayment--see Figure 2) that is bypassed by littoral currents. Beach deposits of Black Point cinder along the northern shore are thus restricted to a well-defined band that lies between elevations of 6401 and about 6435 feet (Photos 11a and b). At lake elevations above and below this band of cinder, the littoral drift along the northern shore is composed primarily of andesitic sand transported to the lake margin from the Bodie Hills by Rancheria, Bridgeport, and Cottonwood creeks.

The amount of sediment delivered to littoral currents by the major tributary streams is also a function of lake level. As long as the lake margin occupies the gently sloping plains of the (untrenched) parent deltas, as it does between

elevations of roughly 6400 and 6450 feet, littoral currents can rework newly deposited stream sediment and transport it to distant points around the lakeshore. If the lake rises above the plain of the parent delta, or drops below it, the supply of stream sediment to the system of longshore currents is effectively eliminated. In the former instance the stream load accumulates in the canyon of the trunk stream, away from the direct influence of littoral processes; in the case of a lake drop, the great bulk of the stream sediment falls off the distal margin of the parent delta into deep water, beyond the reach of waves and currents. While a drop in lake level to below the surface of the delta plain deprives the currents of freshly-deposited stream sediment, it allows the lake margin to impinge on and erode the steep delta-front, thus establishing a new source of littoral drift.

Depth of littoral deposition. On numerous occasions during the summers of 1980 and 1981 it was possible to estimate the depth to which littoral sands were deposited. These measurements were taken immediately after windstorms severe enough to stir whitecaps on the surface of the lake. At the time of each measurement the lake was known to be lower than it had been for at least 130 years, thus assuring that the littoral deposits found in shallow water along the lake shore were thoroughly modern. Fine sand was typically found to a depth of less than one meter, though in one

instance it could be found to a depth of approximately 1.3 meters. Littoral sand might find its way into deeper water during times of very severe winds; as a rough estimate, then, the maximum depth of sand deposition by littoral currents at Mono Lake is taken to be approximately 1.5 meters. Silt transported by littoral currents and as airborne plumes during wind storms may find its way into deeper water.

Significance of algal mats and oolitic sands. In stream cuts, as well as in pits excavated along the western and southwestern shores of the lake, it is common to encounter shallow-water deposits of algal sapropel. These orange-to-brown algal mats typically contain friable, carbonaceous oolitic sand that is easily crushed between the incisors. The sapropel and ooid layers are taken to indicate shallow-water conditions (American Geological Institute, 1972). At Mono Lake the oolitic sands are invariably found either over- or underlying littoral sands; algal mats can be found in similar depositional environments, as well as in the silty lagoonal deposits that accumulate behind (landward of) barrier bars.

Alternating Sequences Of Littoral And Lake-Bottom Sediments And Their Bearing On The Lake Level Curve

During a drop in lake level the regressing shoreline

spreads littoral drift over muds that formerly constituted the deep-lake floor. Subaerial exposure of these deposits due to continued drop in lake level brings about desiccation of the bottom muds and may, under favorable circumstances, permit colonization by vegetation, leading to the development of an organic-rich soil horizon. During the subsequent rise in lake level, waves and currents of the transgressing shoreline rework the beach deposits. Increasing depth of water over newly-inundated shorelands permits the deposition of progressively finer debris, creating an upwardly-fining sequence of sediments. At a lake depth of approximately five feet (see above) littoral deposition ceases and accumulation of biogenic ooze resumes. It is this depositional response to changes in lake level that makes sedimentary sequences of the shorelands a potentially valuable indicator of lake fluctuations.

Based on the cursory observations of the depth to which sand can be deposited by waves and littoral currents (see above), a layer of littoral sand lying between lake-bottom muds can tentatively be taken as evidence that the lake margin dropped to within five feet of the sand layer. (Care must be taken to assure that the sands were indeed deposited littorally, rather than as a turbidite that originated as an avalanche or a mudflow; other evidence of a littoral environment, e.g. oolitic sands, would provide such

assurance.) If the sands occurred in association with a humic horizon, or if they were found to overlie desiccated lake-bottom muds, it could be concluded that the lake margin fell below the elevation of the littoral sands.

It must be borne in mind that even under ideal conditions, with an unlimited number of excavations available, the range of depths (up to or beyond five feet) to which littoral sand can be deposited would make it impossible to relate a littoral deposit to a precise shoreline elevation. (Furthermore, constraints of time and impediments to digging--e.g. flooding of the pit due to the tapping of an aquifer, encountering boulders, etc.--commonly prevent the excavation of an "ideal" network of pits.) Sequences of shoreland sediments are nevertheless of tremendous importance in developing the Mono fluctuation curve. They provide a valuable check on lake fluctuations inferred from other lines of evidence, and in the absence of other information, may provide the best approximation of lake behavior. In the present study information gathered from shoreland pits was found to be in perfect agreement with conclusions drawn from other lines of evidence. Furthermore, the shoreland pits provide important clarification of lake fluctuations that occurred during the period from about 2000 to 1500 years ago--a span of time for which the deltaic sediments, geomorphic evidence, and vegetation evidence provide an

imperfect view.

Stratigraphy from research pits. Several dozen shallow (< 2.5-m deep) pits were excavated on the late Holocene shorelands. Six of these, selected on the basis of their clarity (e.g. relative lack of bioturbation), and the presence of units that can be used as a basis for correlation and chronometric control, are illustrated on Plate 5. Note that the surface elevation of most of the pits lies below 6390 feet. This is because land lying above this elevation has spent considerable time above lake level, allowing bioturbation to render the stratigraphic record indecipherable. The stratigraphy from each of these excavations is discussed in Chapters 3 and 4.

C. GEOMORPHOLOGY OF THE LATE HOLOCENE SHORELANDS

Erosional and depositional landforms that owe their existence to the action of waves and currents at or near the margin of Mono Lake can be used in association with other types of evidence to pinpoint the elevation of former high stands and low stands. A brief discussion of the nature and distribution of these geomorphic features is presented below.

The Nature and Distribution of Littoral Landforms at Mono Lake

Five interrelated factors are of overriding importance in controlling the nature and distribution of late Holocene littoral landforms at Mono Lake. These include the following:

Pre-existing topography of the lands adjacent to the shore. Because Mono Lake occupies a sediment-filled basin whose floor has been traversed many times by the zone of littoral agitation, the lands surrounding the lake are generally of low gradient and relief. Waves and currents acting on these gently inclined shorelands typically build a beach through deposition of littoral drift. The result is an embankment that takes the form of either a bar or a berm. Erosional landforms (i.e. clifflines and wave-cut terraces)

associated with the littoral zone are found only where the lake abuts steep relief. This occurs in the Western Embayment, where the lake margin contours the front of the Sierra Nevada; in the vicinity of Black Point and the northernmost Mono Craters, where the lake impinges on unconsolidated pyroclastic deposits; and where the lake laps against the fronts of deltas, the flanks of sand dunes, and up-faulted blocks of lacustrine sediments (e.g. near Simon's Springs).

The energy of littoral processes and the erodability of the lake-marginal substrate. These two factors work hand-in-hand to determine the degree of development of shoreline landforms around Mono Lake. In the Western Embayment, for instance, where the littoral zone is typically low-energy and the shorelands are composed of resistant bedrock, clifflines tend to be inconspicuous and poorly developed. In the vicinity of Simon's Springs, on the other hand, clifflines are prominent features, reflecting both the erodability of the lacustrine sediments that compose the lake-marginal substrate, and the relatively high energy of the littoral zone in that area.

The availability of longshore drift. The three factors discussed above play an important role in determining the availability of littoral drift, and thus greatly affect the degree of development of shoreline embankments. Along

stretches of lake shore where a large quantity of drift is available to the current system (e.g. downcurrent from Black Point--see discussion, pg. 131-134), embankments tend to be high and bulky. Portions of the lake margin that receive only a meager supply of drift (either because they lack of a drift source or because of the weakness of the currents) are characterized by puny bars and berms, or, in extreme cases, by an absence of embankments. The availability of littoral drift, as well as several of the other factors described above, are in turn directly affected by fluctuations in lake level.

Surface fluctuations of the lake. Fluctuations in lake level are of overriding importance in understanding the distribution and degree of development of shoreline landforms. The influence of lake fluctuations is fourfold: First, a change in surface elevation may force the lake to impinge on or recede from sources of detritus, thus "turning on" or "turning off" the supply of drift. Secondly, a rise or fall in lake level may result in a change in the configuration of the lake margin, creating or eliminating shoreline irregularities that act to impede the transport of littoral drift. Thirdly, the dynamics (i.e. the speed, magnitude, and sign) of the lake fluctuation influence the distribution and degree of development of depositional landforms. Thus, a lake margin that stands within a narrow

elevation interval for a prolonged period of time will deposit a larger embankment than a rapidly receding lake margin, all other factors remaining equal. A rising lake may deposit an even larger embankment, since, during a lake transgression, littoral drift is not only transported downcurrent, but upslope (landward) as well. The accumulation of littoral drift along the shore of a rising lake thus represents not only the debris transported by shoreline currents during a single season, as is the case along a stable lake margin, but also reworked littoral sediments carried upslope during the lake transgression. Finally, a lake surface that is either declining or holding stable against steeply inclined shorelands is capable of eroding only a narrow wave-cut platform. Width of the platform is limited because, as waves move across it toward shore, they expend their energy as frictional drag on its surface. Once the platform reaches some critical width, insufficient wave energy remains at shoreline to accomplish further erosion of the sea cliff, and widening of the platform ceases. When the lake rises against the steeply-inclined surface, on the other hand, waves lose contact with the abrasion platform and batter the cliff, causing its retreat. The waves of a rising lake thus create a relatively broad platform that, depending on the erodability of the substrate, may widen until the

transgression ceases.

Sand Dunes of the Late Holocene Shorelands

Thus far discussion of the geomorphology of the Mono shorelands has been restricted to landforms that are strictly littoral in origin. Closely related to these longshore features are dunes of sand and silt that owe their existence to a combination of littoral and aeolian processes.

Sand dunes have accumulated in a number of environmental settings on the late Holocene shorelands of Mono Lake (Figure 25). Several small dune fields emanate from "withering streams". These occur at and down-wind from the point where intermittent streamflow, disappearing into a permeable substrate, leaves behind a load of deflatable sediments. The largest dune field (approximately 200 ha) attributable to stream withering occurs on the southeastern shorelands, where Dry Creek seeps into the thick mantle of pumice that covers this portion of the basin floor. Less extensive dunefields of similar origin occur in association with the withering Cottonwood Creek, Kirkwood Spring, and "Kirkwood Creek" (draining Kirkwood Spring) on the northern shore, and with several unnamed streams southeast of the lake.

Minor accumulations of aeolian sand can also be found at the brinks of precipitous cliffs, where winds lose contact with the ground surface, instigating deposition of saltating

eluvium. Examples of "brink dunes" can be found along the windward (southwestern) lip of the false summit of Black Point (Lajoie, 1968), along the edge of the cliff at Simon's Springs, and along the eastern brink of the steep-sided Wilson Creek cut.

A third type of sand dune found on the late Holocene shorelands formed as a result of highly localized deflation of longshore drift. Dunes of this sort are typified just west of Bridgeport Creek at an elevation of approximately 6499 feet.

The largest dune field on the late Holocene shorelands of Mono Lake, and the one that bears most directly on the fluctuations in lake level, covers approximately 2400 ha on the northeastern shore. Here, littoral currents sweeping clockwise from the northwestern lake margin collide with counterclockwise currents of the opposite shore, instigating the deposition of sand and silt; this drift is blown into the dunes during times of lake recession. Lajoie (1968) speculated that this dune field accumulated during "Altithermal time"; it will be demonstrated, however, that it formed during the past 3500 years, and that it is composed of three generations of dunes, each of which owes its existence to a transgression and subsequent recession of the lake.

Topographic Profiles of the Late Holocene Shorelands

For purposes of illustrating the geomorphology of the late Holocene shorelands, topographic profiles were drawn along transects extending from 6365 feet (15 feet below present-day lake level) to 6520 feet. Horizontal control of the profiles is based on the 7.5 min. USGS topographic maps, and, at elevations below 6372 feet, on the bathymetry of Scholl and others (1967); elevations of depositional and erosional shoreline features were determined by ground survey using an engineer's level and rod. Maximum allowable closure error for these surveys was one foot. Five of the profiles, selected to represent the wide variety of topographic conditions encountered around the Mono shorelands, are shown on Plate 6. Each is discussed below.

Profile A traverses the northern shore of the lake near Ten-Mile Rd (Plate 6a). The shorelands in this vicinity are in many ways the simplest at Mono Lake, consisting of a gently sloping lake plain (~18/1000) of beach sand, upon which littoral embankments have been deposited, and into which two minor notches have been cut. Most of these features date from modern times, and can be explained in terms of the historic lake fluctuation curve. These historical features will be described first.

The most prominent depositional feature along Profile A is a 600 m-wide, multi-crested embankment of Black Point

cinder that rises from 6401.07 feet at its lakeward margin, to 6431.4 feet at its uppermost crest. Eight subsidiary crests associated with this embankment lie at elevations of 6428.9 feet, 6421.25 feet, 6420.5 feet, 6414.8 feet, 6412.0 feet, 6411.0 feet, 6409.2 feet, and 6402.5 feet. The embankment itself owes its existence to the redeposition of cinder eroded from the flanks of Black Point (see pg. 131-134). Its main crest formed as a storm berm at the time the lake reached its Historic High Stand, while the secondary crests are berms that coincide with subsequent stillstands of the lake (e.g. those that occurred in 1920-24, 1938-47, and 1948-49), and with substantial rises in lake level (i.e. in the years 1952-53, and 1957-58).

Below an elevation of 6401.07 feet (the level at which the lake recedes from the flank of Black Point), ten tiny littoral embankments composed primarily of andesitic sand protrude from 5 to 30 cm above the lake plain. The sediment that composes each of these small bars was carried to the littoral zone by Bridgeport Creek, a stream that flows only during periods of storm runoff and snowmelt. Each bar coincides in elevation with a springtime level of the declining lake surface.

The two wave-cut notches lie at elevations of 6390 feet and 6381 feet. They are the result of substantial rises in lake level--the first in 1967-69, and the second in 1982-84.

These subtle notches occur in association with conspicuous "float lines" of driftwood, vesicular Mono Craters pumice, and anthropogenic detritus (Photo 12). This buoyant debris shoaled at the shoreline after being carried to the lake by the high flows of the incising tributary streams in 1967-69 and 1982-84.

Of particular interest are the features along Profile A that lie above and below the historic shorelands--that is, the features that formed in pre-historic time. The lowest of these is a break in slope at an elevation of 6368 feet. This nick-point was first identified by Scholl and others (1967) in 1964, during their bathymetric survey of the lake. They noted that the break in slope marks the lower edge of a terrace that extends around much of the lake. The feature was called the "25-foot terrace" by Scholl, because it stood under approximately 25 feet of water at the time of the bathymetric survey. This terrace, the distal margin of which is today found under approximately 17 feet of water, is herein called the "Scholl terrace". Scholl and his co-workers speculated that it formed as a result of a decline in lake level during the putative "Altithermal interval" some 4000-7000 years ago; it will be shown subsequently, however, that the terrace was actually cut approximately 1800 years ago during a rise in lake level.

Three late Holocene berms are found above the level of

the Historic High Stand. The largest of these lies at an elevation of 6499 feet. This strandline represents the "Dechambeau Ranch High Stand" (see pg. 220) and, like many of the other features mentioned above, is expressed in one form or another around most of the lake shore. A sizable berm lies at an elevation of 6456 feet, while a somewhat smaller one stands at approximately 6445 feet. It will be shown that the former feature marks the elevation of the "Clover Ranch High Stand" of 220 yrs BP (see pg. 277), and that the latter was produced during the lake recession in post-Clover Ranch time.

Profile B traverses the shorelands of the Western Embayment in the vicinity of the Mono County Marina (Plate 6b). It rises gently (~18/1000) from the Historic Low Stand of 6372 feet, then steepens abruptly (to 66/1000) at an elevation of 6400 feet, where it ascends the surface of a small alluvial fan.

Because of the weak currents and the dearth of drift that characterize this portion of the Mono shorelands, littoral embankments along Profile B are poorly developed. Indeed, only three embankments can be found along the entire transect. The lowest of these lies at the level of the Historic High Stand (6428 feet). The highest is found at 6456 feet, the elevation of the Clover Ranch High Stand of 220 yrs BP. The third berm lies at an intermediate elevation

of 6445.5 feet, and coincides with the post-220 BP recessional shoreline discussed under Profile A above.

Profile B intersects one wave-cut terrace, a feature corresponding in elevation with the Dechambeau Ranch High Stand (6499 feet). At the point of intersection, and for some distance to either side of that point, the terrace is exploited as a county-road grade.

Profile C (Plate 6c) traverses Navy Beach on the lake's southern shore. Gradients along this portion of the shorelands are comparable to those along Profile B. The substrate in this area is composed of Mono Craters tephra reworked by waves and littoral currents. Landforms built from or carved into these mainly-pumiceous sands are easily deflatable, and persist only where they have been colonized by vegetation or cemented with tufa. Remnants of large shoreline embankments deposited within historic times are found at elevations corresponding to the years 1919, 1938-47, 1952, 1958, and 1967-69; smaller embankments lie at the 1960, 1964, and 1986 lake levels.

Above the Historic High Stand along Profile C are four large berms that mark the highstand of 220 yrs BP and the short-lived rises or stillstands that occurred during the subsequent lake regression. These lie at elevations of 6431 feet, 6438 feet, 6447 feet, and 6456 feet. Shoreline features lying above 6456 feet along Profile C have been

buried in airfall tephra from the most recent Mono Craters eruptions.

Profile D traverses the lake's eastern shore near Simon's Springs (Plate 6d), an area that has been disturbed by uplift along the Simon's Spring Fault (Appendix D). The topography along the lower reaches of the profile is generally similar to that along Profiles A and C, with berms and bars marking the position of the lake transgressions and stillstands that have occurred during the past several decades. Below 6412 feet, where the lake crosses the fault, littoral embankments are deposited onto lakebottom sediments of Recent age; above that elevation, upfaulted Wilson Creek sediments compose the substrate. Wave-cut terraces notch the block at 6418.0 feet, 6428.40 feet, 6444.0 feet, and 6455.1 feet; these elevations correspond with, respectively, the stillstand of 1938-47, the Historic High Stand, a strandline of post-220 BP lake recession, and the high stand of 220 yrs BP. A broad wave-cut terrace extends from 6474.35 feet to a cliffline at 6499 feet, the elevation of the Dechambeau Ranch High Stand.

D. VEGETATION AS AN INDICATOR OF LAKE LEVEL FLUCTUATIONS

Vegetation proved to be of major importance in illuminating both the timing and the magnitude of the pre-historic surface fluctuations of Mono Lake. For purposes of discussion this evidence is divided into two themes--dead vegetation of the late Holocene shorelands, and living vegetation of the late Holocene shorelands. Each is discussed in turn.

Dead Vegetation of the Late Holocene Shorelands

Because of its extreme salinity and alkalinity, the water of Mono Lake is highly toxic to vascular plants. No plant species grow within the lake, and any vegetation submerged during a lake transgression is quickly killed. Mortality of vegetation due to a rise in the level of the lake was reported by workers of the late nineteenth and early twentieth centuries (LeConte,1879; Russell, 1889; Huntington, 1917, 1924), and was observed first hand during the transgression of 1982-86.

Most of the vegetation killed by a rise in lake level is likely to be uprooted by waves and longshore currents in the course of the transgression. (This was certainly the case in 1982-84.) A few of the dead plants, however, may persist as rooted snags. *In situ* remains of trees and shrubs killed

during pre-historic lake transgressions have been found at many of the wetter localities around the lake shore. They are most abundant on the plains of the Lee Vining Creek, Mill Creek and Post Office Creek deltas, and along the southern shore of the Western Embayment, where they number in the hundreds. Dozens more are found in association with buried humic horizons in the subsurface sedimentary record.

These stumps can be used in several ways to help decipher the late Holocene surface fluctuations of the lake. First, each rooted derelict provides irrefutable evidence that the lake stood below the elevation of its base at the time of growth. Secondly, a count of the stump's annual rings provides a measure of the minimum amount of time that the lake stood below that elevation. Thirdly, radiocarbon analysis of wood from the stump effectively dates the lake lowstand. Finally, if the stump is found in association with evidence of a shoreline transgression, death of the plant may reasonably be attributed to inundation by a rising lake; in this case radiocarbon analysis of outside rings provides a date on the lake transgression that killed the plant. Radiocarbon analyses were conducted on wood from the outer rings of 12 stumps rooted at various localities on the western shore of Mono Lake. These dates, together with the locations and basal elevations of the stumps from which they were derived, are listed in Table 2.

In at least two instances trees killed by the lake transgression of the late 19th and early 20th centuries can be used to cast light on the pre-historic fluctuation curve. On June 7, 1915, geographer Ellsworth Huntington felled a mountain mahogany (Cercocarpus ledifolius) that had been partially submerged (and thus killed) by a rise of Mono Lake during the previous year. He found the tree, which grew along the western shore of the lake,[11] to be "nearly 150 years old", based on a count of the annual rings (Huntington, 1917, 1924). According to Mr. Herbert Gates of Oakland, California, who accompanied Huntington on the trip to the Mono Basin, the base of the mountain mahogany was submerged in two or three feet of lake water at the time of the visit (quoted in Harding, unpubl.). Referring to the hydrograph on Plate 1, it will be seen that the level of the lake surface in the spring of 1915 was approximately 6425 feet,[12] indicating that the tree was rooted at an elevation of between 6422 and 6423 feet. Considering the toxicity of Mono waters, the Huntington account leads to the conclusion that the surface of the lake did not lie above an elevation of 6422 feet between approximately 1763 and 1914 AD.[13]

On July 2, 1934, presumably in an attempt to corroborate the Huntington account, S.T. Harding cut down a dead mountain mahogany from elevation 6422.5 feet on the shores of Mono

Lake. He provided the following description of the tree (Harding, unpub.):

> "This tree grew 6 feet above the present water. It was cut 3 feet above the ground. It was the largest tree among the group on a point 0.15 mile south of Mono P.O. A tree ring count gave an age of 83 years. Although this tree was killed by a rise in lake level in 1912 its wood was still dense and hard. The rings were not all distinct due to the slow rate of growth of mountain mahogany. The section was polished and oiled and the above result is considered essentially correct. This tree was about 8 inches in diameter."

The writer has come into possession of the section of mountain mahogany described by Harding. He independently derived a count of 83 rings. In ways to be described subsequently, this tree, as well as the 150 year-old speciman described by Huntington, can be used to clarify radiocarbon dates from the immediate pre-historic period.

Between 1980 and 1984 the writer made ring counts of a number of other living and dead trees rooted on the late Holocene shorelands. In no case, however, did these counts contribute in any significant way to the lake level curve derived from other lines of evidence.

Living Vegetation of the Late Holocene Shorelands

Land exposed during a lake recession retains for some time a salinity and alkalinity that approaches, or in some cases even exceeds, that of the lake itself. Soil analyses

conducted by Professor Paul Zinke, U.C. Berkeley, in connection with Federal Litigation No. S-80-696, U.S.D.C, E.D Cal., for instance, show that lands lying below 6428 feet (i.e. lands covered by the lake within historic time) display markedly higher concentrations of sodium, as well as a lower pH, than lands lying above that elevation (i.e. lands not covered by the lake in over 220 years--see discussion of Huntington's mountain mahogany above). They further indicate that the change in the chemistry of the substrate at 6428 feet is abrupt. These analyses point to the existence of a "chemical strandline"--that is, a former shoreline (in this case the Historic High Stand) discernable on the basis of chemical characteristics.

The residual salts and alkaline compounds that impregnate newly exposed shorelands prevent immediate colonization by vegetation (Paul Zinke, pers. comm.; Dean Taylor, pers. comm.). The amount of time that must pass before plants can grow on these lands is dependent on, among other things, the amount of fresh water (including precipitation, surface water and groundwater) available to flush the toxic solubles, the permeability of the substrate (relatively impermeable substrates taking longer to flush), and the salinity and alkalinity tolerance of the vegetation itself. The pattern of vegetation that has become established on lands exposed during the lake recession of the

past six and one-half decades serves to illustrate these factors. That pattern is conspicuous on aerial photos from 1982, several of which are included here as Photos 13a-e. Note on Photo 13a that the newly exposed lands (i.e. those exposed since 1919) adjacent to the western third of the lake (where precipitation is relatively high, where surface water and groundwater are plentiful, and where sediments are coarse and easily flushed of solubles) have been colonized by vegetation nearly to the lake shore. Newly exposed lands along the arid northern (Photo 13b), eastern (Photo 13c), and southern (Photo 13d) shores of the lake, on the other hand, remain barren of vegetation except at spring sites, and where bars and berms of sand elevated above the salt-impregnated shorelands provide favorable habitat.

The vegetation break corresponding to the Historic High Stand (6428 feet) involves not only a change in vegetation density, but in species composition as well (Photo 13e). Above 6428 feet woody vegetation is dominated by Great Basin sagebrush (Artemisia tridentata); subdominant shrub species on these lands include bitterbrush (Purshia tridentata), desert peach (Prunus andersonii), Mormon tea (Ephedra viridis), spiny hopsage (Grayia spinosa), greasewood (Sarcobatus vermiculatus) and wild rose (Rosa woodsii). Below the Historic High Stand rabbitbrush (Chrysothamnus nauseosus var. consimilis) is the dominant arbuscular

species; in only a few scattered localities can any additional shrub species be found.[14]

According to Dr. Dean Taylor (pers. comm. 10/1/85) this abrupt break in species composition at the level of the Historic High Stand results from the above-noted change in the chemistry of the substrate at that elevation. Chrysothamnus nauseosus var. consimilis, according to Dr. Taylor, is the only shrub found in the basin that is capable of metabolizing in the high concentrations of residual salts that characterize large areas of shorelands below 6428 feet.

The Historic High Stand is not the only contour marked by an abrupt change in species composition. Two higher breaks--coinciding with the 6456-foot and the 6499-foot contours--persist on areas of the late Holocene shorelands that are characterized by relatively impermeable substrates, low precipitation, and a dearth of surface- and groundwater. It will be shown in Chapter 3 that these vegetation breaks mark high stands of the lake that occurred 220 yrs BP and approximately 3500 yrs BP, respectively.

E. THE VOLCANIC RECORD AND ITS BEARING ON THE LATE HOLOCENE FLUCTUATIONS OF MONO LAKE

Ejecta from eruptions of the Mono Craters and the Mono Islands is encountered frequently in the late Holocene sediments of the Mono Basin. These tephra deposits are valuable stratigraphic time-lines that can be used to bracket, and in some cases pinpoint, the elevation of the lake surface at the time of an eruption. The brief discussion that follows outlines the late Holocene volcanic record of the Mono Basin, and the manner in which tephra deposits can be utilized to construct a fluctuation curve for late Holocene Mono Lake.

Late Holocene Eruptions of the Mono Craters

Volcanic eruptions from the Mono Craters have blanketed the surrounding region with rhyolitic tephra four times during the past two millennia. The two youngest of these widely dispersed ashes--radiocarbon dated at 605 ± 20 cal BP and 1245 ± 50 cal BP [15] (Sieh and Bursick, 1986; Sieh, 1984) are encountered frequently in exposures of deltaic and shoreland sediments.[16] These youngest ashes are readily identifiable on the basis of color and stratigraphy, making them particularly valuable chronostratigraphic markers.

The two older widely-dispersed ashes are found in the stratigraphic record relatively infrequently, but are nevertheless of considerable importance to the present study. Dating of these two older tephra units is problematical: Professor Steve Lund of the University of Southern California (personal communication, July 21, 1986) reports finding two Mono Craters ashes that are approximately 2000 years old in cores taken from nearby Black and Silver lakes; Batchelder's core from Black Lake contains two aphyric rhyolitic ashes lying above a date of 2190 ±90 yrs BP (Batchelder, 1971). Sieh (pers. commun., 1986) recently dated a Mono Craters ash at 1610 ± 60 yrs BP, while Wood (1977) discovered a Mono Craters ash which he dated at 1990 ±200 yrs BP. Until more precise dates can be assigned, the two lower tephra units utilized in this study will be referred to as the ashes of 1610 yrs BP, and 1990(?) yrs BP.

The utility of the Mono Craters ashes goes beyond their obvious value as chronostratigraphic markers. Airfall tephra deposited beneath the water of the lake can be readily distinguished from ash deposited on land, on the basis of both the character of the ash beds (subaqueously-deposited ash typically being composed of a compact assemblage of undisturbed planer beds), and the character of the sediment directly under- and overlying it. At the very least, then, each ash provides the potential for bracketing the elevation

of the lake surface at the time of its deposition. Furthermore, if an ash is found to compose, or be intercalated in, sedimentary structures characteristic of a shoreline environment, it becomes possible to define precisely the elevation of the lake at the time of the eruption. Based on the application of these principles, it will be shown that the lake surface stood at 6406 feet at the time of the eruption of 605 cal BP (see pg. 262), and at 6392 feet during the eruption of 1245 cal BP (pg. 242).

Late Holocene Eruptions of the Mono Islands

The islands of Mono Lake owe their existence to the episodic eruption and shallow intrusion of magma during the past 2000 years (Chapter 5). At least three of these volcanic events produced ashfalls, one of which (a series of ash eruptions that accompanied, or closely followed, the emergence of Paoha Island sometime between 1723 and 1783 AD--see Chapter 5) can be used in the manner described above to pinpoint the elevation of the lake surface at the time of the eruption. Thus, it will be shown that at the time of the eruptions from the cinder cones on Paoha Island the lake surface stood at an elevation of about 6396 feet.

Most of the volcanic events associated with the Mono Islands gave rise to domes, pinnacles and flows--features that cannot be used to infer the level of the lake at the

time of eruption. One event, however, is exceptional in that it produced thousands of highly vesicular pumice blocks that floated to the shoreline and shoaled, marking the elevation of the lake surface (approx. 6392 feet) at the time of the eruption (around 1700 BP). Details of this eruption are presented beginning on pg. 240.

F. RADIOMETRIC CONTROL OF THE LAKE LEVEL CURVE

Introduction

Chronologic control of the lake level curve comes not only from the dated tephra layers and stumps described in the previous sections, but from radiocarbon analysis of organic detritus collected from critical horizons in the sedimentary record. A brief discussion of the radiocarbon dates used in this study, and of their role in constructing a fluctuation curve for Mono Lake, is presented below.

Dating The Lake Level Fluctuations

Organic detritus abounds in the late Holocene deltaic sediments on Rush, Mill and Lee Vining creeks. These materials include pine needles and cones, charcoal, and leaves, as well as thick mats of plant detritus deposited in delta trenches. With organic detritus so abundant, it is often possible to find datable debris within sedimentary structures associated with a shoreline environment (e.g. foreset beds, bottomset beds directly traceable to foreset beds, and shoreline embankments). Radiocarbon dates derived from such structures, like the dates obtained on the rooted stumps discussed in Section D of this chapter, can often be tied precisely to an elevation of the lake surface. This

makes it possible to relate some radiocarbon dates to an actual, rather than a maximum or a minimum, lake level.

Radiocarbon Dates Cited In This Study

In addition to the dated tephra layers discussed in the previous section, 25 radiocarbon dates provide chronometric control for the lake level curve. Throughout this thesis these radiocarbon dates will be cited as "yrs BP" or simply as "BP". Dendrochronometric equivalents to the radiocarbon dates, calibrated (using one standard deviation) from Stuiver and Pearson (1986), and Pearson and Stuiver (1986), will be given as "cal BP"; thus, 700 ±60 yrs BP (or 700 ±60 BP) is equivalent to 670 ±15 cal BP.

In two cases (between 700 and 600 cal BP, and between 900 and 800 cal BP) multiple dates are available for a single lake transgression. In these instances the dates in each set were reduced to a single number for use on the lake fluctuation curve. This was accomplished by graphing the calibrated dates to determine the minimum interval of overlap.

Each radiocarbon date cited in this study, together with an identification number, a description of the sample, the location and elevation from which the sample was collected, the dendrochronometric equivalent, the laboratory that conducted the analysis, and the significance of the date, is

presented in Table 2 below.

Table 2--Radiocarbon dates cited in this report

ID No.	Lab	Date (BP)	Calibrated date*	Sample description	Sample location	Significance
USGS-1167	Menlo	640 ±60	613 ± 58 cal BP	tree stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. 6388'	Dates rise from low stand of ~700 BP
USGS-1274	Menlo	850 ±50	870 ± 23 cal BP (estimated) 753 ± 58 cal BP	tree stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. 6392'	Dates rise from low stand of ~900 BP
USGS-1275	Menlo	910 ±60	837 ± 87 cal BP	tree stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. 6395'	Dates rise from low stand of ~900 BP
USGS-1276	Menlo	860 ±60	880 ± 23 cal BP 768 ± 64 cal BP	tree stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. 6397'	Dates rise from low stand of ~900 BP
USGS-1277	Menlo	700 ±60	670 ± 15 cal BP	tree stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. 6402'	Dates rise from low stand of ~700 BP
USGS-1310	Menlo	890 ±60	822 ± 94 cal BP	pine cone in organic-rich lake-transgr. seds.	e. wall LV Cr. ele. 6395'	Dates rise from low stand of ~900 BP
USGS-1314	Menlo	1495 ±45	1370 ± 45 cal BP	pine cone in organic-rich lake-transgr. seds.	e. wall LV Cr. ele. 6384'	Dates rise from lake stand of ~1500 BP--provides min. age on eruption of "Java blocks"
USGS-1315	Menlo	600 ±70	603 ± 63 cal BP	non-rooted Jeff pine surface of LV Cr. Δ	~300 m w. of LV Cr. mouth, ele. 6373'	Dates rise from low stand of ~700 BP

Table 2 (cont.)

USGS-1316	Menlo	675 ±50	662 ±18 cal BP 582 ± 16 cal BP	pine cones and sticks in shallow-water sands	e. wall LV Cr. cut ele. 6391'	Dates litt. zone immed. following MC eruption of 605 cal B
USGS-1317	Menlo	220 ±65	290 ± 21 cal BP 178 ± 32 cal BP	charcoal in lacustrine silts	e. wall LV Cr. cut ele. 6430'	Dates rise (or high stand) following low stand of ~300 BP
USGS-1319	Menlo	940 ± 60	858 ± 74 cal BP	Compositae shoot rooted on Mono shorelands	~600 m w. of LV Cr. mouth, ele. 6370'	Dates beginning of rise from low stand of ~900 BP
USGS-1320	Menlo	220 ±60	290 ± 19 cal BP 178 ± 30 cal BP	charcoal in bottomset beds of inset delta	e. wall LV Cr. ele. 6450.5'	Dates high stand of 220 BP
USGS-1321	Menlo	920 ±35	851 ± 67 cal BP	grass shoots in beach sand	e. wall Rsh Cr. ele. ~6380'	Dates rise from low stand of ~900 BP
USGS-1487	Menlo	950 ±50	861 ± 71 cal BP	tree stump rooted in channel of LV Cr.	e. side of LV Cr. ele. ~6402'	Dates rise from low stand of ~900 BP
USGS-1524	Menlo	1625 ±40	1542 ± 30 cal BP	pine cones from fluv. gravels	e. wall LV Cr. ele. ~6384'	Dates lake stand of ~1600 BP-- provides min. age on eruption of Java blocks
USGS-1705	Menlo	1590 ±50'	1475 ± 66 cal BP	pine cones from fluv. gravels	e. wall LV Cr. ele. ~6384'	Dates lake stand of ~1600 BP-- provides min. age on eruption of Java blocks

Table 2 (cont.)

USGS-1704	Menlo	930 ±40'	855 ± 68 cal BP	pine cone in beach sand	e. wall Rsh Cr. ele. ~6380-90'	Dates rise from low stand of ~900 BP
BETA-5115	BetaAn	3490 ±90	3769 ± 118 cal BP	Charcoal from bottomset beds	e. wall of LV Cr. ele. 6485'	Dates high stand of 3490 BP
UCLA-118	UCLA	920 ±90''	831 ± 105 cal BP	tree stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. "about 6400 ft"	Dates rise from low stand of ~900 BP
LDGO-1677 AW	Lamont	770 ±50	699 ± 25 cal BP	shrub stump rooted on surface of LV Cr. Δ	e. of LV Cr. mouth ele. 6399'	Dates rise from low stand of ~700 BP
LDGO-1677 FW	Lamont	860 ±60'''	880 ± 20 cal BP 768 ± 64 cal BP	tree stump (ctnwd?) rooted on PO Cr. Δ	w. of PO Cr. mouth ele. 6390'	Dates rise from low stand of ~900 BP
LDGO-1677 LW	Lamont	940±20	911 ± 9 cal BP 846 ± 16 cal BP 802 ± 6 cal BP	Tufa-encrusted Comp. stump rooted on surface of LV Cr. Δ	e. wall of LV Cr. cut ele. ~6389'	Dates rise from low stand of ~900 BP
LDGO-1677 IW	Lamont	570 ±30	618 ± 6 cal BP 553 ± 11 cal BP	tree stump rooted (?) on surface of LV Cr. Δ	~300 m e. of LV Cr. ele. 6398'	Dates rise from low stand of ~700 BP
LDGO-1677 OW	Lamont	550 ±30	620 ± 7 cal BP 547 ± 11 cal BP	shrub stump rooted on shorelands s. of Mono Co. Marina	southernmost extent of Western Embayment, ele. 6389'	Dates rise from low stand of ~700 BP

Table 2 (cont.)

*calibrated using Stuiver and Pearson (1986), and Pearson and Stuiver (1986). In cases of multiple sidereal equivalents to a given radiocaron date, the preferred equivalent (based on stratigraphic, dendrochronologic, tephrochronologic, and other radiometric evidence) is underlined.

'collected by Michael Perkins in 1982 (personal communication, 1982)

'' collected by D.B. Lawrence in 1960. See Lawrence and Lawrence, 1961.

''' sample is a duplicate of one run by USGS Menlo Park (USGS 1523 = 1035 ±40 BP)

G. TUFA AS AN INDICATOR OF FOSSIL SHORELINES

Introduction

Mono Lake is renowned for the abundance and diversity of its tufa deposits. Surface accumulations of this calcium carbonate precipitate occur widely on the late Holocene shorelands as beach pavements, as castellated sand structures, as towers and domes up to fifteen meters tall, and as a coating on shoreline cobbles and boulders. Several of these forms of tufa are also encountered in the subsurface sedimentary record of late Holocene Mono Lake.

Tufa has been used in a number of different studies to determine and to date former shoreline position (Broecker and Kaufman, 1975; Broecker and Orr, 1958; Benson, 1978). While not of major importance to the present study, tufa was nevertheless used in a few instances as corroborative evidence of fossil-shoreline position. It is therefore discussed here at length.

Previous works. The tufa of Mono Lake was first studied in detail by Russell (1889; see also his Lahontan treatise of 1885) who identified 3 structural varieties--lithoid (compact and stony structure), dendritic (arborescent structure), and thinolitic (structure of interlaced crystals). He observed that while most of the tufa deposits associated with the

enlarged lake of late Pleistocene time are composed of at least two and often all three varieties, the more recent deposits of lower elevations (i.e. those associated with the middle and late Holocene lake) are made up entirely of the lithoid type. In keeping with the focus of this dissertation the discussion that follows emphasizes the lithoid tufa of late Holocene age.

Russell described tufa-cemented beach deposits found at various localities around the Mono Basin, and noted a thin crust of tufa on the shoreline boulders of Negit Island. He proposed a hydrologic mechanism for the formation of the "weird and uncanny" tufa towers that occur in association with freshwater springs. Based on observations of spring water emanating from the summits of partially- and fully-submerged tufa towers at Mono Lake, Russell hypothesized that the towers grow from sublacustrine spring orifices, and that artesian pressure forces spring water upward through porous tufa in the tower core throughout, and for some time following, the process of construction.

The chemistry of tufa formation was first addressed in detail by Dunn (1953). Based on the solubility product of calcium, he argued that precipitation of tufa at Mono Lake is primarily a physicochemical process that occurs instantaneously as a result of the introduction of calcium-bearing fresh water into carbonate-rich lake water.

He called attention to the thick layers of tufa on stranded beach lines along the Sierran front, and attributed them to inflow to the lake by streams and rainwash that drain the calcitic rocks of the escarpment. Dunn also drew a useful distinction between lithoid tufa that is dense and durable ("dense lithoid tufa"), and lithoid tufa that is porous and easily crushed ("porous lithoid tufa").

As a counterpoint to Dunn's work, Scholl and Taft (1964) argued that precipitation of calcium carbonate at Mono Lake is induced by algae. The debate between those who favor a purely physicochemical explanation for the formation of tufa and those who invoke algal activity continues to this day; observations which help to clarify the role of these two processes in the formation of tufa are presented later in this section.

In his dissertation on the late Pleistocene history of the Mono Basin, Lajoie (1968) provided a comprehensive outline of the lithology, distribution, and age (either late Pleistocene or Holocene) of tufa deposits. He described tufa "flanges" with flat to slightly convex undersides that protrude from the flanks of some tufa towers (Photo 14a). Lajoie later collaborated with Cloud (Cloud and Lajoie, 1980) in a report on the bizarre "calcite-impregnated defluidization structures" (sand tufa) of Mono Lake (Photo 14b i and ii).

The rate of tufa deposition was the subject of a recent paper by Jehl (1983). A tufa crust on the outside of a 17-year-old steel drum shoaled along Navy Beach on the south shore of the lake was found to be 43.2 cm thick. Jehl assumed a constant rate of tufa formation, and thus derived an average growth rate of 2.54 cm per year. Observations made in the course of this study show that this figure vastly underestimates the potential growth rate of certain types of tufa (see below).

One of the most striking aspects of the literature on Mono Lake tufa is the paucity of eyewitness accounts of the actual formative process. Russell states that tufa was not being precipitated at the time he studied Mono Lake. Dunn speculated that it was "probably forming" during the period of his field work in the early 1950s, but he, like most subsequent workers, provides no description of tufa formation, suggesting that it was not actively precipitating at the time of the investigations. In recent (July, 1985) conversations with the writer, both Scholl and Lajoie indicated that with the exception of algae-induced precipitation of calcium carbonate seen occurring on the outside of one tufa tower stranded some distance above the lake, they observed no tufa forming in the course of their field work during the 1960s. Indeed, the only known eyewitness account of tufa formation during the years prior

to 1983 was made by photographer Michael Dressler in 1980.[17] He noted that for a one-week period in December of that year, small, fragile blossom-like deposits of tufa formed at the orifices of sublacustrine shoreline springs near South Tufa (Figure 26) on the southern margin of the lake. Dressler photographed these forms, and graciously provided slides for inclusion in this report (Photo 14c).

Tufa as a Shoreline Indicator. The extent to which tufa can be used as a reasonably precise indicator of former shoreline position has been addressed in the literature on Great Basin lakes only in speculative terms. It is often contended that tufa formation is primarily a shoreline phenomenon, but observations and evidence to support this contention are scant. In an early derivation of a radiocarbon chronology for lakes Lahontan and Bonneville, for instance, Broecker and Orr (1958) note that "whereas in most cases [tufa] deposits were probably formed near the lake surface, possibly some were formed at considerable depth." This view is reaffirmed in a later work by Broecker and Kaufman (1975) who state that "...most carbonates are thought to form in shallow water...". In both studies, however, the authors conclude that until a direct link between tufa and shoreline can be established, the precipitate should be used only as an indicator of minimum shoreline elevation.

Benson (1978), in a reevaluation of the Lahontan

chronology developed by Broecker and his co-workers, points out that tufa deposited in close association with lacustrine algae can form only in the euphotic zone--a zone which, at Mono Lake, extends to a depth that ranges seasonally from approximately 3 to 15 m.[18] This margin of uncertainty may allow a reasonable estimate of former shoreline position when tracing the large-scale and long-term fluctuations of a Pleistocene pluvial lake, but it contributes little to the derivation of a high-resolution curve for a Holocene lake, where a change in surface elevation of even 3 m represents a substantial fluctuation. Furthermore, this explanation is of little relevance to tufa that is not deposited in association with lacustrine algae.

The literature regarding the relationship between tufa deposition and the shoreline environment at Mono Lake is only slightly more illuminating. Lajoie concluded that the flange-like forms that protrude from the sides of tufa towers mark the level of the lake surface at the time of their formation. Dunn (op cit) expressed the belief that the tufa that coats the late Pleistocene beach lines along the eastern escarpment of the Mono Sierra formed in a near-shore environment, and Cloud and Lajoie state that the formation of sand tufa occurs "near the shore of the lake"; in none of these studies, however, is the environment of tufa deposition explored in more detail. Observations by Lajoie (pers.

comm.) and Scholl and Taft (op cit) provide an important complication to any generalized theory that seeks to link tufa formation to a shoreline environment. They observed algae-induced precipitation of calcium carbonate on the outside of a tufa tower that stood well above the lake shore. Scholl and Taft, in fact, hazard that algal deposition of dense lithoid tufa is primarily a subaerial, rather than a sublacustrine, phenomenon.

The Distribution, Hydrology, and Formation of Late Holocene Tufa at Mono Lake

Introduction. The low lake levels that characterized the years 1980-1985 permitted observations that illuminate the age and distribution of the various types of tufa, as well as the hydrology and rate of tufa formation, at Mono Lake. This new information, in turn, bears on the use of tufa as an indicator of former shoreline position, and helps to clarify many of the discrepancies, controversies, and contradictions that characterize the existing literature on tufa.

Algal- vs. physicochemically-induced precipitation of tufa. The paucity of eyewitness accounts of tufa formation noted above is in keeping with the writer's experience during his first three years of field work (1980-82) in the Mono Basin. Despite the many months spent along various portions

of the lake shore throughout that period of time, neither he nor fellow scientists working in the basin witnessed even the local deposition of tufa. Indeed, the week-long spate of tufa formation described by Michael Dressler in 1980 (see above) is the only known instance of calcium carbonate precipitation during this period of time. It was thus of tremendous interest when, for a three-month period beginning in mid-July of 1983, for a six-week period beginning at the end of May, 1984, and for at least four months during the late spring, summer, and early fall of 1986, sublacustrine shoreline springs that had previously been pellucid began to be milky white, suggesting the instantaneous, physicochemically-induced precipitation of calcium carbonate (Photo 14d and e). This change in the nature of the springs (or, more probably, the change in the lake waters that induced the precipitation of calcium from the spring waters) was accompanied by the rapid and wholesale deposition of porous-lithoid tufa at hundreds of sublacustrine spring sites near the lake shore. During the weeks and months that followed these lakewide "tufa blooms", most of the springs returned to their normal, clear-flowing condition.

The blooms of 1983, '84, and '86 produced a soft, fragile, and highly porous type of tufa. Precipitation was rapid, at some sites exceding 2 cm per day (see below). Within weeks of the first observations, local concentrations

of this physicochemical precipitate began to change color, turning from the original white or cream, to a light- to bright-orange or green. Inspection of these somewhat older deposits revealed that the color change was due to colonization by algae.

After a year many of these once-soft deposits had become encased in a durable crust of thinly laminated, dense-lithoid tufa. One such speciman, broken with a hammer to reveal the stratigraphy, is illustrated in Photo 14f. Note there that the contact between the porous inner mass and the dense outer shell is underlain by a green band of algae. Not apparent on the photo is the fact that many of the laminae, too, occur in association with thin layers of algae.

These observations strongly suggest that porous lithoid tufa at Mono Lake is a physicochemical deposit that is produced rapidly and episodically, and that, in contrast, dense lithoid tufa is produced slowly and continuously (or perhaps seasonally) in association with algal activity. The fact that the (physicochemical) tufa blooms of 1982, '83, and '86 (as well as Dressler's minor bloom of 1980) coincided with abnormally rapid rises in lake level suggests that rapid lake transgressions, and perhaps the high surface and subsurface inflows that instigate them, may be a major controlling factor in the production of certain deposits of porous lithoid tufa.

The distribution, hydrology, age, and formation of "calcite-impregnated defluidization structures" (sand tufa). According to Cloud and Lajoie (1980), "calcite-impregnated defluidization structures", or sand tufa, are "subvertical concretionary sand structures composed of closely spaced calcite-impregnated columns, tubes, and other configurations with subcylindrical to bizarre cross sections and predominantly vertical orientation". Illustrations of these ornate, castellated forms are provided in Photos 14bi and bii. Cloud and Lajoie note that the calcitic cementation which gives rise to sand tufas occurs in the aphotic subsurface, indicating that the process of calcium carbonate precipitation must be induced physicochemically, rather than algally.

Surface deposits of sand tufa occur at scattered localities along the southern and eastern shores of Mono Lake. They are found primarily below the level of the Historic High Stand (6428 feet), though they do occur at higher elevations. The major concentrations of sand tufa, and other important tufa localities, are mapped on Figure 15. The map of tufa distribution reveals that while sand tufa can occur at most any elevation below 6428 feet, it forms prominent, nearly continuous bands hundreds of meters long between elevations of 6415-6418 feet, and 6425-6428 feet (Photo 15a).

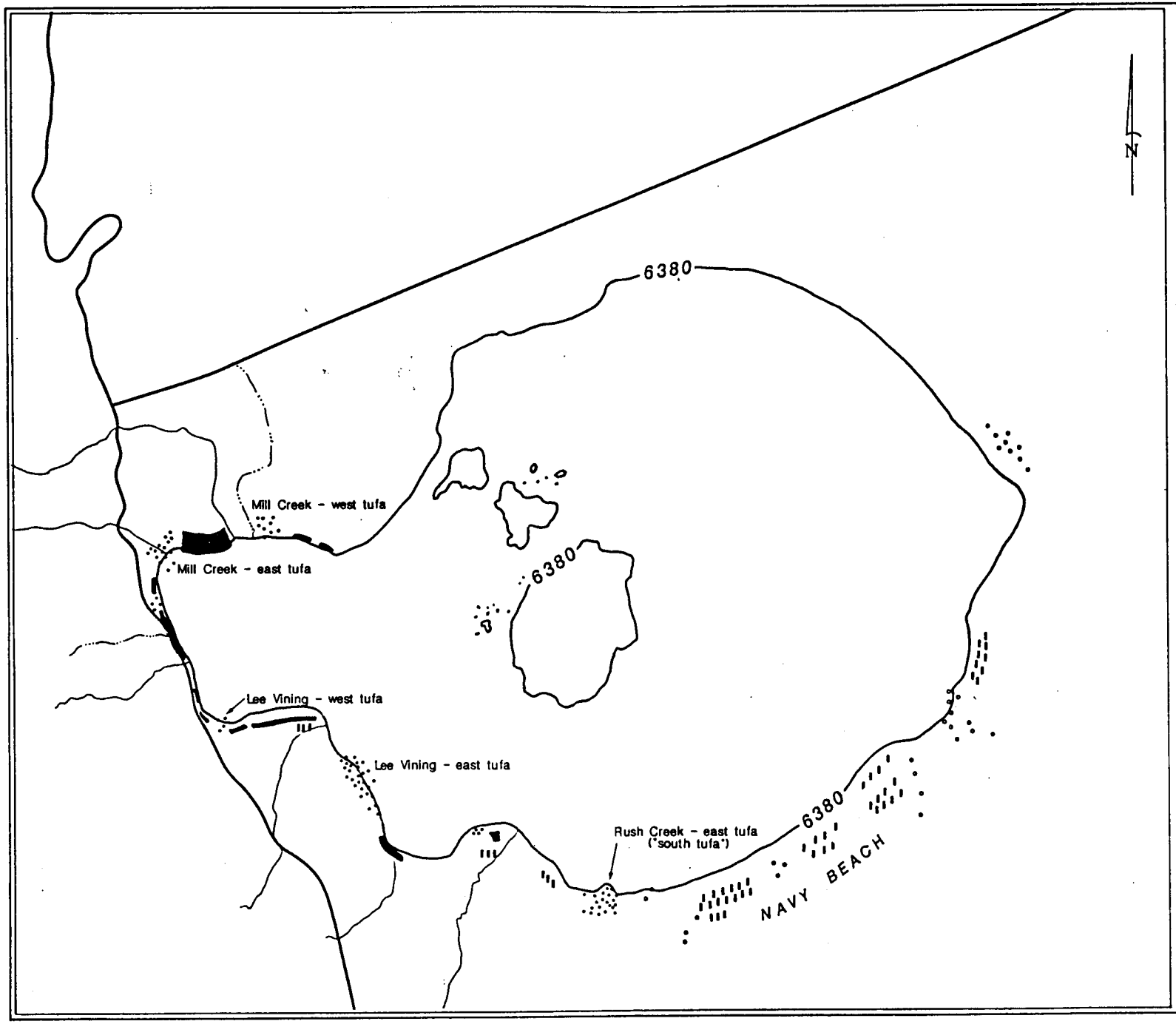


Figure 15. Major surface deposits of tufa on Holocene shorelands.

Sand tufa is most common along the southeastern shore of the lake, where it formed in surface deposits of pumiceous littoral sand that overlie an aquiclude of lacustrine clay. This stratigraphic relationship suggests that the sand tufa formed in sands deposited in modern times. Proof of this occurs in the form of long (>100 m), plastic-covered copper cables that lie on the shore (elevation 6382 feet) at East Navy Beach. These stout (5mm), four-strand cables, which presumably were emplaced by the Navy during their sublacustrine detonation experiments in 1965-66, typically lie between the calcite-impregnated sand and the underlying lacustrine clays, though in a few cases the cables are incorporated into the cemented sands (Photos 15b and c). Clearly, then, the surface deposits of sand tufa lying below 6428 feet along the southeastern shore of the lake are thoroughly modern features.

Cloud and Lajoie describe the hydrology of sand tufa formation as follows:

> "As fresh, calcium-bearing ground water from upslope impinges on or flows through porous sediments saturated with heavier saline water near the shore of the lake, the difference in density, reinforced by hydrologic head, causes the freshwater to rise. Because of the high energy required for mixing, upward flow of freshwater tends to be confined to subcylindrical, vertical pathways... Sufficiently vigorous upward circulation of the freshwater locally displaces saline lake water and limits calcite precipitation to a fairly sharp interface between calcium-bearing freshwater and carbonate-rich lake water, creating solidly indurated, subcylindrical walls... Once the two water masses are physically separated by a solid barrier of calcite cement, precipitation ceases..."

This explanation goes far in accounting for the basic

structures that characterize sand tufa. But the mechanism that the authors propose to set the formative process in motion requires reevaluation. It is difficult to imagine how a relatively light fluid, flowing down a gentle gradient (typically 8-15 feet/1000 feet) through surficial sands, could undermine or "flow through" sediments saturated with a heavier fluid. The very density difference that Cloud and Lajoie invoke to explain the rise of freshwater through the saltwater-saturated sands, it seems, would prevent the fresh groundwater from ever moving under or through those sands in the first place.

One possible means of getting freshwater underneath the saltwater-saturated sands would involve artesian flow of groundwater through conduits in the underlying lacustrine clays. Excavation of sand tufa at a number of localities, however, revealed no evidence of basal springs. The near-absence of tufa towers found in association with sand tufa, and the fact that sand tufa occurs in long, continuous bands that closely follow the contour, likewise argue against local artesian flow being an important factor in its production. Artesian flow, it seems, is not contributing to the formation of sand tufa--a point apparently appreciated by Cloud and Lajoie.

If vertical density currents are to function in surficial littoral sands in the manner described by Cloud and

Lajoie, it would seem that the sand must first be saturated with the lighter fluid, then immersed in the heavier fluid. In the absence of fractures or faults that would allow artesian water to penetrate the underlying aquiclude, freshwater obviously cannot invade the sand as long as that sand remains immersed in the lake. Should the lake drop below the level of the sand, however, lake water would drain from the deposit, giving access to freshwater. Based on this premise, it is hypothesized that sands deposited at the shore of the lake become stranded and saturated with fresh water during a lake recession. Reinundation of the freshwater-saturated sands with lake water, brought about either by wave rush, by seiching, or by a rise in lake level (or perhaps by repeated wave-rush and seiching <u>during</u> a rise in lake level) results in a density-induced exchange of fresh- and saltwater along vertical pathways in the sand, as described by Cloud and Lajoie.

The brief rises in lake level that have annually punctuated the overall recession since 1919 may account for most of the sand tufa seen around the lake. These late-spring and early-summer transgressions come at a time when stranded sands are most likely be saturated with fresh water. Behavior of the lake on a year-to-year basis might also explain the prominent and thoroughly-cemented zones of sand tufa that lie within the elevation intervals 6415-6418

feet and 6425-6428 feet. The lake occupied each of these elevation intervals continuously for ten years, fluctuating seasonally so as to repeatedly inundate, expose, and reinundate a narrow band of shore.[19]

Cloud and Lajoie write that some deposits of sand tufa are capped by a thick (up to 15 cm) slab of calcium carbonate (Photos 15d). The authors venture that the capstone is pedogenic caliche that formed subaerially through evaporative processes following a lake recession that stranded the sand tufa. A close examination of this material (Photo 15e) shows that it is composed of a core of highly porous tufa that is coated with a thin crust of dense laminated tufa--in other words, the capstone is structurally identical to the masses of tufa that were seen forming subaqueously during the tufa blooms of 1982, '83, and '84. These observations, together with the belief that a thick mass of pedogenic caliche could not have formed on the calcite-impregnated defluidization structures within the past two decades, lead the writer to conclude that the slabs that cap the cemented sands are the result of rapid physicochemical precipitation of porous tufa at the margin of the lake (most likely during the process of sand tufa formation), followed by the encasement of this porous material in a sheath of dense algal tufa. With this in mind, it may well be that much of the tufa that was seen growing during the blooms of recent years is the surface

expression of newly forming sand tufa that will be exposed due to deflation during future recessions of the lake.

The distribution, hydrology and formation of beach pavements. Beach pavement is composed of coarse littoral sediments (boulders, cobbles, and/or pebbles, sometimes in a matrix of coarse sand) thoroughly cemented by tufa. Deposits of beach pavement often occur in narrow (2-5m) belts a hundred meters or more long that closely follow the contour. Within the elevation range occupied by the margin of Mono Lake during the past 4,000 years, surface deposits of beach pavement are restricted to the Western Embayment, the Horse Creek Embayment, the southern fringes of Black Point, the fronts of the Mill and Lee Vining creek deltas, and small areas on the plains of the Mill and Rush creek deltas (Figure 15).

Beach pavement appears to be a shallow-groundwater phenomenon that forms where surface water, absorbed by fanglomerate or other coarse deposits some distance above the lake, reemerges through permeable sediments at the shoreline. The necessity of an ample supply of groundwater for the formation of beach pavement is well illustrated in the Horse Creek Embayment. There, coarse sands, pebbles, and cobbles of rhyolitic pumice reworked from the Rush Creek delta compose a sparsely vegetated beach that runs the length of the embayment between 6,402 and 6,409 feet. On aerial photos

this entire swash of abandoned shore appears to be paved with tufa. Ground inspection, however, shows that the beach is cemented only along its northern quarter, where a withering Horse Creek provides the essential groundwater.[20]

In addition to coarse littoral sediments and a plentiful supply of groundwater, formation of beach pavement seems to require a shoreland surface whose gradient exceeds approximately 5%. Thus, while cemented beach debris is common on steeply sloping delta fronts, it is rare on the gently sloping delta plains. Only at favored elevations, where littoral erosion or deposition has markedly steepened the surface, has beach pavement formed on the plains of the deltas.

Having made a distinction between sand tufa and beach pavement, it is important to point out that there can be an intergradation of the two. In its purest form, beach pavement displays no vertical tubes or columns, undoubtedly because the intersticies between the coarse grains of sediment provide the vertical pathways necessary for the exchange of fresh and salt water. But vertical tubes and columns become evident where cobbles and gravels occur within a matrix of littoral sand. In general, the less sand, the more pavement-like the calcite-cemented deposit; the more sand, the more the deposit resembles classic sand tufa.

Tufa towers. As first explained by Russell (1885,1889),

the tufa tower is an artesian phenomenon that forms in association with a spring. While occasional isolated towers can be found at Mono Lake, most occur in "groves" that may include thousands of individuals. Tufa groves occur in two distinct hydrologic settings. In general the most extensive concentrations of towers are found along stretches of shoreline to either side of the late Pleistocene deltas on Rush, Mill and Lee Vining creeks (Figure 15). These groves owe their existence to groundwater that flows from the gravels of the highstanding deltas laterally toward lower elevations on the delta margins. Many, though by no means all, of the towers in these "delta groves" occur in linear or curvilinear assemblages that rise from fractures or faults (Photo 16a). At Lee Vining Tufa and South Tufa, the most extensive tufa groves at Mono Lake, most towers become progressively shorter upslope, resulting in a striking summit accordance that may be related to the height of the piezometric surface. At these two groves, true tower-like forms are restricted to elevations below about 6400 feet. Above that elevation one encounters squat tufa towers here called "ground tufa"--tufa masses of artesian origin that are less than a meter high and that display greater horizontal than vertical development. Ground tufa at these two groves is seldom found above an elevation of 6404 feet (Photo 16b).

The other major concentrations of tufa towers at Mono

Lake occur along faults distant from the deltas. These "fault groves" are most common along the southeastern shore (Lajoie, 1968), where a system of faults trending roughly north/south (see Appendix D) allows the artesian flow of spring water into the lake (Photo 16c). The towers in the fault groves are typically fewer in number than their counterparts on the margins of the deltas; on the other hand, they characteristically extend to higher elevations (above 6430 feet in a few cases) than towers within the delta groves.

The core of the typical tower (be it in a delta-grove or a fault-grove) is composed of fragile, yellow-to-orange-to-brown, porous-lithoid tufa, which characteristically can be crushed under pressure from the thumb nail. This core is encased in at least one sheath of hard, white, massive-to-laminated, dense-lithoid tufa. (In some places more than one sheath is evident--see Photo 16d.) Scholl and Taft (1964), and Lajoie (1968) proposed that the durable sheath is deposited first, and that the resultant hollow pinnacle is subsequently filled with porous tufa, both the core and the sheath being precipitated by algae. Based on the sequence of events observed during the tufa blooms of 1982, '83, and '86, however, it seems more likely that the first step in tufa tower formation is the rapid, physicochemical precipitation of the porous core material, which is subsequently coated

with dense, algal tufa. The fact that the porous inner core is often replete with the desiccated remains of brine fly (Ephydra hians) pupae proves that precipitation of the core material preceded deposition of the dense, impenetrable sheath.

Formation of the flanges that protrude from the flanks of some tufa towers has also ben attributed to algae (Lajoie, 1968). The porous nature of the tufa that composes the flanges, however, and the fact that each flange must have been precipitated rapidly in order to conform to a single lake level, strongly suggest that they were deposited physicochemically, rather than through the action of algae.

Many hundreds of towers found around Mono Lake contain woody branches and twigs, either within the porous tufa of the core, or incorporated within the dense tufa of the tower flanks (Photos 16e and f). Branches have been found in towers at all the major tufa groves except South Tufa. Incorporation of woody material into tufa towers is most common at the Mono County Park on Dechambeau Creek, and on the Mill Creek-North tufa groves (Figure 15). These inclusions of wood can be used to date the tufa towers (see discussion, pg. 198).

The distribution, hydrology, and formation of boulder and cobble rinds. The exposed bed of the western half of Mono Lake is strewn with tens of thousands of boulders

partially embedded in littoral or lake bottom sediments. These boulders are partially to entirely coated with a rind of lithoid tufa. Five types of shoreline boulders can be distinguished on the basis of lithology, distribution, and provenance: The granitic and metamorphic clasts scattered along the shoreline of the Western Embayment owe their present position to rockslides and rockfalls off the steep escarpment of the Sierra Nevada; aphyric pumice, obsidian, and lithic boulders of rhyolite on and east of the Rush Creek Delta were ejected during the Mono Craters eruption of 605 cal BP (see pg. 262); blocks of slightly vesicular basalt and basaltic scoria that dot the shore zone south of Black Point are apparently lag from the erosion of the cinder cone; boulders of Bishop Tuff scattered along the eastern shore are the result of transport down Dry Creek during times of high stream discharge; and the blocks of porphyritic pumice that line the shore from Horse Creek Embayment in the south to near the mouth of Bridgeport Creek in the north originated during a sublacustrine volcanic eruption approximately 1700 years ago (see pg. 240).

The rind of lithoid tufa that coats boulders lying below the Historic High Stand is typically white to very light cream in color, while the boulder rinds above 6428 feet are often yellow to orange or brown. Thickness of the rinds ranges from paper-thin to several cm. A similar rind of tufa

can be found on the flanks of the Negit islets, on boulders along the shoreline fringes of the lava flows on Negit and Paoha islands, and on beach cobbles and boulders lying on and near the major deltas.

Unlike tufa towers, tufa pavements, and sand tufa, formation of which involves groundwater, boulder rinds of tufa are not a groundwater phenomenon. Two lines of reasoning lead to this conclusion: First, very few of the boulders occur at recognizable spring sites. There is not a single known spring on Negit Island, in fact, yet shoreline boulders on the fringes of the Negit lava flows display some of the thickest tufa rinds at the lake (see Photo 32c). Furthermore, if localized spring sites were the source of the calcium-bearing waters, the thickness of tufa on Negit boulders could be expected to vary appreciably from point to point on the island; instead, at any given elevation on a particular lava flow the boulder rinds are of approximately uniform thickness. Secondly, the vast majority of the boulders along the shore of the lake lie on, and are embedded in, sediments not impregnated with tufa. Were groundwater a factor in the precipitation of the tufa rinds, it could be expected that sediments in close proximity to each of the boulders would be at least partially tufa-cemented.

Rather than having a groundwater origin, the calcium essential to the formation of the tufa rinds appears instead

to be abstracted from the hypopycnal stratum of freshwater that covers much of the lake during periods of high stream discharge (Photo 2). That the surficial stratum of fresh water can at times maintain its integrity over large areas of the saline lake was illustrated during the winters of 1982-83 and 1983-84. In anticipation of abnormally high spring snowmelt the LADWP in each of those winters released substantial amounts of water down Rush and Lee Vining creeks. As a result of these releases, much of the lake surface--in most winters too saline to congeal--froze over for the first time in the memory of longtime Mono Basin residents. Mr. Don Banta of Lee Vining viewed the lake from the Conway Summit Vista Point along Highway 395 on a January morning in 1983. He reports that an unbroken sheet of ice stretched from the western shore to, and well beyond, the islands. By Banta's estimate, between two-thirds and four-fifths of the lake surface was frozen over.[21]

The point here, of course, is not that the lake surface froze, but that enough fresh water covered the saline lake to permit freezing from the western shore to well beyond the Mono islands. Consider next that the amount of discharge during each of these two winters was not high by spring and summertime standards. Indeed, the amount of freshwater flowing onto the surface of Mono Lake during the month of July in each of the high-inflow years 1938, '52, '67, '69 and

'83 exceeded the discharge during any winter month of 1982-83 and 1983-84 by a factor of between 2 and 10. It must be considered likely that under inflow conditions like those that occurred during the late spring and summer of 1938, '52, '67, '69 and '83 a stratum of freshwater would cover much if not all of the lake surface, persisting for a period of weeks or even months. Mixing of these two fluids and the consequent precipitation of tufa would most readily occur along the shore of the lake and the fringes of the islands due to wave agitation.

Actual precipitation of tufa along the pycnocline was observed first-hand at Dechambeau Creek during the lake-wide "tufa bloom" of 1984. During the preceding years, this stream, like most others tributary to Mono Lake, had incised in response to the drop in lake level. During the lake rise of 1982 and '83 the Dechambeau Creek channel was engulfed with saline water along its lower reaches, creating hypopycnal conditions within the ria. The writer examined the engulfed portion of the stream several times in early July of 1984; as in dozens of previous visits, he observed the hypopycnal conditions, but saw no evidence of tufa precipitation.

On July 22, a thin encrustation of porous lithoid tufa was observed forming on the walls of the Dechambeau Creek cut at the level of the pycnocline. At the time of these initial

observations precipitation of tufa was limited to points on the channel walls where protruding vegetation and other irregularities set up zones of turbulence, forcing the mixing of the two fluids (Photo 17a). On July 24, just two days after the Dechambeau tufa bloom was first observed, the precipitate covered the walls of the creek channel to a thickness of over 40 cm (Photo 17b). This light-brownish-tan, highly fragile tufa had a structural framework suggestive of a sponge (Photo 17c). It closely resembled in color, structure and texture the porous lithoid tufa that composes the interior of most tufa towers.

Precipitation of tufa within the ria of Dechambeau Creek was short-lived. Whereas tufa formation at many other sites around the lake continued into September and beyond, it persisted only a few weeks in the Dechambeau cut. Furthermore, algae, which at many sites around the lake soon encased the newly-deposited porous tufa in a thin sheath of durable, dense tufa, apparently never acted on the Dechambeau Creek deposit. By October 13, when the Friends of the Pleistocene visited the site, roughly half of the porous tufa had been eroded off the channel walls by streamflow, and in January of 1985 only small patches of the precipitate remained.

It is readily admitted that the hydrologic conditions within the confines of the Dechambeau Creek cut are markedly

different from those along the lake and island shorelines, where the tufa-covered boulders are found. Nevertheless, with observations to indicate that a stratum of calcium-bearing freshwater can cover much, if not most of the lake surface during times of high stream inflow; with evidence that precipitation of tufa does occur due to mixing of fresh- and saltwater at the pycnocline; and in the absence of another source of calcium-bearing water to account for the rinds of tufa that cover the shoreline boulders, an hypothesis that invokes hypopycnal flow to explain the tufa rinds on shoreline boulders and cobbles does not seem untenable.

Tufa-covered stumps. In addition to pavements, towers, calcite-impregnated defluidization structures, boulder and cobble rinds, fragile "blossoms", and the crust on the sides of the Dechambeau Creek cut, tufa at Mono Lake occurs as a thick crust that coats relict tree stumps. The luxuriant growth of rushes and other graminoid vegetation that surrounds the bases of these rooted derelicts today (Photo 18) suggests that the stumps are acting as "wicks", bringing fresh groundwater to the surface by capillary action. It seems plausible that mingling of capillary water with lake water on the outside of the stumps may account for the precipitation of tufa at these sites.

The Problem of Radiocarbon Dating Mono Lake Tufa

Deposits of dense-lithoid tufa are being used with increasing confidence to radiometrically date the late Quaternary fluctuations of Great Basin lakes (Broecker and Walton, 1959; Broecker and Kaufman, 1965; Benson, 1978; Lajoie, pers. comm., 1985). Theoretically-derived coefficients that correct for the dead (^{14}C-free) carbon incorporated in tufa at the time of deposition have been developed for Pleistocene lakes Lahontan and Bonneville, as well as for Holocene water bodies including Walker and Pyramid lakes (Benson, 1978, Broecker and Walton, 1959). These calculations suggest that tufa at present-day Walker and Pyramid lakes should produce radiocarbon dates approximately 400 years too old. Environmental complexity has discouraged similar chronometric work in the Mono Basin. Here, sublacustrine volcanism and geothermal spring activity introduce large amounts of dead carbon to the lake. Addition of dead carbon may well vary both spatially and temporally, further complicating the derivation of correction coefficients.

Given the unusually high carbonate content of Mono Lake water, one would expect the discrepancy between actual and radiocarbon dates on Mono tufa to be considerably greater than at either Walker or Pyramid Lake. Limited empirical

data bear this out. Wood from outer rings of one of the aforementioned tufa-covered stumps yielded a ^{14}C date of 640 years; tufa from the outside of that same stump gave a date of 3240 years--a discrepancy of greater than 2600 years. Until an empirical relationship between actual and radiometrically derived ages of tufa at Mono Lake can be established, it seems best to use the abundance of non-calcareous organic matter available in the late Holocene sediments, rather than tufa deposits, for ^{14}C control of the lake level curve.

Tufa as a Shoreline Indicator at Late Holocene Mono Lake--Summary

For reasons just discussed, tufa cannot yet be employed as a means of dating the late Holocene surface fluctuations of Mono Lake. But strong arguments can be made to support the notion that certain types of tufa deposits may be used as indicators of former shoreline position. The fact that deposits of beach pavement and sand tufa typically hew closely to shoreline contours, for instance, indicates that the mingling of freshwater and lakewater that resulted in tufa precipitation occurred at the shoreline, rather than along some springline running at an angle to the shore. The littoral nature of the sands that compose calcite-impregnated

defluidization structures, together with the apparent need for the sands to first emerge from, then be resubmersed in the lake, further indicates that the formation of sand tufa is necessarily a shoreline phenomenon. Considerable confidence in these interpretations accrues from the fact that wherever found in the subsurface sedimentary record at late Holocene Mono Lake, beach pavement and sand tufa occur in association with what are clearly littoral deposits.

Observations made by the writer, as well as by contemporary and previous workers, attest to the sporadic nature of tufa formation at Mono Lake. It is important to note, then, that while the presence of tufa pavements, oolitic sands and sand tufa may be considered indicative of a shoreline environment, their absence does not attest to non-littoral conditions.

The degree to which other types of tufa can be used as an indication of former shoreline position remains open to question. There is a considerable amount of circumstantial evidence to suggest that deposition of tufa rinds on shoreline boulders and cobbles occurs due to the wave-induced mingling of fresh- and saltwater along the pycnolimnion; to what depth this precipitation can occur, however, is not known. While there is little doubt that the flanges that protrude from the flanks of some tufa towers were deposited at the level of the lake surface, as proposed by Lajoie,

there is no compelling reason to believe that production of the towers themselves is restricted to a shoreline environment. Formation of towers, as well as of the tufa casts that occur on relict stumps, may well occur wherever there is a sufficient population of algae--a factor that could conceivably allow tufa formation at depths of up to 15 m. These types of tufa, therefore, were not used in constructing the pre-historic fluctuation curve for Mono Lake.

FOOTNOTES

[1] It is clear that Gilbert envisioned a case of hypopycnal inflow in describing his model of deltaic sedimentation. He wrote (pg. 104), for instance, of a "superficial stratum of stream water" that "shoots out over the relatively still water of the lake" (emphasis added).

[2] In theory, a highly sinuous prograding stream could maintain an equilibrium slope initially by reducing sinuosity. As sinuosity is lost, however, continued progradation would necessitate aggradation.

[3] In a strict sense it is deposition by the distributaries, rather than by the trunk stream itself, that builds the delta lakeward. A cross section through the unconfined portion of Gilbert's "normal delta", therefore, would not reveal a simple progression of discrete foreset beds, as illustrated in his work on Lake Bonneville, but rather a complex of onlapping foreset cones, evidence of the periodic lateral shifting of the distributaries.

[4] Gilbert noted that the gradient of the delta plain "diminishes gradually lakeward to the foot of the deposit slope [that is, to the distal margin of the delta plain], so that the longitudinal profile is slightly concave upward. At the head of the deposit slope [i.e. the point at which the trunk stream bifurcates to form the delta] there is often an abrupt change of grade."

[5] The stated pattern of delta evolution is, at least in one respect, highly improbable: Thus, it is unrealistic to assume that a Gilbert-type delta built into a previously non-fluctuating lake could be at different times both submerged and incised due to wholesale changes in lake level, as suggested in the model. Throughout the North American Great Basin, in fact, virtually all parent deltas of Holocene age owe their existence not to a prolonged stillstand (the mode of formation suggested in the model), but rather to the drop in lake level and consequent incision of high-standing Pleistocene deltas that occurred early in Holocene time (see discussion, pgs. 119-120).

[6] The early Holocene lake regression was punctuated by at least 14 pronounced stillstands or minor rises, each of which is marked by a prominent shoreline embankment in "Mono Valley" north of the present-day lake. These features correspond to the following lake elevations (in feet): 7033,

6962, 6933, 6905, 6861, 6846, 6819, 6780, 6769, 6755, 6742, 6691, 6685, and 6605. Three of these strandlines (at 6819', 6769', and 6755'), as well as several others (at 6668', 6640', 6590', and 6558'), are expressed as erosional terraces on Black Point. With no chronometric control over events in early or middle Holocene time, it is presently impossible to assign ages to these lake-recessional features.

[7] Since Mono Lake (in contrast to Lake Russell) is by definition a Holocene entity, the deltas of Mono Lake are likewise Holocene in age. It is thus redundant to speak of the "Holocene deltas of Mono Lake".

[8] Seven littoral embankments mark the shoreline recession of the mid-1920s through mid-1930s on the Rush Creek delta. These seven embankments coincide in elevation with the surface of the lake in each of the years 1925 through 1931. Bars and berms deposited during the lake recession of 1932-1937 were obliterated in 1938 and '39, when the lake rose over four feet in response to abnormally high inflow.

[9] The flow of Mill Creek is not controlled by LADWP, but rather by Southern California Edison, which diverts it through a power generating station north of the stream near the front of the Sierra Nevada. From the generating plant the water flows through a system of irrigation channels, ultimately ending up in Wilson Creek. The flow of Mill Creek has thus been diminished by this diversion, while that of Wilson Creek, under natural conditions a tiny ephemeral stream, has been substantially increased. (This increase in flow, rather than a drop in base level, accounts for the dramatic incision of Wilson Creek that has occurred since about 1940.) Because of leakage from the dam at Lundy Lake a small amount of water flows down Mill Creek even in dry years, carring sediment that is deposited at the stream mouth.

[10] Holmes (1980) and Wornardt (1964) catalogued the diatom taxa present in the sediments of Lake Russell.

[11] According to Harding (unpub.), this tree grew about 0.2 mile north of Hammond's Hotel and 1.5 miles south of Mono Lake P.O.

[12] On April 24, 1915 the lake surface stood at 6425.27 feet; by July 13 of the following year it had risen to 6426.51 feet. Lake readings taken between these two dates are considered to be "obviously in error" by the USGS.

[13] Lajoie, (1968, p.111) mistakenly interpreted this evidence to indicate that the lake had not stood above 6419 feet for at least 150 years prior to 1857.

[14] Mr. Kevin Dummer of Albany, California, prepared a vegetation map of the historic shorelands of Mono Lake as a state exhibit for Federal Litigation No. S-80-696, U.S.D.C., E.D. Cal. The map is recommended to all who wish to pursue questions related to the rate and dynamics of vegetation colonization of the Mono shorelands.

[15] See discussion of calibrated radiocarbon dates, Chapter 2, Section F.

[16] Recently Sieh (pers. communication) discovered and dated a pyroclastic deposit that was ejected from the Mono Craters approximately 900 years BP. It appears that the tephra from this eruption is restricted to an area south of the lake; nowhere has it been identified in cuts or pits in the study area of this thesis. It is thus not included in this discussion of the "widely dispersed" Mono Craters tephras.

[17] Michael Dressler, Palo Alto, California, pers. comm., July, 1985.

[18] Professor John Melack, U.C. Santa Barbara, pers. comm., April 21, 1985.

[19] The lake margin occupied the interval 6425-6428 feet between 1916 and 1925, and the interval 6415-6418 between 1938-1948.

[20] The distribution of riparian vegetation also reflects the relative abundance of groundwater in the northern quarter of the Horse Creek Embayment.

[21] According to longtime Mono Basin resident Don Banta (pers. comm., 1985) the lake surface in the Western Embayment freezes often during the winter months. January of 1983 was the first time that he had observed large areas of the rest of the lake freeze over.

CHAPTER 3

THE PRE-HISTORIC FLUCTUATIONS OF MONO LAKE

Introduction

Having examined the various types of evidence that can be brought to bear in constructing a pre-historic fluctuation curve for Mono Lake, it is now possible to trace the lake fluctuations themselves. Following a discussion aimed at correcting certain misconceptions about the behavior of the lake in mid-Holocene time, the late Holocene changes in lake level are presented from oldest to youngest, beginning with the high stand of 3490 yrs BP.

The purpose here is not to present all existing evidence for each point on the curve, but simply to establish the curve using the most straightforward evidence available. Subsequently (Chapter 4), several stratigraphic sections described in the thesis will be discussed in the context of the lake fluctuation curve, thus providing a "check" on the curve.

The lake level curve spanning the past 3500 radiocarbon years is shown on Figure 16. The lake fluctuations are plotted against radiocarbon years from 3500 BP to 1610 BP, and against calibrated radiocarbon dates for the past 1610

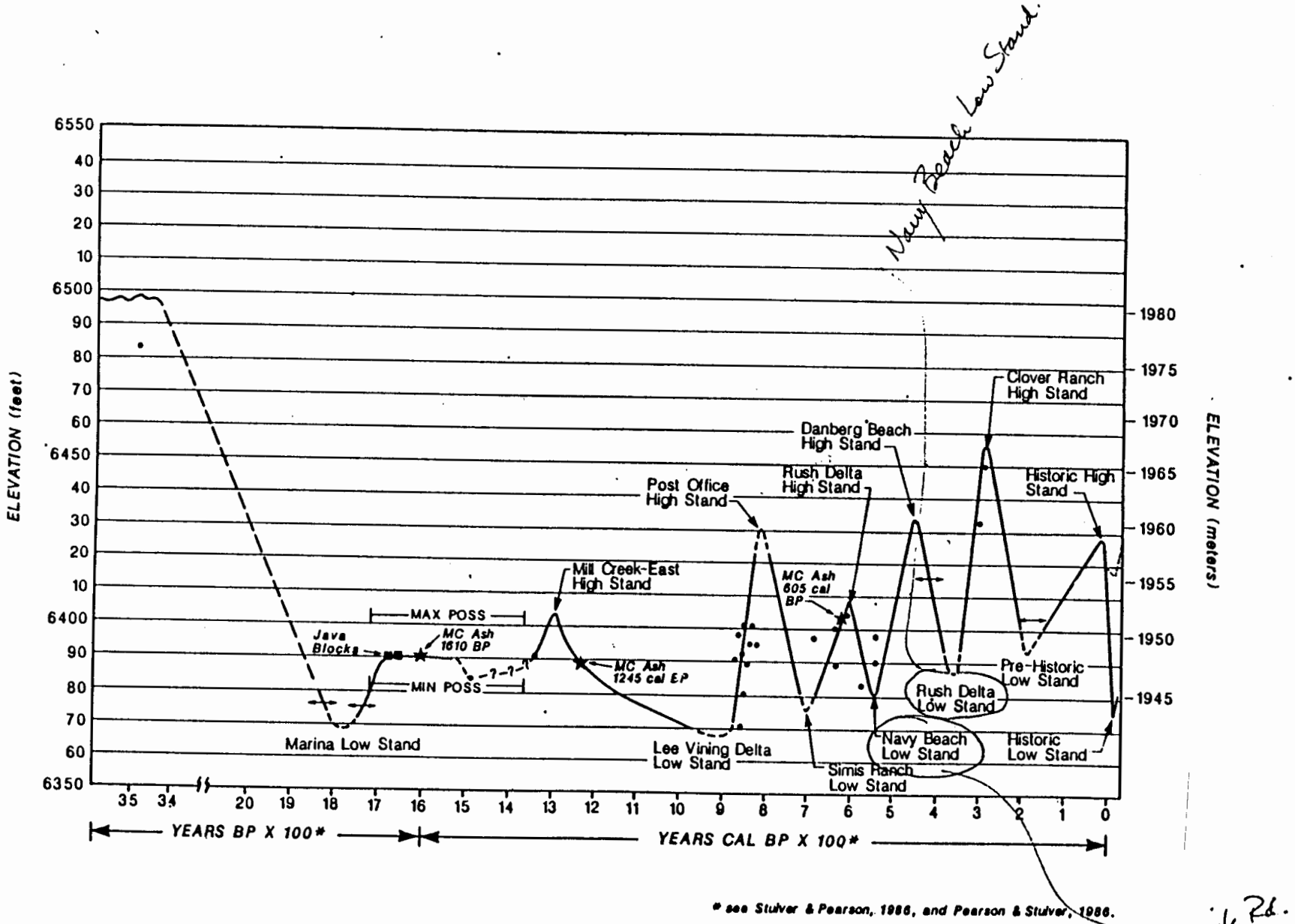


Figure 16. Late Holocene fluctuations in the surface elevation of Mono Lake.

years. Note too that the fluctuations are depicted as straight segments linking high stands with low stands and vice versa. It must be appreciated that in actuality each transgression and recession was characterized by short-term reversals and stillstands, evidence of which can sometimes be discerned in the sedimentary and geomorphic records, but the timing and duration of which cannot be accurately determined. In drawing the lake fluctuation curve, and in considering the paleoclimatic implications of the curve (Chapter 6), then, the intricacies of individual transgressions and recessions have been ignored.

Prelude in Mid-Holocene Time

Since the 1930s and '40s, when Ernst Antevs first proposed his three-fold climatic division for the Holocene of western North America (Antevs, 1931, 1948), much has been written of the "Altithermal", a supposed period of warm, dry climatic conditions that persisted from 7000 to 4000 years ago. The concept of an Altithermal interval is so deeply entrenched in the Great Basin literature that in many quarters it has become synonymous with "mid-Holocene". Despite recent arguments (e.g. Martin, 1963; Aschmann, 1958; Harper and Alder, 1970) challenging the authenticity of Antevs' "Long Drought" (Antevs, 1953, 1955), the belief in "3,000 years of excessive warmth" (Matthes, 1942a), "a

widespread period of maximum aridity" (Born, 1972), and "an extremely warm climatic period" (Heizer and Elsasser, 1980), in the Great Basin between ~7000 and ~4000 years ago lives on. The purpose of this section is to examine the assumptions and reasoning that led Antevs and other early workers to infer the existence of a Great Basin Altithermal interval. It will be shown that the tripartite model, as applied to the Great Basin of North America, is a concept rooted in preconception, misinformation, and circular reasoning, and that it has led to erroneous and counterproductive speculation that has prejudiced the interpretation of Great Basin saline lakes, including Mono Lake.

Origins of the tripartite climatic model. Antevs' tripartite division of the Holocene is based on the Swedish climatic chronology, which includes a period of "Post-Glacial temperature maximum" lasting from approximately 7000 to 4000 years ago (Antevs, 1931, 1952). Antevs believed that the Great Basin lacustrine record provided a basis for applying this same climatic chronology to the western United States. According to his model, the early Holocene, from 9000 to 7000 years ago, was a period of cool, moist climatic conditions that kept closed lakes at levels higher than those of modern times. Antevs envisioned rising temperatures in the Great Basin toward the end of this period; he thus named it the

"Anathermal" ("ana" = upward). He believed that the Anathermal interval was followed by 3000 years of Altithermal conditions, when terminal lakes of the Great Basin disappeared due to the persistence of aridity and high temperatures ("alti" = high). The supposed reappearance of the lakes some 4000 years ago marked the end of Altithermal time and the beginning of the "Medithermal", an interval that Antevs perceived as being intermediate in temperature and moisture conditions ("medi" = of intermediate degree) (Antevs, 1948).

Antevs' evidence for both the nature of his proposed Great Basin climates and the timing of the climatic changes is surprisingly scant. His conclusions rest entirely on the presumed fluctuations of three Great Basin water bodies: Abert and Summer lakes in southeastern Oregon, and Owens Lake in east-central California. He defined the beginning of the Altithermal interval on the basis of the sedimentary record at Summer Lake. Following the stratigraphic work of Allison (1945), who identified what he believed to be Mazama ash in Summer Lake sediments, Antevs concluded that at the time of the Mazama eruption the lake surface stood "at least 45 feet above the highest stand attained during the Medithermal [that is, during the past 4000 years], and at least 90 feet above the present [1940's] lake level." Based on this information, and on presumed sedimentation rates, Antevs wrote that prior

to, and "for at least 1500 years" following the eruption of Mt. Mazama, "the climate was distinctly moister than at present." Antevs believed the Mazama ash to be approximately 8500 years old; he thus concluded that a cool, moist climate prevailed until around 7000 years ago, when warm, dry conditions ushered in the Altithermal interval (Antevs, 1948). This ~7000-year date was especially appealing to Antevs, since the Swedish chronology, to which he so closely adhered (Antevs, 1931; 1936, 1956), includes the onset of warm, dry conditions at that same time.

It is now known that the eruption of Mt. Mazama took place not 8500 years ago, but approximately 6800 years BP (Bacon, 1983). If Antevs' belief that 1500 years of mesic conditions followed the Mazama eruption is applied to this date, it would have to be concluded that climatic conditions "were distinctly moister than at present" until perhaps 5300 years ago--in other words, that the climate was more mesic than at present throughout the first two-thirds of the "Altithermal interval". Antevs was confronted with this apparent contradiction in the early 1950s, when Arnold and Libby (1951) ran the first radiocarbon dates on the Mazama eruption. So convinced was Antevs that the Altithermal began 7000 years ago that he rejected the radiocarbon dates as being "improbable" (Antevs, 1955).

Antevs' method of assigning a date to the beginning of his Altithermal interval was undermined in the mid-1960s, when Allison (1966) reported that the Summer Lake tephra which he had interpreted to be from Mt. Mazama was actually an ash that was ejected from an unknown source more than 30,700 years ago. The implications of this correction relative to the beginning of "Altithermal time" have been overlooked, however, and Antevs' interpretation of the Summer Lake record continues to be cited as evidence for the onset of "Altithermal conditions".

Antevs contended that the mid-Holocene in the Great Basin was characterized by the disappearance of terminal lakes. He based this conclusion not on direct evidence of lake desiccation, but on salt budgets derived by Van Winkle (1914) at Summer and Abert lakes, and by Gale (1915) at Owens Lake. Gale estimated the accumulation time for the sodium in Owens Lake to be 3500 years, and suggested that this much time had elapsed since the lake was last "freshened" by overflow. Antevs accepted Gale's estimate of accumulation time (rather, he rounded it to 4000 years), but argued that the lake could not have overflowed during the centuries and millennia prior to 4000 years ago because of the warm, dry conditions that he believed prevailed during that interval. He maintained instead that the "freshening" was a result of the deflation and burial of salts due to desiccation of the

lake. Some 4000 years ago, by Antevs' interpretation, the lake reappeared, marking the end of Altithermal time (Antevs, 1938). Clearly, Antevs' use of Owens Lake as "proof" of a warm, dry mid-Holocene is predicated on his assumption that the lake desiccated rather than overflowed prior to 4000 years ago; this is but one of many cases in which he resorted to circular reasoning in order to "prove" the existence of a Great Basin Altithermal interval.

The question of whether Gale's results indicate desiccation, as opposed to overflow, of Owens Lake in mid-Holocene time is rendered moot by recent reevaluations of the Owens Lake salt economy. Langbein (1961), in his work on the salinity of terminal lakes, calculated the accumulation time for sodium at Owens Lake to be just 1700 years, rather than the 3500 years reported by Gale; similarly, calculations by Smith (1976) indicate that the salts in Owens Lake "appear to be the residue of about 2000 years of evaporative concentration." In light of modern information, then, Owens Lake's last freshening cannot be used either to prove the existence, or to mark the termination, of "Altithermal time"; indeed, until the climatically-induced surface fluctuations of mid-Holocene Owens Lake have been determined, that lake is irrelevant to a discussion of the "Altithermal interval".

Antevs' belief in a change from warm/dry to cool/moist

conditions 4000 years ago (Antevs, 1938, 1948) was reinforced by the salt budgets for Abert and Summer lakes--two lakes which did not overflow, and which therefore could have been freshened only by desiccation. Van Winkle's calculations indicating sodium-accumulation times of 4000 years, however, have been shown to be mathmatically "defective" by Langbein (1961). Though Langbein did not recalculate the sodium economy for Summer Lake, his reevaluation of the Abert budget yielded a value of just 500 years. The Oregon lakes, then, like Owens Lake, say nothing about the commencement, existence, or termination of an Altithermal interval.

Thus, it can be seen that Antevs' Altithermal interval is a concept founded on erroneous interpretations, circular reasoning, and preconceptions stemming from the Swedish chronology; the evidence cited by Antevs in his attempt to extend the Swedish sequence to the Great Basin is, in light of modern information, irrelevant to a discussion of the climatic conditions that characterized mid-Holocene time. Despite the weakness of its conceptual foundation, however, Antevs' post-glacial climatic sequence has persisted for decades with little criticism. The simplicity (as well as the apparent authority) of the model made it especially attractive to archeologists, biologists and geologists. Shortly after the tripartite sequence was put into print, scientists from these other disciplines began to reinforce

and perpetuate the Ana-, Alti-, and Medithermal concept. François Matthes (1938, 1939, 1942a, 1942b), for instance, took an interest in the Altithermal interval because of its potential applicability to problems of Holocene glaciation in the Sierra Nevada and other mountain ranges of the western United States. Matthes ventured that the same warm, dry conditions that reputedly desiccated Owens Lake in mid-Holocene time would have melted any ice persisting from the last Pleistocene glaciation. The present-day glacierets of the Sierra, he reasoned, are not remnants of Pleistocene ice tongues, but rather the product of a minor reglaciation (his "Little Ice Age") that began concurrent with what Antevs believed to be the rebirth of Owens Lake some 4000 years ago (Matthes, 1939, 1942b).

Matthes made no quantitative comparison between the climatic conditions necessary to desiccate Owens Lake and the conditions needed to waste the Sierran glaciers. His belief that Antevs' proposed lake desiccation was tantamount to glacier extinction is mere conjecture. In the absence of actual evidence of the mid-Holocene demise of Sierran glaciers,[1] Matthes' conclusions simply assume, rather than prove, the existence of "Altithermal" climatic conditions. This point apparently escaped Antevs, who, in another case of circular reasoning, cited Matthes' conclusions as independently-derived corroboration of an Altithermal

interval. Writing in his widely-circulated publication of 1948, Antevs paraphrased Matthes to the effect that during mid-Holocene time there was "complete or essential disappearance of permanent ice in the mountains, which means a long warm age."

Matthes' work helped bolster the Altithermal concept in another important way. In 1940 he attempted to "verify" Antevs' presumption that Owens Lake desiccated in mid-Holocene time. Citing the logs of cores extracted from the lake floor, Matthes reported that the sediments immediately underlying the lake are composed of lacustrine clays, and that these clays are in turn underlain by alluvial sands and gravels. He interpreted this sedimentary sequence as proof of Antevs' lake-desiccation hypothesis: the alluvial sediments, according to Matthes, "undoubtedly indicate a prolonged period of dessication [sic]" when disappearance of the lake permitted streams to carry coarse sediment onto the basin floor; he assigned the alluvium to the Altithermal period. The overlying lacustrine clays, by Matthes' interpretation, indicate the reappearance and continued existence of the lake in Medithermal time (Matthes, 1940).

At first glance Matthes' work does appear to corroborate the Antevs hypothesis of Altithermal lake desiccation. But the thicknesses of the stratigraphic units that underlie

Owens Lake belie Matthes' interpretation. The alluvium constitutes "several hundred feet", according to him, while the overlying clay body is "over 400 feet thick" (Matthes, 1940). To assign the accumulation of more than 400 feet of clay to post-Altithermal time, as Matthes did, is untenable; it requires an accumulation rate of approximtately one foot per decade--far in excess of known clay accumulation rates at other comparable terminal lakes.[2] Moreover, his interpretation requires either that the Owens Lake depression was over 700 feet deeper 7000 years ago than it is at present, or, alternatively, that there has been more than 700 feet of relative subsidence of the Owens Lake floor since the beginning of the "Altithermal interval". More likely, the sequence of sediments that Matthes described from Owens Lake represents an accumulation time of many hundreds of thousands of years.[3]

Surprisingly, Matthes' work at Owens Lake, and its bearing on mid-Holocene glacier extinction, escaped published criticism. That work, and Antevs' reiteration of it, continue to be cited as evidence of an "Altithermal interval".

Perpetuation of the Altithermal axiom. A detailed review of the many cases in which the tripartite model has been perpetuated uncritically (and thereby reinforced) is

beyond the scope of the present work. Suffice it to say that Matthes was but the first of dozens of Great Basin scientists to sieze upon Antevs' Altithermal concept. Unaware of the complexities and vicissitudes of post-glacial climate (see below), and swayed by a term ("Altithermal") and its many synonyms (e.g. megathermal, xerothermal, thermal maximum, climatic optimum, post-Glacial temperature maximum, The Long Drought, etc.) that beg the question of mid-Holocene climatic conditions, many workers, like Matthes, have accepted Antevs' sequence as axiomatic, forcing their findings into the Procrustean bed of the tripartite model.

At the very least, the Antevs model has fostered an overly simplistic view of Holocene climate in the Great Basin. This has led to an underemphasis on, and a lack of appreciation for, short-term (e.g. centuries-long) changes in climate. Yet as Peter Mehringer has pointed out, it is probable that climatic variation *within* each of Antevs' three major subdivisions was greater than any differences *between* the major subdivisions (Mehringer, 1985). While there can be little doubt, for example, that there were periods of relatively warm, dry climate during the mid-Holocene (just as there have been times of warm dry climate during the late Holocene), increasing evidence indicates that these xeric spells were puncutuated with conditions cool and moist enough to instigate minor glaciation in the Sierra Nevada (Curry,

1969) and the Rocky Mountains (Richmond, 1960; see also Benedict and Olson, 1978). Nor can the climatic conditions that existed during the so-called "Medithermal" interval be characterized in the simple terms used by Antevs. Rather than being a period of "intermediate" climatic conditions, the last 4000 years has been characterized by significant glacier advance, as well as glacier extinction;[4] it has been a time during which Abert, Summer, and Owens lakes reached relatively high surface elevations, as well as a time when, based on Langbein's and Smith's salt budgets, those same lakes desiccated; and, as will be shown, it has been a period during which the surface of Mono Lake has fluctuated often and widely, over a vertical range of up to 40 meters.

One unfortunate consequence of this oversimplification has been that in the absence of chronometric control, workers have tended to assign any geological or biological evidence of marked Holocene xericity to "Altithermal time", thus ignoring the possibility that severe and persistent droughts may have occurred during the supposedly climatically moderate "Anathermal" and "Medithermal" intervals. Workers at Great Salt Lake, for instance, suggest that the submerged desiccation polygons that cover the lake floor are Altithermal features that formed when the lake dried up "during one or more mid-Holocene intervals of maximum aridity" (Currey, 1980). While it is indeed possible that

the lake desiccated in mid-Holocene time, it is highly unlikely that the submerged polygons would be visible on aerial photos today if they were covered with 4000 years of lacustrine sediment; until formation of the polygons can be dated, the possibility that the lake desiccated within post-"Altithermal" time must be entertained.[5]

Mono Lake in mid-Holocene time. Mono Lake has been the subject of similar speculation. Scholl and his co-workers (1967), for instance, tentatively attribute formation of the sublacustrine terrace that surrounds the lake at an elevation of approximately 6368 feet to a drop in lake level during Altithermal time. Lajoie (1968) proposed a similar age and explanation for this "Scholl terrace", and speculated that the sand dunes north of the lake were also features of the Altithermal interval. It will be shown in later sections of this work, however, that the terrace was formed just ~1800 years ago (and indeed marks the late Holocene low stand of the lake), and that the sand dunes are likewise features of late Holocene time.

This study yielded no direct evidence that might cast light on the behavior of Mono Lake during the mid-Holocene.[6] At this time it is known only that during the early or middle portions of the Holocene Epoch the lake's tributary streams cut canyons graded to a lake surface at or below the

approximate level of the Historic High Stand. These canyons were engulfed by the lake during a transgression that began sometime before 3490 yrs BP.

3490 yrs BP--The Dechambeau Ranch High Stand

Introduction

Thirty-four hundred and ninety radiocarbon years ago Mono Lake attained a high stand (hereafter called the "Dechambeau Ranch High Stand") of 6499 feet, a level that it had not occupied since the decline of Pleistocene Lake Russell, and that it has not reached since. At the time of the high stand the canyons of the major tributary streams were engulfed by the lake, instigating the deposition of confined-onset deltas and fill terraces. The lake left a geomorphic and vegetative strandline that persists today on many areas of the shorelands.

The configuration of the lake margin at the time of the Dechambeau Ranch High Stand is shown on Figure 17. The expanded lake had a circumference of 77,490 meters and a surface area of 78,665 acres (= 31,835 ha). Evidence to be discussed in Chapter 5 indicates that no islands existed at the time of the Dechambeau Ranch High Stand.

Elevation of the Dechambeau Ranch High Stand

Nature of the strandline. The geomorphic strandline associated with the Dechambeau Ranch High Stand can be traced around most of the lake (see topographic profiles, Plate 6).

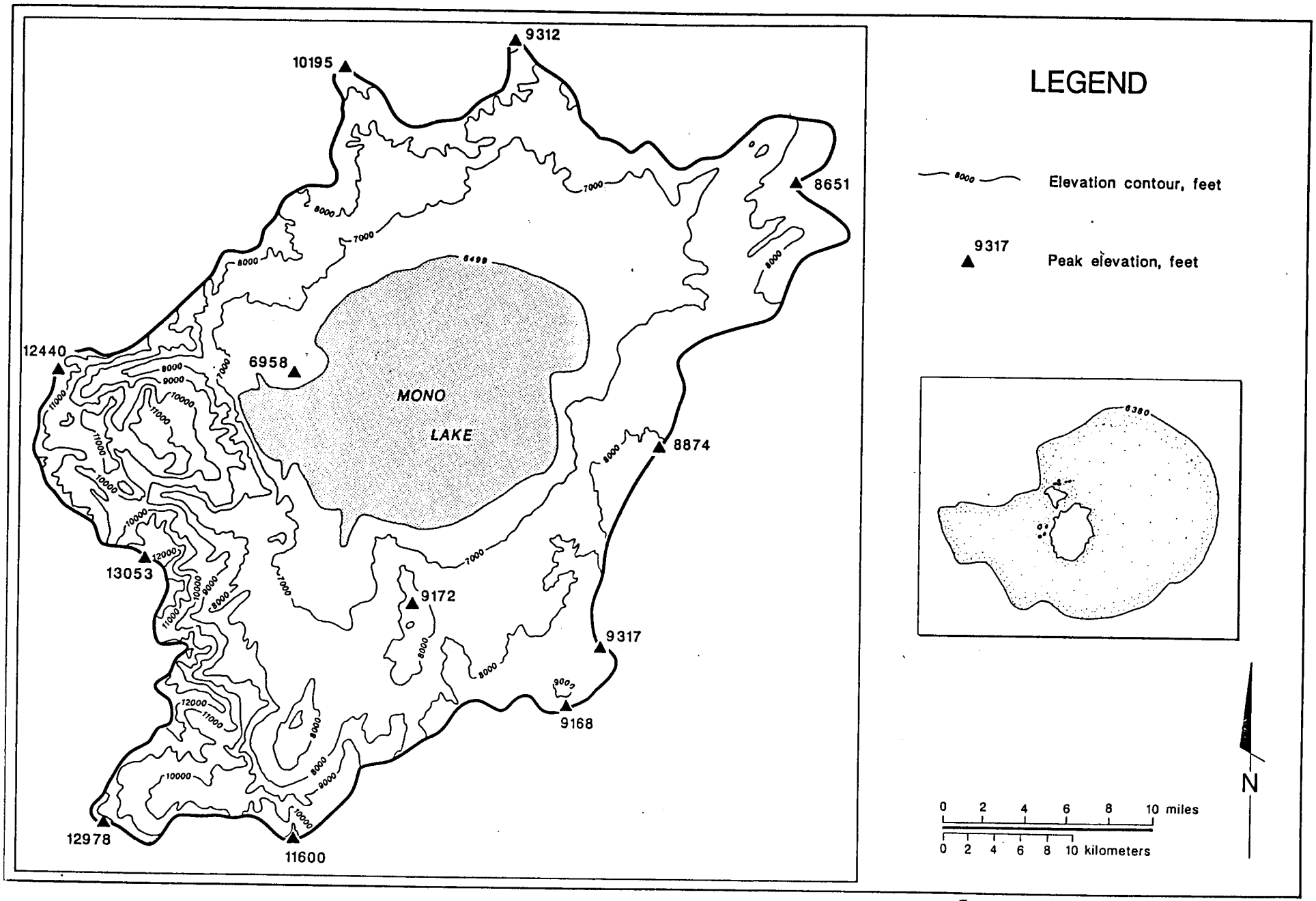


Figure 17. Configuration of Mono Lake at the time of the Dechambeau Ranch High Stand, ~3500 B.P.

It takes the form of an abrasion platform and cliffline on shorelands with a gradient in excess of approximately 4%. This includes the fronts of the Pleistocene deltas, the eastern and western flanks of Black Point, the Western, Dechambeau Ranch, and Horse Creek embayments, and long stretches of the northern and southeastern shorelands. On flatter shorelands, including those around Bridgeport and Cottonwood creeks and a short stretch northeast of Simon's Springs, the strandline is expressed as a broad embankment that locally (e.g. immediately west of Bridgeport Creek) has been deflated to produce small fields of dunes. In Mono Valley, where aeolian processes exert a stong influence on the topography, the high stand is marked by discontinuous ridges of sand that can reach heights of up to six meters. The strandline is represented by a bay-mouth bar in the Horse Creek Embayment, and it truncates the surface expression of a NE-SW trending fault in Mono Valley (Appendix D).

In only a few places is the strandline associated with the Dechambeau Ranch High Stand not evident. Between Rush Creek and the Mono Mills-to-Mono Lake jeep trail (Figure 2) it lies buried beneath pyroclastics from recent eruptions of the Mono Craters. East of Dry Creek the shoreline is overlain by a sheet of aeolian sand. It has been effaced from the steep southern (lakeward) flank of Black Point as well as from precipitous portions of the Sierran escarpment

due to undercutting by waves, and is typically covered by mudflow and avalanche debris in the vicinity of the intermittant Sierran streams.

Elevation of the strandline. The strandline described above was leveled at 18 sites around the lakeshore. It was found to lie at an elevation of 6499 (± 2) feet at all but two of the sites, where slightly higher elevations (up to 6504 feet) were measured. Since it is nowhere possible to pinpoint precisely the shoreline angle associated with this or any other high stand of the lake, these slightly higher values may reflect measurement imprecision, or localized "overbuilding" due to storm surging, rather than tectonic deformation.[7]

Many strandlines attributable to the early Holocene recession of Lake Russell lie above 6499 feet. What, then, is the basis for concluding that the strandline at that elevation is not simply another recessional feature of early Holocene time? And furthermore, how can it be established that during the late Holocene Mono Lake rose only to, and not above, 6499 feet?

Several features indicate that the lake rose to, rather than fell to, the shoreline at 6499 feet. First, the strandline is marked by a broad wave-cut terrace (a clear indication of a lake transgression) that truncates the lacustrine silts of the Wilson Creek Formation at many sites

around the lake shore (e.g. southeast of Simon's Springs and in the vicinity of Wilson Creek). At no sites between 6499 feet and 6700 feet has such a terrace been found. Less obvious, but perhaps even more convincing, are the confined-onset deltas and associated fill-terraces that were deposited in the trunk-stream canyons at the time of the high stand. The best preserved of these lies at a point labled "F" on Lee Vining Delta index map (Plate 3). A photograph of this ancillary delta is shown on Photo 19. Since the lake has to have first dropped low enough to instigate incision by the streams, and then risen to engulf the resultant canyons, the confined-onset deltas can be taken as irrefutable evidence of a lake transgression.

Thirdly, along many stretches of the shorelands the strandline at 6499 feet coincides with an abrupt vegetation boundary. Near Wilson Creek this vegetation break is expressed as a change from relatively alkaline-tolerant vegetation (including Artemisia, Chrysothamnus, and Elymus) below 6499 feet, to alkaline intolerant vegetation (dominated by Purshia and Ephedra) above that elevation (Photos 20a and b). In the Horse Creek Embayment the strandline is characterized by a sharp change in the incidence of alkaline-intolerant Purshia tridentata, from an estimated 40% of the brush cover below 6499 feet, to over 70% above the strandline. Other obvious vegetation breaks corresponding to

the elevation of the Dechambeau Ranch High Stand occur in the Dechambeau Ranch Embayment, and immediately west of the 119th Parallel on the lake's northern shore.[8] This vegetative strandline, and the lack of such a line above 6499 feet, strongly suggests that the lake had not occupied lands above this elevation for many thousands of years prior to Dechambeau Ranch time. It, in combination with the truncated Wilson Creek beds and the inset deltas, leaves little doubt that the strandline at 6499 feet represents a high stand of Mono Lake, rather than a recessional feature of Lake Russell.

Age of the Dechambeau Ranch High Stand

Both the truncated Wilson Creek beds and the confined-onset delta on Lee Vining Creek indicate that the Dechambeau Ranch High Stand occurred after the early Holocene recession of Lake Russell. Indeed, the persistence of a chemical/vegetal standline suggests the passage of a significant amount of time between the recession of Lake Russell and the Dechambeau Ranch High Stand. On Mill Creek, an inset regressive fill terrace (pg. 113) deposited during the recession from the Dechambeau Ranch High Stand lies stratigraphically beneath sediments that include three Mono Craters tephras, indicating that the Dechambeau Ranch High Stand occurred at least 1610 radiocarbon years ago, and

perhaps more than 1990 radiocarbon years ago. Bottomset beds associated with the Dechambeau Ranch-age confined onset delta on Lee Vining Creek can be demonstrated to lie stratigraphically beneath a sequence of sediments dating from before ~1700 yrs BP.

The conclusions drawn from these relationships--that the high stand occurred within Mono Lake time, but prior to perhaps 2000 years ago--are in keeping with the results of a radiocarbon date derived from detrital charcoal that was collected from low in the bottomset beds of the aforementioned confined-onset delta on Lee Vining Creek (see "Ober cut", Plate 3E, and Photo 29). That charcoal yielded an age of 3490 ±80 yrs BP (=3769 ±118 cal BP), effectively dating the beginning of the high stand.

Deposition of the Generation-1 Dunes

The spectacular dune field on the northern shorelands of Mono Lake is composed of three generations of sand dunes (pg. 145). The oldest of these is made up of low (1-3 m), evenly spaced lunettes (Photos 21a and b) that are today largely stablized by vegetation. With only a few exceptions the bases of these Generation-1 (G-1) dunes lie at and below an elevation of 6499 feet. The dunes could not have survived the Dechambeau Ranch transgression, and therefore must have

formed some time following the high stand. The close correspondence between the landward limit of the G-1 dunes and the Dechambeau Ranch High Stand suggests that they formed as the recession progressed, and that they were quickly colonized by vegetation, preventing the dispersal of sand onto lands lying above the strandline.

The recession from the Dechambeau Ranch High Stand was interrupted on at least two occasions. These pauses are marked in the dune field by high sand ridges, the bases of which lie at approximately 6470 and 6475 feet; elsewhere around the lake the pauses are expressed as low berms and bars.

Duration of the Dechambeau Ranch High Stand

It has not been possible to date the duration of the Dechambeau Ranch High Stand or the timing of the subsequent lake recession. That the streams were able to build bulky confined-onset deltas and associated fill-terraces graded to or slightly below a lake level of 6499 feet suggests that the high stand lasted centuries or more. But the actual duration of the Dechambeau Ranch High Stand, and the timing of the subsequent decline in lake level, remain unknown. Only one thing about the chronology of the recession can be said with confidence: that by the time of the Mono Craters eruption 1990(?) yrs BP Mono Lake was sinking toward its lowest level

in the last 3500 years.

~1820 yrs BP--The Marina Recession and Low Stand

Introduction

By approximately 1820 yrs BP the surface of Mono Lake had declined to a level as low as any attained in late Holocene time. This low stand, here referred to as the Marina Low Stand, is expressed in shoreland sections as desiccated lacustrine clays overlain by a sheet of oolitic and Sierran littoral sands. Sediments exposed in stream cuts show that Lee Vining Creek incised its parent delta in response to the Marina Recession, creating a subsidiary delta.

During Marina time the lake surface reached an elevation of approximately 6368 feet. At the time of the low stand the lake surface had an area of 36,000 acres (Figure 18). In the course of the subsequent transgression the lake carved an abrasion platform that persists today as a subaqueous terrace around much of the lake shore.

Evidence of the Marina Low Stand

Evidence of the Marina Low Stand can be found in the walls of sections excavated at the Mono County Marina north of Lee Vining. Logs of two of the Marina pits are shown on Plate 5. The lowest of these two sections (Plate 5E), with a

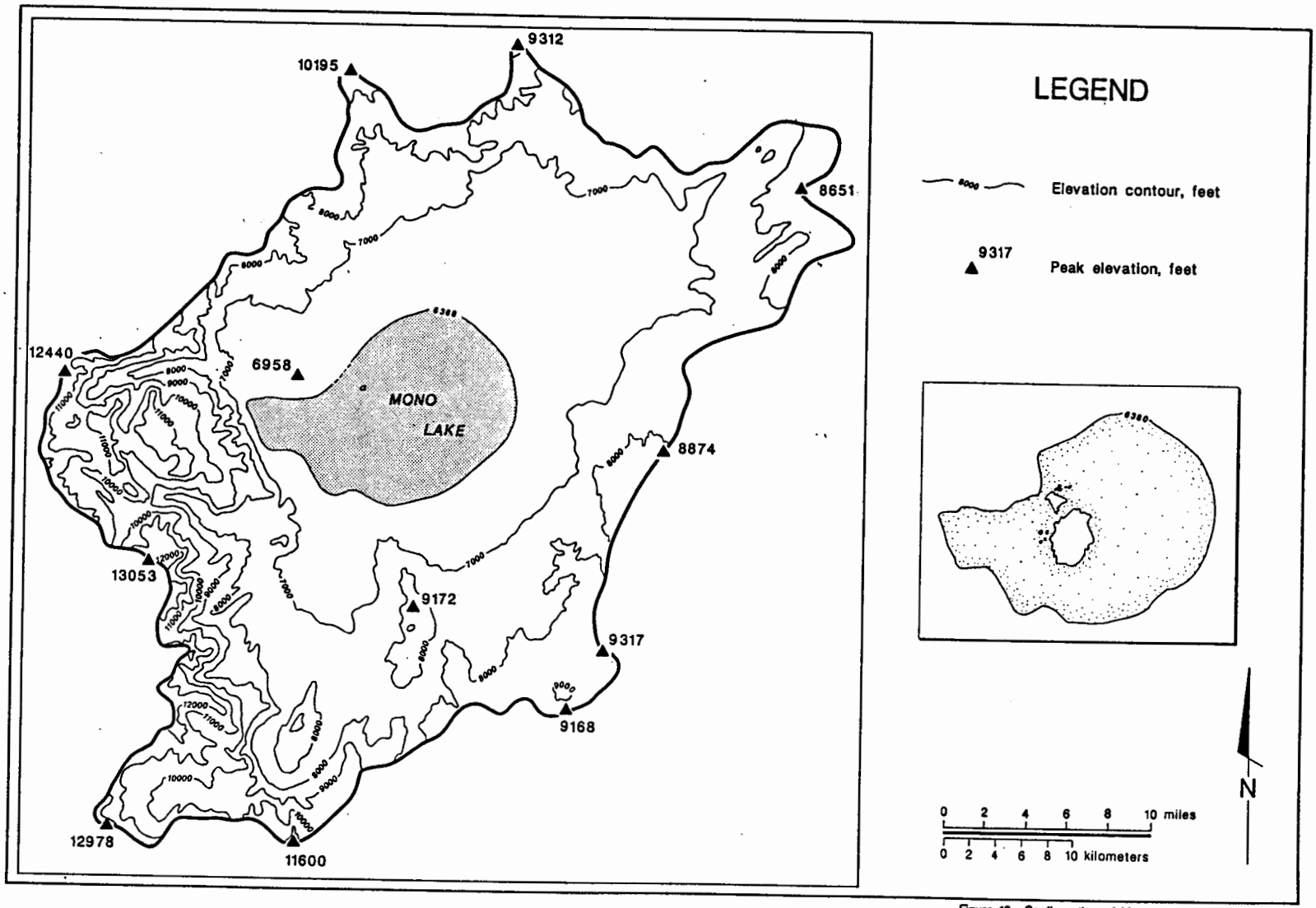


Figure 18. Configuration of Mono Lake at the time of the Marina Low Stand, ~1800 B.P.

surface elevation of 6380 feet, reaches a depth of 1.8 m. A core taken next to this pit extends to a depth of 10.5 m. This pit and adjacent core are treated here as one section (Marina Pit 1).

The lower 9 m of Marina Pit 1 is composed of rhythmically laminated to chaotic deep-water clays that contain occasional to abundant grains of coarse sand and pieces of angular gravel believed to have been deposited by avalanches or mudflows from the adjacent Sierran escarpment. These lowest sediments lack littoral sands, algal mats, A-horizons, oolitic sands, and desiccated horizons, indicating that the lake margin did not retreat to a point below the site of the pit throughout the period represented by the basal nine meters of sediment; preliminary paleomagnetic analysis by Mr. Mark Newton of the University of Southern California (written communication, 1986) of a core taken at this same site suggests that the lower nine meters of sediment dates to well before 4500 BP.

The earliest sign of a shoreline environment in Marina Pit 1 occurs at a depth of around 1.5 m, where 228 mm of well-sorted, biotite-rich littoral sand (unit I) overlies clays (units J_i and J_{iii}) that were exposed to the atmosphere long enough to cause desiccation. These sands are in turn overlain by undesiccated silts and clays (units H_{ii} and

portions of unit H_{iv}), indicating that the drying of clay units J_i and J_{iii} must have occurred due to exposure to the atmosphere during Marina time, rather than during a subsequent low stand.

Elevation of the Marina Low Stand

This same sequence of sediments was found at a depth of around one meter in a slightly lower Marina excavation (surface elevation 6378 feet) during the summer of 1983, indicating that during Marina time the lake surface stood below an elevation of 6375 feet. (This pit is not illustrated on Plate 5.) Geomorphological evidence in the form of an erosional terrace strongly suggests that during Marina time the lake stood at a still lower level. This subaqueous terrace (the "Scholl terrace"--see pg. 146), which encircles much of the lake, is strewn with ~1700-year-old pumice blocks (pg. 237), indicating that it must have been cut prior to that time. With evidence to demonstrate that the lake did not drop low enough to cut such a terrace for many thousands of years prior to Marina time, nor between Marina time and the time that the pumice blocks were deposited (see below), it must be concluded that the terrace is a product of wave erosion during the Marina Low Stand (or, more precisely, during the recovery from the Marina Low

Stand).

The distal margin of the terrace (the lakeward limit of the eroded surface) today lies at 6368 feet. Judging from excavations further upslope, however, the original terrace surface, represented by the littoral sands (unit I) of Marina Pit 1, is under one meter of sediment, thus placing the margin of the terrace at the time of formation at approximately 6365 feet. If it is assumed that littoral abrasion at Mono Lake extends to a depth of approximately 1 meter, it can be concluded that the lake surface stood at an elevation of 6368 feet at the time of the Marina Low Stand.

Dating the Marina Low Stand

In Marina Pit 1 the sands associated with the Marina Low Stand lie stratigraphically above a white, sandy to silty airfall deposit of Mono Craters tephra (designated Unit J_{ii} on Plate 5E). The same relationship can be seen in Marina Pit 2 (Plate 5F), an exposure excavated 10 vertical feet above Pit 1. Note in Marina Pit 2 that the littoral sands also lie stratigraphically below another deposit of Mono Craters tephra. These two deposits of volcanic ash are the third and fourth youngest Mono Craters tephras encountered in shoreland sediments around Mono Lake. While not as well dated as their younger counterparts, they are believed to be

1610 and 1990(?) radiocarbon years old, respectively. Lying as it does between these two ashes, the littoral sand associated with the Marina Low Stand is, as a first approximation, assigned an age of between 1600 and 2000 yrs BP.

Sediments exposed in the Lee Vining Creek delta trench near the mouth of the stream provide further evidence of the Marina recession, and confirm that the low stand occurred prior to 1600 BP. Note on the Lee Vining "Stumpcut" (Plate 3A) that a deposit of coarse cobble-gravel (Unit J) lies at the base of the section, beneath sediments radiocarbon dated at 1625 yrs BP. The basal cobble gravel is clearly alluvial, and therefore must have been deposited as a subsidiary delta by Lee Vining Creek when the stream was graded to a lake surface at or below the elevation of the Historic Low Stand (6372 feet) in Marina time. The pumice blocks that overlie the Scholl terrace likewise overlie this subsidiary delta. They, like the subsidary delta itself, lie stratigraphically beneath the date of 1625 BP. With no direct date yet available on either the Marina Low Stand or the superposed pumice blocks, the low stand is tentatively placed one-third of the way between the constraining dates of 1990 BP and 1625 BP (that is, at ~1820 BP), while deposition of the pumice blocks is placed two-thirds of the way between these two dates (that is, at ~1700 BP). The pumice blocks, and their

bearing on the elevation of the lake surface at the time they were deposited, are discussed in more detail on page 240. It should be borne in mind that the date applied here to the Marina Low Stand is interpolated; a paleomagnetic date of ~1900 BP on the low stand derived by Mr. Mark Newton of USC may well be a more accurate approximation of Marina time.

Recovery from the Marina Low Stand

While the topography of the Mono shorelands was undoubtedly altered by littoral processes as the lake declined in immediately pre-Marina time, wholesale modification awaited the subsequent lake transgression. It was during this period of recovery that the Scholl terrace was cut. The rising lake truncated the shorelands, eroding the basal clays and the littoral sediments that had been deposited during the lake decline, as well as any humic horizon that had formed on the exposed lake sediments during the lowstand. This truncation is seen in both of the Marina pits, where coarse littoral sands unconformably overlie desiccated clays, without an intervening transitional sequence of sediments. Erosion associated with the post-Marina transgression may explain the inability to find remains of Marina-age trees and shrubs such as the rooted derelicts dating from subsequent declines in lake level. With this in mind, it should be noted that the episode of

cutting associated with the post-Marina lake transgression pre-conditioned the shorelands (up to an elevation of 6404 feet) for subsequent fluctuations, creating an abrasion platform over which the lake could later rise and fall with little erosional modification. As a consequence, A-horizons and rooted vegetation that developed during subsequent low stands would, in most areas of the shorelands below 6404 feet, survive later fluctuations in lake level.

The post-Marina rise in lake level is clearly displayed in the sedimentary record in Marina Pits 1 and 2. There the littoral sands associated with Marina time fine upward into shallow-water oolitic sands (unit H_i) and silty clays (unit H_{ii}). The fibrous mat of compressed plant remains (Unit I) that overlies the basal cobble-gravel (Unit J) on the Lee Vining Creek "Stump Cut" (Plate 3A) is similar to units known to have been deposited during later rises in lake level, and may represent the post-Marina transgression.[9]

By perhaps 1800 BP Mono Lake was rebounding from the extreme low stage of the previous decades. Not for 900 years would it even approach levels comparable to those of the Marina Low Stand.

~1820 BP to 1245 cal BP

Introduction

The transgression that spelled an end to the Marina Low Stand around 1800 years ago was of small magnitude; indeed, during the next five centuries the lake surface barely reached levels comparable to those attained under natural conditions during historic time. Throughout this interval the lake was remarkably stable, fluctuating between elevations of 6382 and 6404 feet. One noteworthy sublacustrine volcanic event--the eruption of Java Islet--and two major Mono Craters eruption--those of 1610 BP and 1245 cal BP--occurred during the period. Ejecta produced during two of these volcanic events marks the position of the shoreline at the time of the eruptions.

Evidence

Because of the small magnitude of the fluctuations that occurred during all but the final phases of the period ~1800 BP - 1245 cal BP, precise lake elevations can only rarely be tied to specific points in time. Based on sedimentary sections exposed in stream cuts and research pits, however, it is possible to delineate the maximum and minimum elevations attained by the lake during this period.

Marina Pits 1 and 2 (Plate 5E and F, respectively) are

key to establishing the behavior of the lake during the period ~1800 BP - 1245 cal BP. Note in Pit 1 that clays, silty clays, and clayey silts (Units H_{ii}, H_{iv}, and H_{v}) lie between the sands associated with the Marina Low Stand (Unit I) and the Mono Craters tephra of 1245 cal BP (Unit H_{vi}). This portion of the pit (between 6377 and 6378 feet) lacks littoral sands, indicating that the lake remained at least 3-5 feet above 6377 feet throughout the period in question. The equivalent section of Marina Pit 2, in contrast, includes six layers of well-sorted, biotite-rich sand that lie between desiccated deposits of clays and silty clays, suggesting that on numerous occasions the lake margin dropped to or below the elevation of the sand-intercalated silts and clays (~6387 feet). Along the walls of the Lee Vining Creek "Stumpcut" (Plate 3A) fluvial cobbles and gravels (Unit G_{i}) from this interval grade lakeward into littoral sands and pea-gravels (Unit G_{ii}) that pinch out at 6382 feet, indicating that the lake declined to, or at least approached, that elevation. Accordingly, and with evidence from Marina Pit 1 indicating that the lake margin remained above 6378 feet, 6382 feet is considered the minimum elevation occupied by the lake between ~1800 BP and 1245 cal BP. Pine cones collected from this cobble-gravel (Unit G_{i}) yield dates of 1625 $\pm$40 BP (USGS

1524, = 1542 ±30 cal BP) and 1590 ±50 BP (USGS 1705, = 1475 ±66 cal BP). A date of around 1610 yrs BP (or 1510 cal BP) is thus placed on this minimum elevation.

Throughout most of the period ~1800 BP - 1245 cal BP the lake seems to have stayed within perhaps 10-12 feet of the minimum elevation (6382 feet), as evidenced by the ubiquity of silt in Units H_{ii} and H_{iv} in Marina Pit 1, and the abundance of bedded and dispersed sand in the equivalant units of Marina Pit 2. Toward the top of Unit H, however, just below the Mono Craters tephra of 1245 cal BP, sediments in both pits fine upward, suggesting a deepening of the lake. Evidence of a lake transgression just prior to the eruption of 1245 cal BP is also seen in the Lee Vining Creek "Stump cut", where the fluvial cobbles and gravels of Unit G_i grade upward into well-sorted littoral sands. A pinecone retrieved from these transgressive sands at an elevation of 6384 feet dates at 1495 ±45 BP (USGS 1314, = 1370 cal BP).

The level to which the lake rose during this transgression of ~1370 cal BP can be determined from sedimentary sequences exposed in "Milldown cut" along the eastern wall of Mill Creek (Plate 4D). Note in the downstream portion of this section that backset beds of well-sorted sands and pea-gravels (Unit I) compose a littoral embankment (crest elevation 6404 feet) that lies

stratigraphically below the Mono Craters tephra of 1245 cal BP (Unit H), but above an older tephra deposit (Unit J_{11}), dating from either 1610 or 1990(?) BP. This embankment rests on the post-Dechambeau Ranch A-hroizon. No higher littoral deposit from the period 1990(?) BP - 1245 cal BP can be found at this or any other exposure. It is therefore concluded that around 1370 cal BP the lake rose from an elevation of approximately 6384 feet to 6404 feet. This transgression and high stand, here called the Mill Creek-East High Stand, marks the first time in half a millennium that the lake surface reached (if only barely) levels comparable to those attained under natural conditions during historic time.

The Eruption of Java Islet and its Bearing on the Level of Mono Lake, ~1700 BP

Lining the western shorelands of Mono Lake from slightly east of 10-Mile Road to the Horse Creek Embayment are tens of thousands of large (to >2m), highly vesicular, tufa-covered pumice blocks (Photos 22a and b). These biotite-bearing dacite blocks, mentioned previously in connection with the Scholl terrace, vary in color from light grey to dark grey, with some clasts exhibiting alternating dark and light banding. Shape of the vesicles is variable, ranging from spherical to highly elongate. Large vesicles (>5mm) are

commonly criss-crossed with a complex web of thin glass strands.

The blocks are common at and below an elevation of 6390 feet; they are virtually non-existant above that contour. Pumice chunks broken from the blocks readily float on the heavy water of Mono Lake. This, together with their widespread distribution and the abruptness of their upper elevational limit, strongly suggests that following their production during a sublacustrine eruption the buoyant blocks floated to the surface of the lake and blew to shore, where they shoaled, waterlogged, and developed a rind of tufa. Given the size of the blocks (<1 m) lying at the upper limit of distribution, it is estimated that they would shoal in perhaps two feet of water; the elevation of the lake surface at the time the blocks were deposited, then, is placed at 6392 feet.

The pumice blocks are most abundant along the lake shore to the northwest of Negit Island, where they number in the dozens per acre. This suggests that they originated in the vicinity of the Negit Archipelago. They are similar in color, structure, and trace-element composition to the pumiceous "core" of Java Islet (see Figure 19). Java, therefore, is considered the likely source of the blocks, though other vents still submerged may have been involved in their production.[10]

The "Java blocks" came to rest on the Scholl terrace, indicating that they were produced sometime after the Marina Low Stand of ~1825 yrs BP. This same conclusion can be drawn from the stratigraphy of Marina Pit 1 (Plate 5E), where a discontinuous horizon of angular, biotite-bearing and vesicular pumice cobbles and gravels (Unit H_{iii}) believed to be contemporaneous with the "Java blocks" lies within the clayey silts and silty clays that overlie the littoral sands of the Marina Low Stand. Along "Stump cut" in the Lee Vining Creek delta trench (Plate 3A) the blocks overlie a deposit of coarse stream gravels graded to the approximate elevation of the Marina Low Stand, and underlie the above-mentioned pine cones of 1590 and 1625 yrs BP. The eruption of Java, and the deposition of the Java blocks, is therefore placed between the date of the overlying pinecone (1610 BP) and the interpolated date of the Marina Low Stand (~1825 BP)--that is, at around 1700 BP.

The Mono Craters Tephra of 1245 cal BP and its Bearing on the Lake Fluctuation Curve

Introduction. Directly overlying sediments associated with the Mill Creek-East Transgression and High Stand (including the lake-transgressive sequence on the Lee Vining Creek "Stump cut", the lacustrine clays in Marina Pit 1, and

the embankment that marks the Mill Creek-East High Stand on the "Milldown cut") is the Mono Craters tephra of 1245 cal BP (Sieh and Bursik, 1986; Wood, 1977). This ash unit can be used to pinpoint the elevation of the lake surface at the time of its deposition.

The tephra of 1245 cal BP. The Mono Craters tephra of 1245 cal BP was first described by Spencer Wood (his "tephra 2"), who discovered it in meadow deposits of the central and southern Sierra Nevada (Wood, 1977). His radiocarbon date of 1190 (±80) yrs BP is derived from the outer rings of a fallen tree, buried in a meadow near the north fork of the Kings River, that is directly overlain by the tephra. Recently Sieh (1984) derived a dendrochronologically calibrated date of 1245 cal BP on wood that was charred during the eruption. Radiometrically-dated deposits exposed in the walls of the delta trench on Lee Vining Creek corroborate this date within broad limits. There, the tephra lies stratigraphically above the previously described 1370-year-old pinecone, and below rooted stumps dated at around 866 cal BP.

Tephra from the eruption of 1245 cal BP is encountered frequently in cuts and pits throughout the northern, western, and southwestern Mono Basin. In the immediate vicinity of the lake, the airfall deposit is typically composed of two 2- to 5-cm-thick layers of fine ash that sandwich a thin (< 1cm) layer of fine lapilli; at some sites the sequence includes a

thin basal unit of fine lapilli or coarse ash (Photo 23a). The upper unit of fine ash is white in color, while the lower unit is typically brownish to purplish. Where it is exposed in stream cuts the tephra is usually fluvially reworked, and may reach thicknesses of up to a meter or more (Photo 23b).

The surface elevation of Mono Lake 1245 cal BP. Wherever it is found at elevations above 6390 feet in the Mono Basin the tephra of 1245 cal BP occurs in association with sediments indicative of a subaerial environment. In shoreland pits, for instance, the ash typically either overlies, or has been homogenized into, an A-horizon. At these sites the ash is typically truncated, turbated, discontinuous, and friable, with the original airfall sequence only rarely preserved. In the walls of streamcuts above this elevation, the ash is found either incorporated in fluvial gravels, or overlying an A-horizon, again indicating subaerial deposition.

At exposures below 6385 feet the tephra of 1245 cal BP overlies deep-water lacustrine sediments. Here the ash is compact, planer bedded, and of uniform thickness, with individual airfall subunits traceable laterally for many meters. Clearly, then, the ash fell into the lake at elevations below 6385 feet, and onto land surfaces at elevations above 6390 feet.

The sequence of sediments exposed in the Lee Vining

Creek "Terrace cut" (Plate 3C) further clarifies the position of the lake margin at the time of the Mono Craters eruption of 1245 cal BP. There, at an elevation of 6388 feet, the ash (unit F) lies sandwiched between deposits of coarse, well-sorted, littoral sand. Across the stream, at the "big-thick" cut (Photo 23b), the ash composes climbing-rippled delta-foreset beds (Photo 23c) that merge with ashy topset beds of a delta-front-platform environment at 6387 feet. It is therefore concluded that at 1245 cal BP the lake stood at an elevation of 6388 feet.

Conclusions

The period between ~1800 yrs BP and 1245 cal BP is remarkable for both the relative stability of Mono Lake, and the persistantly low levels (relative to natural historical conditions) at which the lake was maintained. The bedded and dispersed sands exposed in Marina Pit 2 constitute evidence that throughout much of the interval the lake surface remained close to 6387 feet, and the lack of sand in relevant portions of Marina Pit 1 argues that it remained at least several feet above 6378 feet. A dated deposit of fluvial and littoral gravels exposed in the "Stump cut" section on Lee Vining Creek indicates that around 1510 cal BP the lake surface approached 6382 feet, the lowest elevation at which there is evidence of shoreline sediments. The float-line of

"Java blocks" fixes the lake surface of approximately 1700 BP at 6392 feet.

Not until the final phases of the interval did the lake rise sufficiently to instigate an upward fining of sediments in Marina Pits 1 and 2 and in the Lee Vining "Stump cut". This transgression culminated in the Mill Creek-East High Stand (6404 feet) shortly after 1370 cal BP. The lake then began to recede, and by 1245 cal BP, at the time of the Mono Craters eruption, had reached an elevation of 6388 feet.

During the ensuing three centuries the lake would continue its decline; by approximately 875 years ago it would again reach the extreme low levels that characterized the Marina Low Stand of nine centuries before.

1245 to 866 cal BP

The Lee Vining Delta Recession and Low Stand

Introduction

The lake recession that began prior to the Mono Craters eruption of 1245 cal BP continued, with minor transgressions and pauses, for several centuries. By roughly 875 years ago the lake margin had reoccupied the distal fringe of the Scholl terrace. Woody vegetation followed the receding lake margin, colonizing well-watered portions of the shorelands to elevations as low as 6373 feet. Geomorphological evidence argues that the lake did not drop below 6368 feet.

This low stand, here called the Lee Vining Delta Low Stand, ended 866 cal BP when the lake rose rapidly in response to increased inflow.

Evidence

During the mid-1950s, as Mono Lake receded toward an elevation of 6400 feet, the rooted remains of shrub and tree stumps began to protrude from the declining lake surface. These derelicts were first reported in the early 1960s from Lee Vining Creek by D.B. Lawrence (Lawrence and Lawrence, 1961). During the past two decades hundreds more rooted snags have emerged from the declining lake (Photos 24a and

b). They are most abundant on portions of the shorelands where fresh water is plentiful, including areas near Simon's Springs and Warm Springs, the Western Embayment, and the Lee Vining and Mill Creek deltas. (Any trees that grew on the delta of Rush Creek are today hidden beneath the thick mantle of reworked tephra that has been deposited by that stream since the last eruption of the Mono Craters.) These rooted derelicts include at least two arboreal species--Pinus jefferyi and Populus trichocarpa--and two arbuscular types--Salix sp. and Chrysothamnus sp. Stumps of trees are restricted to elevations above 6388 feet, while shrub stumps can be found as much as 15 feet lower.

Wood collected from the outermost rings of 13 *in situ* tree and shrub stumps was radiocarbon dated. The results of the ^{14}C assays show clearly that these paleo-woodlands and -shrublands are composed of at least two, and most likely three generations of stumps. Ages of the nine dated members of the oldest generation range from 837 ±87 cal BP to 880 ±23 cal BP. The narrowest age interval shared by the nine Generation-1 stumps is 866 ±9 cal BP. It will be demonstrated in the following section that the death of these Generation-1 (G-1) trees and shrubs approximately 866 cal BP coincided with a rise in lake level.

Not surprisingly, the stumps rooted at relatively high elevations (up to 6402 feet) display more annual rings than

those at lower levels. Several of the tree stumps growing at or near an elevation of 6398 feet are made up of approximately 50 rings. The lowest of the *in situ* stumps discovered to date[11]--a small Chrysothamnus(?) rooted approximately 3000 m west of the mouth of Lee Vining Creek at an elevation of 6373 feet--lived for only eight years. Given the inability of vascular plants to survive in the bitter waters of Mono Lake, these G-1 stumps provide irrefutable evidence that the lake stood below an elevation of 6398 feet for at least a half century, and below 6373 feet for at least eight years, immediately prior to ~866 cal BP.

Exposures along the walls of fresh stream cuts reveal additional stumps of this same age, buried under alluvial, littoral, and lacustral sediments. These newly-exposed stumps occur in association with a buried A-horizon (the "A-horizon of the ~1000 BP low stand"--see, for example, the "Stump cut" exposure, Plate 3A) that formed as the lake receeded to the Lee Vining Delta Recession. This same A-horizon, associated with herbaceous and/or woody plant remains, can be found in most cuts and pits around the western and southwestern shores of the lake. It is particularly well developed in a section exposed along the east wall of Dechambeau Creek (the "Dechambeau Creek cut", Plate 5A) where a freshwater marsh similar to that of today fostered a thick accumulation of sod. Along Dechambeau

Creek, as elsewhere, the humic horizon associated with the Lee Vining Delta Recession and Low Stand can be traced to (and arguably below) an elevation of 6378 feet.

A further telltale sign of the Lee Vining Delta Low Stand occurs in the form of fine-grained subsurface sediments that display desiccation cracks and a blocky structure attributable to dehydration-induced shrinkage. These characteristics are common in Units H_{iv} and H_{v} (clays and silty clays) of Marina Pit 1.

Elevation of the Lee Vining Delta Low Stand

In the course of the Lee Vining Delta Recesssion and Low Stand, as well as during the subsequent transgression (see below), the lake spread a veneer of littoral and oolitic sand over the lower reaches of the late Holocene shorelands. These sands are encountered at a depth of up to 60 cm in pits excavated at an elevation of 6373 feet, indicating that the sands reached to at least 6371 feet. Given that the lake surface has to have dropped to 6372 feet or lower to allow the Chrysothamnus to grow at 6373 feet (see above), and given that littoral sands can be deposited in at least a meter of water, these deposits provide little basis for further clarifying the elevation of the Lee Vining Creek Low Stand.

Geomorphological evidence strongly suggests that the

lake did not drop below the level of the Scholl terrace during Lee Vining Delta time. Based on observations made during studies of the Paoha Islets between 1983 and '86, it is clear that when a rising lake margin impinges against shorelands whose slope exceeds the "equilibrium gradient" (determined on the one hand by resistence of shoreland materials to erosion, and on the other by the energy of the erosional processes), the rising lake beats that steeper surface landward, creating an abrasion platform and cliffline. Truncation of the sedimentary record results. It can be expected that if the lake had dropped one foot (two feet) below the surface of the Scholl terrace during the Lee Vining Creek Recession and Low Stand, roughly one foot (two feet) of sediment would have been removed during the subsequent transgression. While there is a suggestion in low-elevation pits that the sediments immediately overlying the Mono Craters ash of 1245 cal BP are reworked, there is no sign of wholesale truncation; indeed, the fact that the tephra of 1245 cal BP does persist in low-elevation shoreland sections argues that the lake did not drop far enough below the Scholl terrace (if indeed it dropped below it at all) to undercut the ash during the subsequent transgression. With no evidence to indicate that the lake dropped below the distal margin of the Scholl terrace, it is concluded that during Lee Vining Delta time the lake surface reached a level

somewhere between 6368 and 6371 feet.

The Lee Vining Delta Low Stand marks the last time that the shoreline reached the lower reaches of the Scholl Terrace under natural conditions. From this exceptionally low level the lake would rise sharply, inundating shorelands that had been exposed for 1000 years or more.

~866 cal BP

The Post Office Transgression and High Stand

Introduction

The Lee Vining Delta Low Stand ended around 866 cal BP when Mono Lake began to swell in response to increased inflow. The rising lake flooded the delta trenches and inundated the shorelands, killing the vegetation cover and depositing a sheet of sands, silts, and clays over a well- to poorly-developed A-horizon.

The ~60-vertical-foot transgression culminated at or slightly below an elevation of 6430 feet. This, the "Post Office High Stand", marks the first time in a millenium that the lake reached levels which, by historic standards, can be considered high.

Evidence

That the death of the Generation-1 shrubs and trees approximately 866 cal BP (pg. 248) coincided with a rise in lake level can be demonstrated at a number of deltaic and shoreland sections around Mono Lake. Along the west wall of Rush Creek the transgression is expressed as a layer of beach sand that buries a weak and discontinuous A-horizon. (This section is not illustrated.) A calibrated radiocarbon date

of 851 ±67 cal BP (USGS-1321 =920 ±35 yrs BP) on unidentified graminoid shoots collected from this horizon effectively dates the death and burial of the vegetation cover. A pinecone discovered in this same unit along the east wall of Rush Creek by Mr. Mike Perkins of Berkeley, California in 1983 provides a virtually identical date of 855 ±68 cal BP (USGS-1704 =930 ±40 yrs BP).

At "Stump cut" near the mouth of Lee Vining Creek (Plate 3A) silts and fine sands (Units E_{ii} and E_{iii}) bury a humic horizon (the "A-horizon of the ~1000 BP low stand") in which is rooted the remains of numerous shrub stumps. ^{14}C analysis of wood from one of these individuals places the death of the vegetation and burial of the humic horizon at 846 ±16 cal BP (LDGO-1677 LW =940 ±30 yrs BP).

The fine sand that buries this humic horizon can be traced upstream to the Lee Vining Creek "Terrace cut" (Plate 3C). Here, these sands (designated Unit C at the "Terrace cut") are rich in vegetal detritus which in some places composes a fibrous mat up to 12 cm thick. A pinecone extracted from this mat dates at 822 ±94 cal BP (USGS-1310 =890 ±60 yrs BP).

The sands and plant remains that make up Unit C on the Lee Vining "Terrace cut" unconformably overlie approximately 75 cm of fluvial cobble-gravel composed of well-rounded

clasts to 17 cm. Based on principles of deltaic sedimentation described previously (Section A of Chapter 2), this sequence of coarse fluvial detritus unconformably overlain by fine lacustrine sediments would suggest the inundation by a rising lake of an alluvial terrace perched above the floor of a delta trench. The existence of a delta trench at this site ~866 cal BP can be demonstrated from field relationships. Note on Photos 24a and b that the ~860-year-old stumps rooted on the plain of the Lee Vining Creek delta flare abruptly at their bases as they widen downward into a root system. The basal flare exhibited by the stumps clearly coincides with the present-day surface of the delta plain, indicating that the plain-surface of 866 cal BP was little different from that of today. Based on radiocarbon dates already cited, the surface on which these stumps are rooted is clearly contemporaneous with the surface of the putative stream terrace exposed in the Lee Vining Creek "Terrace cut". The two surfaces lie within ~50 horizontal meters of one another, yet are separated by more than 3 vertical meters. The alluvial surface must therefore be a feature of a trench that bisected the Lee Vining Creek delta of ~866 cal BP. This terrace, oxidized at its surface and overlain by the fine sands and vegetal detritus of the transgression of ~866 cal BP, can be traced discontinuously upstream for over 500 meters where, at an elevation of around

6420 feet, it disappears beneath a thick accumulation of overburden.

Elevation of the Post Office High Stand

The fine sands and organic detritus that overlie the exhumed trench-terrace along the eastern wall of the Lee Vining Creek cut provide evidence that the lake reached an elevation of at least 6420 feet during the transgression of 866 cal BP. Still farthur upstream, at the Lee Vining Creek "Meander-cut" (Plate 3B), littoral sands overlie a thick (100+ cm) dark brown to black A-horizon (the "post--~2000 BP A-horizon) that formed on coarse and fine alluvium (Unit F) during the 1000+ years of persistently low lake levels that followed the Dechambeau Ranch High Stand.[12] Charcoal was collected from the littoral sands, though no radiocarbon dates were obtained on the materials. The age of the sand can be constrained, however, using tephrochronologic evidence. The Mono Craters tephra of 605 cal BP (Unit D at the "Meander cut") overlies a weak A-horizon that developed on the littoral sands, while pockets of the 1245-year-old ash can be found within the underlying soil (Unit F). Since only two lake transgressions (that of 866 cal BP and that of ~680 cal BP--see below) occurred during the six centuries that separates the two Mono Craters ashes, and since it can be demonstrated that the later of these two transgressions

reached an elevation of only 6409 feet, the sands that overlie the post-Dechambeau Ranch soil on Lee Vining Creek must have been deposited during Post Office Creek time.

Another good exposure of the post--~2000 BP A-horizon occurs along the east wall of Mill Creek at the "Upmill cut" (Plate 4C). There it is overlain by the two most recent Mono Craters tephras (Units F and H). Sandwiched between the two ash units is a thin layer of littoral(?) sands and gravels Unit G). This unit pinches out landward at an elevation of approximately 6430 feet, suggesting that the lake rose to, but not above, this elevation. It is therefore tentatively concluded that the Post Office Creek High Stand lies at an elevation of 6430 feet.[13]

From its Post Office High Stand Mono Lake would again decline, exposing newly-deposited sands and gravels to vegetation colonization and pedogenesis.

~800 to 680 cal BP--The Simis Ranch Recession and Low Stand

Introduction

During the century or so that followed the Post Office High Stand Mono Lake returned to low levels, sinking some fifty feet to an elevation somewhat below 6379 feet immediately before 680 cal BP. This recession and low stand, here called the Simis Ranch Low Stand, is expressed in cuts and pits as lake-recessional sediments capped with a weakly developed A-horizon. Stumps of trees and shrubs that colonized the newly exposed shorelands during this period persist today as rooted snags; dates on these plant remains provide an upper constraining age on the termination of the lake contraction.

Evidence

As the lake withdrew from the Post Office High Stand littoral sediments were spread over the former lake floor. In time, vegetation colonized these sediments, leading to the development of an A-horizon. Clear exposures of this "post-866 cal BP A-horizon" can be seen in the Lee Vining Creek "Meander-cut" (Plate 3B). There the humic horizon developed on gravelly coarse sands (Unit E_{iv}) that overlie and locally truncate the fine sands, silts, and organic-rich

silts of the Post Office High Stand. This soil can be traced downstream to an elevation of approximately 6888 feet on the Lee Vining "Stump cut".

At a number of sites around the shorelands deep-water clays and silty clays associated with the high stand of 866 cal BP are overlain by littoral sands. This relationship is evident at an elevation of approximatly 6379 feet in Marina Pit 1 (Plate 5E). Here the clays (Unit F) lack an A-horizon, but contain abundant fragments of roots, suggesting that an existing humic horizon was truncated during a rise in lake level. (This sequence of events is also suggested by the lack of transitional deposits, including oolitic sands, between the littoral and deep-water sediments.) The sands (Unit E), themselves lacking plant detritus, are therefore interpreted to be transgressional rather than recessional. Nevertheless, these sands, in combination with the abundance of plant detritus in the underlying clays, leave little doubt that the lake dropped to below this elevation during Simis Ranch time.

How much lower than 6379 feet the lake dropped during the Simis Ranch Recession cannot be ascertained from existing cuts and pits. Nor can the distribution of vegetation that grew at low elevations during Simis Ranch time be used to clarify the ultimate level of the low stand; thus far, stumps from this era have been found only as low as 6388

feet. In drawing the lake level curve, therefore, a solid line is shown descending to an elevation of 6379 feet (the elevation of the sands in Marina Pit 1); a dashed line extends to 6375 feet. Radiocarbon dating of more low-lying *in situ* vegetation, and future excavations on presently-inundated shorelands, may permit a more precise evaluation of the level of the Simis Ranch Low Stand.

The ~50-foot recession that began around 800 cal BP persisted for just over a century. Trees that grew on lands uncovered during the Simis Ranch Recession would be killed beginning about 680 cal BP, as Mono Lake rose to its "Rush Delta High Stand".

680 to 605 CAL BP

The Rush Delta Transgression and High Stand

Introduction

By roughly seven centuries ago Mono Lake was rising from the Simis Ranch Low Stand, killing vegetation and spreading a blanket of lake-transgressive sediments over the previously exposed shorelands. Radiocarbon analysis of wood from rooted stumps killed by the lake rise places the beginning of the transgression at ~680 cal BP, while tephra from the most recent eruption of the Mono Craters fixes both the date (605 cal BP) and the elevation (6406-8 feet) of the resultant high stand (here called the Rush Delta High Stand).

Evidence

Radiocarbon analysis on the thirteen rooted shrub and tree stumps listed in Table 2 indicates that at least two of the individuals died just under seven centuries ago.[15] Dates on these "Generation-2" stumps are 699 ±25 cal BP (LDGO 1677 AW =770 ±50 yrs BP) and 670 ±15 cal BP (USGS 1277 =700 ± 60 yrs BP). The narrowest age interval shared by these two derelicts is 680 ±5 cal BP; this date, then, is used to mark the beginning of the "Rush Delta Transgression".

The tree-kill of ~680 cal BP, like that of ~866 cal BP,

coincided with a rise in lake level that can be demonstrated from sedimentary sequences exposed in many different cuts and pits. The previously-discussed transgressive sands (Unit E) exposed at elevation 6379 feet in Marina Pit 1 (Plate 5E) grade upwards into oolitic sands, then into clays of deep water; these clays are in turn overlain by a white volcanic ash. On the Lee Vining "Stump cut" (Plate 3A) the post-866 cal BP A-horizon is overlain by the fine, quartz and oolitic sands of Unit D. Near the top of Unit D a third type of sand, composed of white pumice, becomes an important constituent of these shallow-water sediments. The advent of the pumice sands in Unit D of "Stump cut" and of volcanic ash (Unit D_{iii}) in Marina Pit 1 marks the Mono Craters eruption of 605 cal BP.

The Mono Craters Tephra of 605 cal BP and its Bearing on the Lake Fluctuation Curve

Introduction. Six centuries ago a series of eruptions from vents along the crest of the Mono Craters sent plumes of ash and lapilli over Mono Lake. The tephra blanketed vegetated surfaces on subaerial portions of the late Holocene shorelands, and covered the muds of the lake bottom. Waves and littoral currents incorporated the ejecta into beach deposits, while streams reworked and deposited it as delta

topset, foreset, and bottomset beds. Subaerial, sublacustrine, littoral, and deltaic deposits of this tephra can be used to show conclusively that the surface of Mono Lake stood at an elevation of 6405-6406 feet at the time of the eruption.

The tephra of 605 cal BP. Tephra from the most recent eruption of the Mono Craters was first recognized and briefly described by Wood and Brooks (1979), who believed it to be the product of Panum Dome (northernmost of the Mono Domes). Subsequent detailed analysis of the stratigraphy, age, and distribution of the tephra by Sieh (1983; in press) indicates that it was ejected from several vents along the crest of the Mono Craters approximately 605 cal BP.

Ejecta from this most recent spate of Mono Craters eruptions has been found at hundreds of sites around the late Holocene shorelands of Mono Lake. Along the southern shore, in the near vicinity of its sources, the tephra may include pyroclastic flow deposits composed of poorly sorted pumice and grey-lithic and obsidian clasts ranging in size from silt to boulders. At sites more distant from the eruptive centers, the tephra deposit is made up of a series of thin (5-10mm) airfall-ash beds with a total thickness on the order of 5-10cm. This sequence of fine ash typically overlies a basal layer of coarse ash or fine lapilli. The basal layer, and the lack of a lapilli layer midway through the ash

sequence, usually makes the tephra of 605 cal BP readily distinguishable from that produced during the eruption of 1245 cal BP (see Photo 23a).

The surface elevation of Mono Lake 605 cal BP. At elevations above 6406 feet on the Mono shorelands the ash of 605 cal BP typically overlies a soil. At these elevations the ash is discontinuous and highly variable in thickness over short distances. Individual subunits within the airfall sequence can seldom be traced laterally more than one meter. At these sites the ash appears to have settled subaerially on a vegetated surface.

At elevations below about 6406 feet, the ash typically overlies either shallow-water sands and gravels, or deep-lake muds. Here the airfall deposit is composed of compact planer beds of unvarying thickness--suggestive of quiet-water deposition.

Both the subaerial and quiet-water facies of the Mono Craters ash of 605 cal BP can be seen in the "Milldown cut" along the eastern wall of Mill Creek. Also displayed in this section is a littoral facies of the tephra. Note there (Plate 4D), and on Photo 25, that at an elevation of 6406 feet the airfall ash sequence (Unit Fil_c) is intercalated with thin layers of well-sorted, medium quartz-sand. This transition from a subaerial environment at elevations above

6406 feet, through an apparently littoral environment at around 6406 feet, to a quiet-water environment below that elevation strongly suggests that the lake surface stood at an elevation of around 6406 feet at the time the ash was deposited.

This conclusion is corroborated in a section exposed along the west wall of the Rush Creek cut, approximately 300 meters downstream from the lowest county-road crossing (the "Clover Ranch crossing"). The section is pictured on Photo 26. Note that near the base of the section delta topset, foreset, and bottomset beds composed of Mono Craters tephra overlie beach sands derived from both the Mono Craters and the Sierra Nevada. The foreset beds terminate against topsets at an elevation of 6406 feet, confirming that the lake stood at, or slightly below,[14] that elevation at the time of the Mono Craters eruption of 605 cal BP.

Elevation of the Rush Delta High Stand

Evidence for a slight rise in lake level immediately following the eruption of 605 cal BP can be seen in the Milldown cut (Plate 4D). There the tephra of 605 cal BP is overlain by littoral sands (Units F_{iii} and F_{iv}) that coarsen upwards into a broad berm composed of tufa-frosted pebbly beach shingle.[16] The crest of the berm stands at 6409 feet,

while both the sands and the shingle pinch out upstream at an elevation of approximately 6407 feet. Neither here nor elsewhere can sediments associated with the Rush Delta High Stand be found at elevations higher than 6407-9 feet. Furthermore, these lake-transgressional sediments are capped by a humic horizon that melds with the post-866 cal BP soil at the point where the sediments pinch out, providing evidence that the lake did not reach to elevations higher than the crest of the berm. The Rush Delta High Stand is therefore placed at 6409 feet. Only after a substantial drop in lake level (the 10-Mile Road recession) would the lake again return to these elevations.

605 to 550 cal BP

The 10-Mile Road Recession and Low Stand

Evidence

The Rush Delta High Stand was followed by a rapid 30-foot drop in lake level that culminated shortly before 550 cal BP at an elevation of around 6380 feet (the "10-Mile Road Low Stand"). The drop in lake level is recorded as a change from deep- to shallow-water deposits in sedimentary sections on the Mono shorelands. At an elevation of 6380 feet in the "10-Mile Pit" (Plate 5B), for instance, the ash of 605 cal BP (Unit H) is overlain by a thin layer of biogenic ooze (Unit G) that accumulated during the final years of the Rush Delta Transgression and during the early stages of the ensuing drop in lake level. The ooze is in turn overlain by a thin layer of littoral sands (Unit F) that represent the 10-Mile Road Low Stand. No transitional deposits are found between the sands and the clays, suggesting that the deep-water deposits were truncated as the lake margin receded toward, or readvanced from, the 10-Mile Road Low Stand.

A similar sequence of sediments is exposed at elevation 6380 feet in Marina Pit 1 (Plate 5E). There, the clays of the Rush Delta Transgression and High Stand were locally stripped by waves and longshore currents as the lake margin

approached 6380 feet during 10-mile Road time. The culminating low stand is recorded as littoral sands (Unit C that overlie these locally truncated clays.

On the Lee Vining Creek "Stump cut" (Plate 3A) deposits of quartz, pumice, and oolitic sands dating from the 10-Mile Road Recession emerged from the declining lake and were colonized by vegetation, giving rise to an A-horizon (the post-605 cal BP A-horizon) that persists today at elevations as low as 6391 feet.

Evidence for a Change in the Course of Rush Creek

Stream cuts exposed near the mouth of Rush Creek provide evidence of the 10-Mile Road Recession, as well as for a marked shift in the course of the stream that occurred during 10-mile Road time. Prior to 605 cal BP Rush Creek flowed into Mono Lake by way of a delta trench situated up to 1000 m west of the present-day stream. Photo 6a illustrates the location of the ancient delta trench, and of the subsidiary delta that accumulated at its mouth. Both of these features are today evident in the field; the trench is preserved as a ragged declivity partially to completely filled with thoroughly cemented volcanic detritus, while the ancient subsidiary delta shows itself as a deposit of coarse Sierran alluvium that protrudes from the front of the parent delta.

The mass of ejecta made available to Rush Creek by the

Mono Craters eruption of 605 cal BP clogged the stream with volcanic gravel, sand, and silt, causing it to fill its old trench and take a new path to the lake shore. At least a portion of the stream branched east, dumping its load of freshly erupted volcanic debris at the lake margin in the vicinity of the present-day stream coarse. This portion of the shorelands, which previously lacked alluvial sediments, suddenly became part of the Rush Creek delta. The change in depositional environment is recorded in the "Lower Rush cut" (Plate 2A) as foreset gravels and sands (Units F and G) that overlie littoral sands, ejecta from the Mono Craters eruption of 605 cal BP, and silts of the Rush Delta High Stand (Units H and I). Henceforth this area would be the focus of deposition by Rush Creek.

Elevation of the 10-Mile Road Low Stand

The precise elevation of the 10-Mile Road Low Stand can not be determined from available stratigraphic sections. The foreset beds exposed in the "Lower Rush cut" can be traced downstream to 6396 feet, where they abut littoral sands and gravels of Unit G. The post-605 cal BP A-horizon that formed on sands deposited in the vicinity of Lee Vining Creek during the 10-Mile Road Recession reaches to 6388 feet or lower. Littoral sands from 10-Mile Road time can be found at elevations as low as 6380 feet in both 10-Mile Road pit and

Marina Pit 1, indicating that the lake margin reached an elevation of 6385 feet or lower; on the other hand, the lack of desiccation cracks in the underlying clays at these sites strongly suggests that the clays never emerged from the lake, and thus, that the declining lake margin did not drop below 6380 feet in 10-Mile Road time. For now, the 10-Mile Road Low Stand is placed at 6380 feet, subject to fine tuning on the basis of future stratigraphic analyses.

The 10-Mile Road Recession and Low Stand was short lived. By 550 cal BP Mono Lake was again rising, killing shrubs that had grown at low elevations on the shorelands during the brief period of exposure.

550 to ~460 cal BP

The Danberg Beach Transgression and High Stand

Introduction

By 550 years ago Mono Lake was again on the rise. The lake expansion is recorded in shoreland pits (Plate 5, sections B-E) as littoral sediments that grade upwards into biogenic ooze. In sections exposed along the walls of the delta trenches on Rush and Mill creeks lake-transgressive deposits can be followed upstream to a conspicuous buried strandline at an elevation of 6434 feet. Stratigraphic relationships demonstrate that the lake did not rise above this elevation in the course of the transgression. In the absence of direct chronometric control, this high stand, here called the Danberg Beach High Stand, is tentatively placed at 460 cal BP.

Evidence of the Lake Transgression

The decline in lake level that culminated in the 10-Mile Road Low Stand permitted the growth of small shrubs to elevations as low as, and perhaps lower than, 6389 feet. The remains of these shrubs constitute the third generation of relict vegetation that persists today on the shorelands of Mono Lake. Presently only two dates--553 ±11 cal BP (LDGO

1677-IW =570 ±30 BP) and 547 ±11 cal BP (LDGO 1677-OW =550 ±30 BP) have been obtained on G-3 derelicts. The average of these two dates (550 cal BP) is used to mark the beginning of the Danberg Beach Transgression.

Sedimentary evidence of the Danberg Beach Transgression can be seen in the Lee Vining "Stump cut" (Plate 3A), where laminated lacustrine silts (Unit C_1) overlie the weak soil (the post-605 cal BP A-horizon) that formed during the 10-mile Road Recession and Low Stand. These silts can be traced discontinuously upstream to an elevation of 6423 feet in the "Meander cut" (Plate 3B, unit C_1) where they overlie a weak humic horizon that developed on the Mono Craters ash of 605 cal BP.

At the "Lower Rush cut" on Rush Creek (Plate 2A) the foreset gravels and sands (Unit F) and the associated littoral sands (Unit G) deposited during 10-Mile Road time were partially truncated by waves during the Danberg Beach Transgression; the resultant abrasion platform, corrugated with oscillation ripples on its surface, is blanketed with silts (Unit E) that were deposited during the Danberg Beach Transgression and High Stand. These laminated silts can be followed upstream to the Rush Creek "Downclover cut" (Plate 2C, Unit B_1) where they overlie fluvial terrace gravels

deposited during the 10-mile Road Recession and Low Stand. The silts grade upstream into a deposit of littoral sands and beach gravels (Unit B_{ii}) at an elevation of 6434 feet.

On the Mill Creek "Berm cut" (Plate 4B) the Danberg Beach High Stand is represented by a broad embankment of tufa-frosted beach shingle (Unit F_v) that overlies a soil-capped deposit of cobble gravel. (Note that this cobble gravel incorporates the Mono Craters ash of 605 cal BP.) The crest of the embankment stands at 6433.9 feet.

Elevation of the Danberg Beach High Stand

Both the beach deposit (Unit B_{ii}) on the Rush Creek "Downclover cut" and the broad berm (Unit F_v) on the Mill Creek "Berm cut" lie at an elevation of 6434 feet. No higher deposits associated with the Danberg Beach Transgression can be found. Sections exposed further upstream (e.g. on the Mill Creek "Hair cut"--Plate 4A, and on the Lee Vining Creek "Flicker cut"--Plate 3D) show evidence of only one post-605 cal BP transgression--that of 290 cal BP (see below). Indeed, where the broad embankment displayed in the "Berm cut" pinches out on its landward side the crowning A-horizon merges with the soil that underlies it, demonstrating that the lake reached no higher than this elevation in Danberg

Beach time. The Danberg Beach High Stand is therefore placed at 6434 feet.

Age of the Danberg Beach High Stand

Radiocarbon assays on wood from the previously-described G-3 brush stumps provide a reliable date (550 cal BP) on the beginning of the Danberg Beach Transgression. No other dates from this transgression are available, however. For purposes of constructing the lake level curve it has been assumed that the fluctuations that occurred between 550 cal BP and 290 cal BP (including two transgressions and one recession--see Figure 16) were of equal length. The Danberg Beach High Stand is thus placed at 460 cal BP--one-third of the way between these two radiocarbon dates.

~460 to- ~375 cal BP --The Navy Beach Recession and Low Stand

Deposits associated with the Danberg Beach Transgression and High Stand are typically capped by a weak soil, indicating a period of exposure during which vegetation colonized the newly-emergent surface. This soil is designated the "post--~400 BP A-horizon" on the Lee Vining Creek "Meander cut", on the Mill Creek "Berm cut", and on the Rush Creek "Downclover cut". The soil cannot be found at elevations below about 6400 feet, suggesting that any time that the lake spent below this elevation in Navy Beach time was brief.

The recession is expressed as a change from deep- to shallow-water sediments in shoreland pits. At an elevation of 6379 feet in the 10-Mile Road Pit (Plate 5B) clays deposited during Danberg Beach time coarsen upwards into clayey silts and silty clays. Along Navy Beach (Plate 5D) very fine sand reached a comparable elevation. No coarsening of sediment associated with this recession can be detected in Marina Pit 1. These observations suggest that the lake approached, but did not drop below an elevation of about 6384 feet during Navy Beach time.

Low-elevation stream cuts likewise record the Navy Beach Recession, but provide no basis for pinpointing the elevation

of the culminating low stand. Laminated lacustrine silts Unit C_i) that mark the deepening water of Danberg Beach time on the Lee Vining "Stump cut" (Plate 3A) grade upwards into shallow-water oolitic sands (Unit C_{ii}) that appear to have been truncated at elevations below 6390 feet. On Lower Rush Creek stream gravels were deposited at least as low as 6398 feet, but may well have continued to lower elevations, only to have the record obliterated by the modern incision of Rush Creek.

The best approximation of the elevation of the Navy Beach Low Stand is derived from shoreland-pit stratigraphy; a lake level of 6385 feet accounts for the silt and very fine sand found in the pits at Navy Beach and 10-Mile Road, and is therefore used to mark the lowstand. With no direct radiometric control over this low stand it is placed at 375 cal BP--two-thirds of the way between the 10-Mile Road Low Stand of 550 cal BP and the Clover Ranch High Stand of 290 cal BP.

~375 to 290 cal BP

The Clover Ranch Transgression and High Stand

Introduction

Following the Navy Beach Recession Mono Lake began its final pre-historic rise. This transgression, here named the Clover Ranch Transgression, culminated 290(?) cal BP at an elevation of 6456 feet--a late Holocene lake level second only to the Dechambeau Ranch High Stand of ~3490 BP.

The Clover Ranch Transgression instigated the deposition of the "Generation-2 dunes" north of Mono Lake, and resulted in the formation of confined-onset deltas on Rush and Lee Vining creeks. The high stand left a bold geomorphic strandline that persists today around the entire lake; it is accentuated on some areas of the Mono shorelands by an abrupt break in the density of the vegetation cover.

Evidence

The Clover Ranch Transgression is expressed in the pits at South Tufa, Navy Beach, and 10-Mile Road. There, sands and silts associated with the Navy Beach Recession and Low Stand fine upwardly into deep-lake clays.

In mid-elevation stream cuts (e.g. the "Berm cut" and "Milldown cut" on Mill Creek--Plates 4B and 4D) the weak soil

that developed in Navy Beach time (the "post-400 BP A-horizon") is overlain by lacustrine silts of the Clover Ranch Transgression and High Stand. This same relationship is also displayed in the Rush Creek "Downclover cut" (Plate 2C) and the Lee Vining "Meander cut" (Plate 3B), where the silts bury tree stumps rooted in the post-400 BP soil; wood from several of these stumps has been collected for later radiocarbon analysis.

The Clover Ranch-age silts exposed in the Mill Creek "Berm cut" can be followed continuously upstream to the "Hair cut" (Plate 4A). At higher exposures on Mill Creek the silt deposit grades into gravelly sands and sandy gravels that terminate against an abrasion platform cut into an early-stage subsidiary delta. (The county cemetery sits atop this early Holocene subsidiary delta.)

A similar progression of sediments can be seen along the eastern wall of the delta trench on Lee Vining Creek (Plate 3): the Clover Ranch-age silts (Units B_i and B_{ii}) exposed in "Meander cut" can be followed to the "Double-berm cut" (Plate 3G, Unit A), where they become rich in detrital charcoal. Radiocarbon analysis of this charcoal provides a date of 220 $\pm$65 yrs BP (Table 2, USGS 1317). This same silt deposit becomes progressively sandier upstream, ultimately grading into gravelly sands and sandy gravels in the lower reaches of

the trunk-stream canyon at the "Flicker cut" (Plate 3D). Detrital charcoal extracted from this canyon deposit dates at 220 ±60 yrs BP (Table 2, USGS 1320).

The dated sands and gravels (Unit 3D) exposed in the "Flicker cut" are overlain by topset and foreset gravels that compose a confined-onset delta. A fill-terrace graded to this ancillary delta can be followed hundreds of meters upstream. A confined-onset delta likewise formed in the lower reaches of the Rush Creek canyon in Clover Ranch time; an aerial view of this feature is provided on Photo 6a; a streamcut through the deposit (the "Upclover cut") is pictured on Photo 27a.

Elevation of the Clover Ranch High Stand

Coinciding in elevation with the confined-onset deltas on Rush and Lee Vining creeks is a conspicuous geomorphic strandline that encircles the entire lake. It forms a broad embankment on shorelands with a gradient of less than about 4% (e.g. along Navy Beach), and a cliff on steeper slopes (e.g. along the eastern flank of Black Point, on the steep deposit of pumice east of the Rush Creek delta, and against the early-stage subsidiary deltas that abut the fronts of the Late Pleistocene deltas on Rush, Mill, and Lee Vining creeks).[17]

At many localities along the shorelands the strandline

is accentuated by an abrupt change in the density of the vegetation cover, as illustrated on Photo 13d. At several sites it is marked by a distinct change in the color of the substrate, from white (or at least highly reflective) above the line, to darker below it; field inspection reveals that the color change is due to the removal of the white blanket of Mono Craters tephra from lands lying below the Clover Ranch strandline.

The elevation of the strandline was measured at approximately two dozen points around the lake shore (including at the confined-onset deltas on Rush and Lee Vining Creeks). It was found to lie at between 6455 and 6458 feet, the discrepancy being due to the inability to define the precise relationship between the landform and the causal shoreline. At one site--the distal margin of the "block avalanche" that eminates north-northwestward from Panum Crater (Photo 6a)--this relationship is relatively unambiguous. There the strandline takes the form of a shingle-strewn abrasion platform that terminates landward at a steep cliff. Both the cliffline and the landward margin of the shingle layer lie at 6456 feet; that elevation, then, is used to mark the level of the Clover Ranch High Stand on the lake fluctuation curve. This wave-notched block avalanche is of additional interest because it confirms that the lake has been as high as, but no higher than, 6456 feet since the

block avalanche was deposited during the last Mono Craters eruption 605 years ago.

Age of the Clover Ranch High Stand

Based on the two radiocarbon dates described above the age of the Clover Ranch High Stand is placed at 220 yrs BP. Calibration of this date is problematical. Due to the erratic nature of the calibration curve for the past 300 sidereal years, a radiocarbon date of 220 ±60 BP has three possible calander equivalents:[18] AD 1660 (±19), AD 1773 (±30), and AD 1947 (±9) (Stuiver and Pearson, 1986). The latest of these dates can be dismissed out of hand. A reasonable choice between the two older possibilities can be made based on dendrochronological evidence: the 150-year-old mountain mahogany that was killed when the lake rose to 6422 feet in 1914 (pg. 155) demonstrates that the lake surface remained below 6422 feet after 1763 AD, a fact that is in obvious conflict with any interpretation that would have the lake at 6456 feet in 1773. A date of 1660 AD on the Clover Ranch High Stand is thus favored.

It should be noted that a date of 1660 AD (=290 cal BP) on the Clover Ranch High Stand, while a reasonable calibration of the available radiocarbon ages, is of questionable accuracy. Unlike most of the late Holocene transgressions and recessions of Mono Lake, the dates of

which correlate well with wetness indices derived from the tree-ring record from nearby bristlecone pines (Chapter 7), the Clover Ranch High Stand occurs at a time when, according to the tree rings, Mono Lake should have been declining. It is strongly suspected, based on the dendroclimatological evidence, that Mono Lake reached the Clover Ranch High Stand shortly after AD 1600, rather than around 1660. The previously mention stumps on Lee Vining and Rush creeks, rooted in the post-400 BP A-horizon and buried in Clover Ranch-age silts, have been collected for radiocarbon analysis, and should help to resolve this apparent inconsistency. For the present, the Clover Ranch High Stand is assumed to have occurred in AD 1660(?).

Deposition of the Generation-2 Dunes

The original lakeward extent of the Generation-1 dunes (pg. 226) on the north shore of Mono Lake, and the degree to which the G-1 dunefield was modified by the Post Office and Danberg Beach transgressions, are unknown. One may surmise that any G-1 dunes that stood at elevations as low as 6430-34 feet were obliterated by these rises in lake level, and furthermore, that the transgressions dumped the reworked sand at their respective highest strandlines, forming new concentrations of dunes. Whatever the configuration of the dunefield at the beginning of Clover Ranch time, it was

greatly altered when the lake margin advanced across it in the course of the rise to 6456 feet. Reworked dune sand, as well as deflatable drift delivered to the north shore by littoral currents during the course of the Clover Ranch Transgression, was shunted landward by wind and waves. The supply of sand continued as the lake receeded from the high stand. Today, a complex of bulky hairpin dunes eminates landward from the Clover Ranch strandline at 6456 feet (Photos 21a and b). These largely-unvegetated accumulations of sand, here called the Generation-2 dunes, have overridden, and continue to override, the much smaller lunettes of Generation-1. The largest of the G-2 dunes today covers the now-abandoned Bodie-Benton railroad bed, indicating that since the time of the rail construction in 1881 the dune has advanced a minimum of 115 meters (Photo 21c).

During the centuries that followed the Clover Ranch High Stand Mono Lake would decline approximately 60 feet to its "Pre-Historic Low Stand", then rise slightly to lie at 6407 (±1) feet when Alexis von Schmidt entered the Mono Basin in the mid-1850s.

290 cal BP to AD 1857--The Pre-Historic Recession and Low Stand

Shortly after 290(?) cal BP, Mono Lake began to decline, reaching a low stand (here called the Pre-Historic Low Stand) at an elevation of approximately 6396 feet. Pronounced littoral embankments lying below the Clover Ranch High Stand at elevations of 6447, 6438, and 6431 feet (Photos 6a and 13d) provide evidence that the lake lingered at, or reoccupied, these levels in the course of the recession.

Age and Elevation of the Pre-Historic Low Stand

Sediments deposited during and immediately following Clover Ranch time are capped with a soil (the "post-290 cal BP A-horizon") that can be seen on Meander cut (Plate 3B), Double-berm cut (Plate 3G), Upmill cut (Plate 4C), Downclover cut (Plate 2C), Hair cut (Plate 4A), and Stump cut (Plate 3A). This soil cannot be found at elevations below 6423 feet. As the lake is known from historic records (Chapter 1) to have declined to at least 6404 feet during the centuries following the Clover Ranch High Stand, the post-290 cal BP A-horizon provides no basis for determining the elevation of the pre-Historic Low Stand.

The approximate level of that low stand can be inferred from sediments exposed in delta trenches and shoreland pits.

At the 10-Mile Road and Navy Beach pits (Plates 5B and D), as well as in Marina Pit 1 (Plate 5E), sand did not reach 6380 feet in Pre-Historic time; the lake surface must therefore have remained above an elevation of 6385 feet. Latest pre-historic sediments exposed in shallow pits excavated at slightly higher elevations on the shorelands likewise lack littoral deposits, suggesting that the lake surface during that time remained above an elevation of approximately 6392 feet.

A stratum of littoral sand, corrugated with oscillation ripples on its surface, reached an elevation of 6393 feet in the South Tufa Pit (Plate 5C) during Pre-Historic time, indicating that the lake retreated to or below 6398 feet; the lack of desiccation in the underlying clays at this site suggests that the lake remained above 6393 feet. As a first approximation, the low stand might be placed midway between these two elevations--that is, at 6395.5 feet.

Along the east wall of the delta trench on Mill Creek stream gravels associated with the Pre-Historic Recession grade into pea-gravels and littoral sands at an elevation of 6396 feet. This elevation, then, is taken to be the approximate level to which Mono Lake declined in Pre-Historic time.

The precise timing of the Pre-Historic Recession and Low Stand is not known. Huntington's 150-year-old mountain

mahogany, killed by the lake rise in 1914, indicates that the lake surface was below an elevation of 6422 feet by AD 1764. Sometime before the mid-1850s the lake reached its Pre-Historic Low Stand, and by 1857 had risen to an elevation of 6407 ±1 feet (Chapter 1), a level that can be determined from the plats and notes of Colonel Alexis Waldemer von Schmidt.

1857-1919 AD

Stratigraphy of the Historic Transgression and High Stand

From its level in 1857 Mono Lake lake rose, reaching its Historic High Stand of 6428 feet in 1919. Deposits associated with this rise take the form of littoral sands and biogenic ooze in the shoreland pits; in the delta trenches on Rush, Mill, and Lee Vining Creeks littoral sands and gravels, and lacustrine silts, can be seen to overlie the "post-290(?) cal BP A-horizon". A littoral embankment marks the Historic High Stand around much of the lake margin. It can be seen in cross section on the Lee Vining "Meander cut" (Plate 3B) and on the Mill Creek "Berm cut" (Plate 4B).

This most recent lake transgression, and the subsequent recession, instigated the deposition of a third generation of dunes north of Mono Lake. The G-3 dunes are illustrated on Photo 21d.

The decline in lake level that began in 1919 AD is described in Chapter 1. The receding shoreline spread littoral sediment over the silts and clays of the Historic High Stand. An incipient A-horizon is presently forming on vegetated portions of the newly exposed shorelands (see Plates 2-4); elsewhere a salt crust has formed on the relicted lands.

FOOTNOTES

[1] By the early 1940's Matthes (1941) had provided evidence that the glaciers did indeed disappear from the Sierra Nevada at some time during the Holocene; his correlation of this event with the Altithermal interval, however, remained pure conjecture. It can now be shown that the episode of glacier extinction for which he provided evidence actually occurred during "Medithermal" time. See Footnote 4 below.

[2] G.I. Smith (1983) derived short-term sedimentation rates at Searles Lake that range from approximately 10 cm to 53 cm per 1000 years. His "overall sedimentation rate" (extending over the past >3 milion years) of about 22 cm per 1000 years is close to the rate of 26 cm per 1000 years calculated for the latter half of the Holocene at Great Salt Lake by McKenzie and Eberli (1985). Shelton (1966) reports a sedimentation rate at the Black Sea of 50 cm per 1000 years, a figure comparable to the deep-lake rate derived from a limited number of exposures at late Holocene Mono Lake by this writer. Mark Newton of University of Southern California (personal communication, 2/2/87) reports that he counts 13 laminae per cm in early Holocene sediments from Mono Lake; if these laminations are varves, as suspected, this yields an accumulation rate of aound 77 cm per thousand years. These sedimentation rates range from approximately 1/40 to 1/135 the rate reported by Matthes for Owens Lake.

[3] A core from Owens Lake logged by Smith and Pratt (1957) shows the stratigraphy to be considerably more complex than described by Matthes. The core includes a tephra layer at a depth of approximately 767 feet, which Andrei Sarna-Wajcicki (pers. commun. to G.I. Smith, October, 1986) reports is "probably" the Lava Creek member of the .62 million-year-old Perlette ash (G.I. Smith, pers. comm., 10/2/86). Sarna-Wojcicki (pers. commun. to G.I. Smith, October, 1986) further reports what appear to be shards of the Bishop ash (=.714 million years) at a depth of 858 feet. This suggests that the section described by Matthes is roughly two orders of magnitude older than his estimate of 7000 years.

[4] Matthes observed that the moraines associated with the most recent Holocene glaciation in the Sierra Nevada (now designated the Matthes glaciation by Birman, 1964; see also Curry, 1969) overlie talus that could have accumulated only during a period of glacier extinction. He took this to be evidence of Antevs' reputed Altithermal interval. Matthes was unaware of an earlier and more extensive late-Holocene glaciation (the "Recess Peak" glaciation of Birman, op cit.,

p. 74), the moraines of which lie some distance (typically 1-2 km) down-canyon from the Matthes moraines. Applying Matthes' reasoning to present-day understanding of the Holocene glacial deposits, it must be concluded that the Matthes and Recess Peak glaciations were separated by a period of deglaciation.

[5] In this regard it is interesting to note that, based in part on an analysis of sunspot records, Willett (1977) suggests that Great Salt Lake desiccated during the 14th century AD.

[6] The Pelagos bathymetric survey picked up a subdued, discontinuous terrace-like feature in a few places around the lake at an elevation of 6363 feet--5 feet below the elevation of the Scholl terrace. No information was found in the course of the present study that could be used to shed light on the origin of this terrace-like feature. It is worth pointing out, however, that if this feature is an abrasion platform (as opposed, say, to an accumulation of sediment deposited at the foot of the Scholl terrace at the time the terrace was cut), it has to have been produced by a drop (and subsequent rise) in lake level that occurred during either early or middle Holocene time. Furthermore, it should be noted that because of the changes in the stage/volume, stage/salinity, and volume/salinity relationships that have occurred since early and middle Holocene time, the climatic conditions that would have been required to force the level of Mono Lake to 6363 feet in mid-Holocene time are virtually identical to the conditions required to force the lake to 6368 feet in late Holocene time. Thus, even if the terrace-like feature is indeed a product of an early or mid-Holocene drop in lake level to 6363 feet, it is an indication of climatic conditions no more xeric than those which occurred for at least two centuries-long periods during the late Holocene.

[7] On the other hand, the higher values were measured in the area east (on the upthrown side) of the Simon's Springs Fault (Appendix D), and may indeed be higher due to tectonic displacement.

[8] Approximately 1/2 km west of the 119th parallel on the lake's northern shore Artemisia dominates above 6499 feet while Chrysothamnus is the dominant shrub species on lands lakeward of that elevation; near the center of the Dechambeau Ranch Embayment, an Artemisia/Purshia/Chrysothamnus brushland above 6499 feet gives way to a stand of Chrysothamnus below, while approximately 1/2 km farther north the lands above the

strandline are marked by a paucity of Elymus cinereus while those immediately below support an abundance of that grass; at several sites between Warm Springs and Simon's Springs a Sarcobatus brushland below 6499 feet changes abruptly to an Artemisia brushland above that elevation.

[9] Organic detritus from this mat was collected, but has not been dated.

[10] The only other known source of biotite-bearing dacite pumice in the Mono Basin is located on Twain Islet. XRF analysis indicates that the chemical composition of the Twain pumice differs considerably from that of Java and the shoreland blocks. See XRF analyses, Figure 19.

[11] Submerged portions of the Scholl Terrace in the vicinity of the ancient woodlands were searched for still lower rooted specimens using snorkel and mask; despite excellent visibility, no rooted plant remains could be found below 6373 feet.

[12] The soil over which the lake transgressed in Post Office Creek time varies markedly in its development from one site to the next, not only because of substrate differences (ranging from coarse cobble gravel ill-suited to vegetation colonization and soil formation, to sands and silts readily colonized and quick to accumulate organic detritus), but because of different exposure times. Thus, lands lying below 6404 feet were inundated by a rise in lake level around 1370 cal BP (the Mill Creek-East Transgression and High Stand) and, by Post Office Creek time, had been exposed for only four centuries or less; the A-horizon below 6404, therefore, typically consists of a thin (<4 cm), discontinuous darkening of the substrate that may be capped with a thin and discontinuous A_o horizon. Lands lying above 6404 feet, on the other hand, had been exposed for a millennium or more when they were inundated in Post Office Creek time. At these higher elevations the soil is relatively thick (to 60 cm), dark brown to black, and continuous over long distances. See Photos 28, 30, and 31.

[13] I am not entirely satisfied with this conclusion. The exposures along Lee Vining Creek provide clear evidence that the lake reached at least 6422 feet during Post Office Creek time. Evidence from the Mill Creek "Upmill-cut" suggesting a high stand elevation of 6430 feet, however, is equivocal. The sands and gravels (Unit G) that lie between the two uppermost Mono Craters ashes may in fact be fluvial (deposited by Mill Creek as the stream agraded in response to

the rise in lake level) rather than littoral, as tentatively concluded here. Further suspicion is cast by the apparent absence of Post-Office Creek-age littoral sediments at elevation 6427-28 feet in the Lee Vining Creek "Double-berm cut" (Plate 3G). It may be, therefore, that the Post Office Creek High Stand lies between elevations of 6422 feet (the elevation of Unit E in the Lee Vining "Meander-cut"), and 6427 feet (the elevation of the post-2000 BP A-horizon at the Lee Vining "Double-berm cut"), rather than at 6430 feet.

[14] The radiocarbon dates from two other stumps yield ages of 603 ±63 cal BP (USGS 1315 =600 ±70 yrs BP) and 613 ±58 cal BP (USGS 1167 =640 ±60 yrs BP). Because of the high standard deviations associated with these dates, the trees could conceivably have been killed during the transgresion of ~680 cal BP; it seems more likely, however, that they died during the subsequent transgression (the Danberg Beach Transgression of ~550 cal BP).

[15] Based on his isopach analysis of the tephra of 605 cal BP, Professor Kerry Sieh indicates that the average thickness of ejecta over Mono Lake is approximately one foot. It is thus likely that the deposition of the Mono Craters tephra forced a rise in lake level of approximately one foot, and that the lake stood at roughly 6405 feet at the time the eruptive sequence commenced.

[16] It appears that deposition of the littoral sands of Unit F on Milldown-cut may have been interrupted briefly by a minor decline in lake level; this interuption is suggested by the presence of a weak and discontinuous humic horizon roughly midway through the sand unit.

[17] A 2-km stretch of Highway 395 along the shore of the Western Embayment coincides in elevation with this strandline, suggesting that engineers may have exploited a wave-cut notch in constructing the roadbed.

[18] These three sidereal equivalents are derived using ± one standard deviation from the radiocarbon date.

CHAPTER 4

THE MONO CUTS AND PITS: LATE HOLOCENE STRATIGRAPHY IN THE CONTEXT OF THE LAKE FLUCTUATION CURVE

Introduction

The purpose of the previous chapter was to establish the late Holocene fluctuation curve for Mono Lake. This was accomplished by picking and choosing from different stratigraphic sections the sedimentary sequences that most clearly illustrate the late Holocene transgressions and recessions of the lake. In the process many of the sections illustrated on Plates 2-5 were adequately described (e.g. the Lee Vining Stump cut, Terrace cut, and Flicker cut; the Mill Creek Berm cut; and the pits at 10-Mile road, Navy Beach, and the County Marina). Several of the other sections, however, were either described only in small part, or have yet to be mentioned. In what follows, the stratigraphy and geomorphology of each of the sections illustrated on Plates 2 through 5 that has not been scrutinized in the preceeding pages is discussed in the context of the late Holocene lake history. Following this discussion the reader is left to check each of the stratigraphic sections illustrated on

Plates 2-5 against the lake level curve provided on Figure 16.

Plate 2: Stratigraphy exposed in the Rush Creek Delta Trench

Plate 2C: "Downclover cut". The Rush Creek Downclover cut (Plate 2C and Photo 27b) lies aproximately 70 meters downstream from the County Road crossing at Clover Ranch. A thick deposit of unsorted, angular pyroclasts from the Mono Craters eruption of 605 cal BP makes up the basal unit (Unit D) of the section. The absence of stream gravels low in the cut (indeed, their absence low in sections exposed all along the present coarse of lower Rush Creek), indicates that at the time of the eruption the bed of the stream lay some distance from the Downclover site. The presence of the aforementioned relict trench and subsidiary delta (pg. 268), and the lack of deltaic deposits to the east of the present-day stream, strongly suggest that at the time of the eruption Rush Creek followed a course several hundred meters to the west of its present position.

The 605 cal BP eruption of the Mono Craters centered on the northern end of the chain, at shortest distance less than 2 km from Rush Creek. The event wreaked havoc on the lower reaches of the drainage: pyroclastic flows eminating from the site of Panum Dome temporarily dammed the stream; the formerly pellucid waters became choked with coarse and fine

pumiceous sediment; the creek filled its delta trench with pyroclasts, then overflowed along a new path to the lake shore.

That new path lay across the Downclover site. In two phases of shallow incision, Rush Creek cut gravel-veneered straths into the newly deposited pyroclastic flow (Unit D). The earliest gravel unit (Unit C_i) is composed almost entirely of reworked ejecta, and dates from a time when the creek was still clogged with volcanic sediment. A slightly younger inset deposit of lag gravels (Unit C_{ii}) is made up mainly of Sierran clasts. It was deposited after the stream had cleared a course through the fresh ejecta, and had resumed carrying a load more like that of the pre-eruption period. These terrace gravels of Unit C mark the first time in at least several thousand years that Rush Creek assumed a course this far east.

The Rush Creek Transgression, which peaked shortly after the Mono Craters eruption of 605 cal BP, reached an elevation of only 6409 feet, and therefore is not represented by deposits on the Downclover cut (basal elevation = 6415 feet). Nor can direct evidence of the subsequent 10-Mile Road Recession be seen here, though the depth to which the stream incised Unit D during this time was likely controlled by the level of the low stand.

The Danberg Beach Transgression brought the lake to the elevation of the Downclover site, resulting in the deposition of more than a meter of laminated silt (Unit Bi) on the lag gravels of Unit C. The silts of Unit B_i grade upstream into beach gravels (Unit B_{ii}) at an elevation of 6434 feet--the highest elevation at which deposits associated with the Danberg Beach Transgression can be found.

Subsequent retreat of the lake during Navy Beach time exposed the silts of Unit B_i. Vegetation colonized the newly emergent surface, leading to the development of an A-horizon (the "post-400 BP A-horizon"). This soil, and the vegetation rooted in it, were drowned during Clover Ranch time, as the lake rose to and beyond the Downclover site. Clover Ranch-age silts (Unit A), rippled by waves, cover the post-400 BP A-horizon and its associated stumps to a depth of over 1.5 m.

With the recession of the lake in Pre-Historic time soil formation again commenced. The Historic Transgression peaked at 6428 feet, short of the Downclover site; development of the "post-290 cal BP A-horizon" thus continues today.

Plate 2B: The "Toppled tufa" cut. This simple section appears along the western wall of the Rush Creek delta

trench, roughly 400 m downstream from the road crossing at Clover Ranch. Here the same pyroclastic flow deposit (Unit F) that makes up the basal unit of the Downclover cut overlies well-sorted beach sands (Unit G) assumed to be from the Rush Delta Transgression.

Any depositional or pedogenic record that formed on the surface of this pyroclastic deposit during Rush Delta and 10-Mile Road time was removed by littoral planation as the lake rose in Danberg Beach time. The upper surface of the pyroclastic deposit constitutes a featureless abrasion platform that slopes gently lakeward.

This planer surface is overlain by laminated silts and clayey silts (Unit E) of the Danberg Beach Transgression and High Stand. Stream gravels (Unit D) from the subsequent recession (the Navy Beach Recession) overlie and partially truncate these Danberg Beach-age silts. This sedimentary sequence is repeated in Units C and B, where the silts and clayey silts of the Clover Ranch Transgression and High Stand are overlain and partially truncated by the fluvial gravels of the Pre-Historic Recession. A discontinuous soil (the post-290 cal BP A-horizon) that formed during this recession is preserved under thoroughly bioturbated and rhizome-impregnated sands and gravels of the Historic Transgression and High Stand and the modern recession.

Plate 3: Stratigraphy Exposed in the Lee Vining Creek Delta Trench

Plate 3B: "Meander cut". The section at Meander cut was first exposed in May of 1983. It is composed of both "active" and "passive" deltaic deposits, and represents one of the most instructive of all the stratigraphic sections on the Mono shorelands. Among the many features of interest are five buried A-horizons. The section is pictured on Photo 28.

The basal unit (Unit F) of coarse and fine alluvium composes a thick (>60 cm) dark brown soil that formed during the millennium-long post-Dechambeau Ranch time when the lake remained below the elevation of the Meander site. While this unit is thoroughly bioturbated, small pockets of the Mono Craters ash of 1245 cal BP can be found locally.

Overlying this soil are silts, sands, and gravels (Unit E) associated with the Post Office Transgression and the subsequent (Simis Ranch) recession. Over most of the exposure Unit E begins as a deposit of laminated silt (Unit E_{ii}) that in some places coarsens upward into, and elsewhere is truncated by, littoral sands and gravels (Unit E_{iv}). A thin A-horizon (the post-866 cal BP A-horizon) that represents a period of stability during Simis Ranch time caps Unit E in the middle reaches of the exposure; it has been removed by stream erosion at the cut's upstream end, and by

littoral planation at the downstream end. The Mono Craters tephra of 605 cal BP (Unit D) mantles the post-866 cal BP soil, and is itself capped by a thin A-horizon (the "post-605 cal BP A-horizon").

Overlying the Mono Craters ash of 605 cal BP at the Meander site are sediments associated with three transgressive/regressive cycles. The earliest of these (Danberg Beach Transgression / Navy Beach Recession cycle) is represented by a basal unit of lacustrine silts (Unit C_i) that coarsens into littoral sands and gravels (Units C_{ii} and C_{iii}). During the recession the stream, having aggraded from the delta trench, swept over the former beach surface, depositing cobble and pebble gravel (Units C_{iv} and C_v), and partially truncating the underlying littoral deposits. The continued drop in base level forced the stream to incise a new delta trench, a portion of which is exposed at the upstream end of the Meander cut. (Note near the downstream end of the Meander section that in the coarse of the Navy Beach Recession the stream first cut, and then filled, a small channel that truncates Danberg Beach-age deposits.) A thin, nearly continuous A-horizon (the "post-400 BP A-horizon") covers the deposits of Navy Beach time.

Sediments associated with the second of the post-605

cal BP lake cycles take the form of laminated lacustrine silts (Unit B_i) that coarsen upwardly into silty sands and sandy silts (Unit B_{ii}), then into littoral sands. (Note the degree to which the lacustrine silts are confined to the delta trench; here, as elsewhere--e.g. the Rush Creek Downclover cut--the silts have tended to accumulate in the submerged declivilty, thus depriving the delta plain of fine sediment.) A soil (the post-290 cal BP A-horizon) that developed during Pre-Historic time caps these deposits.

The last of the three post-605 cal BP lake cycles (the Historic Transgression and Recession) is represented by a sheet of littoral sand that forms embankments at 6428 and 6427 feet. An incipient A-horizon is currently forming on this historic deposit.

Plate 3E: The "Ober cut". This exposure (Photo 29) lies along an incised braid of Lee Vining Creek at an elevation of 6485-6491 feet. Overlying a coarse cobble gravel (Unit E) at the base of the section is nearly a meter of oxidized to gleyed clayey silts and silty clays (Unit D) of the Dechambeau Ranch High Stand. Charcoal at the base of Unit D provides a date of 3490 ±90 yrs BP on that high stand (see Table 2, BetaAn, 5115). This deposit of fine lacustrine sediment can be traced along numerous exposures downstream to elevations as low as 6460 feet. It can be followed upstream

to 6488 feet, where it is overlain by topset and foreset beds of the Dechambeau Ranch-age confined-onset delta (Photo 19).

Unit D is overlain by 30 cm of gravelly coarse sand (Unit C), presumably dating from the post-Dechambeau Ranch lake recession. A ~10cm-thick A-horizon, representing a period of stability, developed on this deposit. The soil is in turn covered by a Mono Craters tephra (Unit B). The original stratigrphy of this bioturbated tephra is preserved at several points along the exposure; the presence of a lapilli layer in the middle of the deposit suggests that the tephra dates from the eruption of 1245 cal BP.

Forty-five cm of of sandy silts and silty sands (Unit A) overlies the ash. The surface of this uppermost unit of Ober cut coincides with the surface of the fill-terrace that terminates downstream at the Clover Ranch-age confined-onset delta; Unit A is therefore assumed to be part of the channel-backfill that was deposited when the lake engulfed the lower reaches of the Lee Vining Delta Canyon 290(?) cal BP; accordingly, the soil that caps Unit A at Ober cut is tentativly correlated with the "post-290 cal BP A-horizon" of sites further downstream.

Plate 3F: The Lee Vining "Clean cut". "Clean cut" (Photo 30) lies across the stream from Ober cut, on the eastern wall of the main channel of Lee Vining Creek. The exposure reveals a depositional history similar to that in

the Ober cut. At the base of the section are oxidized gravels and clayey sands (Unit D) that compose the bottomset beds of the 3500-year-old confined-onset delta (indeed, these beds can be traced continuously to the confined-onset delta). Overlying Unit D are coarse-gravelly sands that were deposited by the stream as it incised the confined-onset delta in post-Dechambeau Ranch time. This alluvium composes a terrace on which an A-horizon has developed. (A terrace of similar origin capped with a contemporaneous soil makes up the basal half of the "Upmill cut" on Mill Creek--compare Photos 30 and 31.) The Mono Craters ash of 1245 cal BP covers the soil, and is in turn overlain by 80 cm of coarse sand (Unit A), believed to have been deposited by rills draining the colluvium-covered wall of the stream canyon. The timing of this last stage in the depositional history of "Clean cut" is not known.

Plate 5A: Stratigraphy Exposed in the Dechambeau Creek Cut.

The Dechambeau Creek cut is of interest not only because it provides a record of fluctuations in lake level, but because the environment of deposition represented by the site is fundamentally different from any other at Mono Lake. Like Rush, Mill, and Lee Vining creeks, Dechambeau Creek flows perennially. On the other hand, it is far smaller than the other perennial streams and, equally important, drains

what is primarily an unglaciated alluvial, rather than a glaciated bedrock, catchment. This mitigates the extreme seasonality, as well as the high interannual variability, of flow that characterizes the other perennial tributaries. This combination of factors results in a stream that carries sediment no coarser than coarse sand. (Note also that, due to a lack of glacially pulverized rock in the drainage basin, Dechambeau Creek carries little silt beyond that made available by the reworking of volcanic ash deposits.) The accumulation of sediment at the mouth of Dechambeau Creek thus lacks the dramatic shifts from very coarse to very fine sediment that characterizes the other deltas.

Sediments exposed in the Dechambeau Creek cut span the past 1245+ years. At the base of the section is a deposit of laminated clay (Unit J_i) that represents the Mill Creek-East Transgression and High Stand, as well as an indeterminate amount of pre-Mill Creek-East time. Unit J_i is of interest because it is the only clay deposit found in the section that is largely silt-free. The Mono Craters eruption of 1245 cal BP, (Unit J_{ii} in the Dechambeau Creek cut), as well as the eruption of 605 cal BP, provided the creek with sources of silty tephra that have not yet been exhausted. The hypopycnal current at the mouth of the stream is apparently

capable of carrying the silt some distance into open water. As a result, the high stands that have occurred since 1245 cal BP are represented in the Dechambeau Creek cut by silty (ashy) clays, rather than by pure clays.

During the decades following the Mono Craters eruption of 1245 cal BP Dechmabeau Creek was choked with ash. At the point where the section was logged the silt that accumulated immediately following the eruption (Unit I_i) is 17 cm thick. Slightly farther upstream, and on the opposite wall of the cut, this deposit is up to 60 cm thick, and displays large-scale convolutions believed to owe their existence to seismically-induced liquifaction. These convoluted silts were briefly discussed by Wood and Stine (1983).

The Lee Vining Delta Recession and Low Stand is recorded in the Dechambeau Creek cut as 8 cm of silty (ashy) littoral sand (Unit I_{ii}) that was deposited as the lake receded across the site. Colonization of these sands by marsh vegetation led to the accumulation of a thick mat of sod that persists today as a humic horizon (the A-horizon of the ~1000 BP low stand).

The Post Office Transgression and High Stand is represented in the Dechambeau Creek cut by laminated silty (ashy) clays (Unit H_i), while sediments representing the

subsequent decline in the lake level (the Simis Ranch Recession) are made up of an upwardly coarsening sequence of clayey silts (Unit H_{ii}), fine silts (Unit H_{iii}), and silts (Unit H_{iv}). The surface of this lake-recessional sequence, and any soil that had formed on it during the Simis Ranch Low Stand, were truncated when the lake rose just prior to the Mono Craters eruption of 605 cal BP. The transgression is recorded as littoral sands (Unit G_i) that unconformably overlie the rootlet-rich silts of Unit H.

The Mono Craters ash of 605 cal BP (designated Unit G_{ii} at the Dechambeau Creek cut) appears in a stratigraphic context unlike that seen in shoreland pits at a comparable elevation. Here the ash is neither overlain nor underlain by deep-water sediments. While the absence of an overlying sheet of clays may reasonably be attributed to truncation during the Navy Beach Recession, the lack of clays at the base of the ash is more perplexing: no satisfactory explanation comes to mind. Except that the ash itself displays all the markings of having been deposited in standing water beyond the littoral zone (it is composed of compact planer beds of consistant thickness that can be traced laterally for many meters, and lacks interbeds of littoral sand), one could not infer from this exposure that

the site was covered in over 25 feet of water at, and for some time after, the time of the eruption.

The lake receded to below the site of the cut during the decades following the eruption (10-Mile Road time), as evidenced by the littoral sands (Unit G_{iii}) and attendant A-horizon (the post-605 cal BP A-horizon) that overlie the ash. The A-horizon is in turn overlain by an alternating sequence of silty clays (Units F, D, and B) representing the Danberg Beach, Clover Ranch, and Historic transgressions, and littoral sands (Units E, C, and A) representing the Navy Beach, Pre-Historic, and Historic recessions. A thick humic horizon composed of freshwater marsh vegetation caps the section.

CHAPTER 5

HISTORY OF THE MONO ISLANDS

Introduction

Paleohydroclimatic interpretation of the Mono Lake fluctuation curve (Chapter 6) must be predicated on an understanding of the relationships between lake level, lake surface area, and lake volume, and the way that they have varied through time. Significant changes in these relationships have occurred within late Holocene time due to volcanically-induced island building. This chapter examines the history of the Mono Islands, and the ways in which their development has altered the morphometry of the lake basin.

Previous Works

Since 1863, when members of the California Geological Survey visited the Mono Basin, the age of the Mono Islands (Photo 32a) has been a matter of curiosity and speculation. Like others who would later study the region, survey members were struck with the geomorphically youthful appearance of the islands. Expedition botanist William Henry Brewer wrote that the cone on Negit Island looked "more recent than any other I have seen in the state" (Farquhar, 1949). Geologist Josiah Whitney made a similar comparison, and noted that

"there is every indication that the volcanic action [on Paoha] has ceased at a very recent period, or, rather, that it has not fully died out" (Whitney, 1865).[1]

Joseph LeConte (1879) was the first to attempt to date the islands. Stratigraphic relationships led him to conclude that Paoha Island was post-glacial (post-Champlain) in age. Similarly, Israel Russell (1889) reasoned that since Negit Island lacks lacustral sediments, it must post-date the late Pleistocene high stand of the lake.

Not until the 1960s were further attempts made to date the volcanic edifices in Mono Lake. Scholl and his co-workers (1967) observed that the islands lack the highstanding shorelines that were etched around the rest of the basin in latest Pleistocene time. This, together with its rugged appearance and lack of an integrated drainage network, led them to conclude that Paoha Island is post-Pleistocene in age. They ventured that Negit Island "may well be less than several thousand years old and may possibly be only several hundred years old."

Lajoie (1968; see also Reed, 1977), drawing on the work of Scholl, pointed out that sublacustrine terraces, including the "25-foot" terrace that surrounds much of the lake at an elevation of around 6368 feet, are absent on Paoha Island. Believing the terrace to be "Altithermal" in age (see pgs. 206-219), Lajoie concluded that the island must be less than

4000 years old. He further constrained the age of the islands by observing that they lack a shoreline associated with the lake's "Holocene high stand" (estimated by him to lie at an elevation of 6480 feet; now known to be at 6499 feet). Lajoie believed the age of the Holocene high stand to be approximately 3000 years (now dated at 3490 BP), and thus reasoned that the islands must have formed within the past three millennia.

The works cited above, as well as virtually all other relevant studies (Gilbert, *in* Cohen and Ribbe, 1966; Lee, 1969; Mason, 1967; Wood, 1977; Bailey, 1980) conclude that the islands of Mono Lake are post-Pleistocene in age.[2] The sole exception lies in the work of Cohen and Ribbe (1966; see also Ribbe and Cohen, 1966). Following Charles Gilbert's discovery of newberyite ($MgHPO_4 \cdot 3H_2O$), a pseudomorph of struvite ($MgNH_4PO_4 \cdot 6H_2O$), in the Pleistocene sediments exposed on Paoha Island (Gilbert, *in* Cohen and Ribbe, 1966), these workers reasoned that since struvite is typically found in association with guano deposits, ". . . we now have evidence that Paoha Island was a popular rookery . . . during the late Pleistocene, when birds must have literally covered the island, much as they do today on modern guano islands." The folly of this interpretation was pointed up by Lajoie (1968), who noted that the struvite (later newberyite) grew in

laminated mud on the quiet bottom of a deep lake, and not subaerially on the top of an island.

Information gained in the course of field work between 1980 and 1986 confirms the late Holocene age of the Mono Islands. Based on this information it will be shown that Negit Island and the Negit Islets formed due to episodic volcanism between roughly 2000 and 270 years ago, that Paoha Island broke the surface of the lake sometime after ~1685 AD, and that the cones and coulee on the northeastern corner of Paoha date from after ~1723 AD.

The Mono Islands

Negit Island

Negit Island ("the black island") is a ~200-acre complex of cones, domes, and flows composed primarily of dacite (64.95% to 66.32% SiO_2--chemical analyses by Joachim Hampel, Department of Geology, UCB), that is situated to the northeast of Black Point (Figs. 2 and 19; Photos 32b and c). The feature has existed as an island throughout most of historic time, though between 1978 and 1981 it was connected to the mainland by a landbridge.

The geomorphology of Negit Island has been described only in general, and contradictory, terms. Russell (1889)

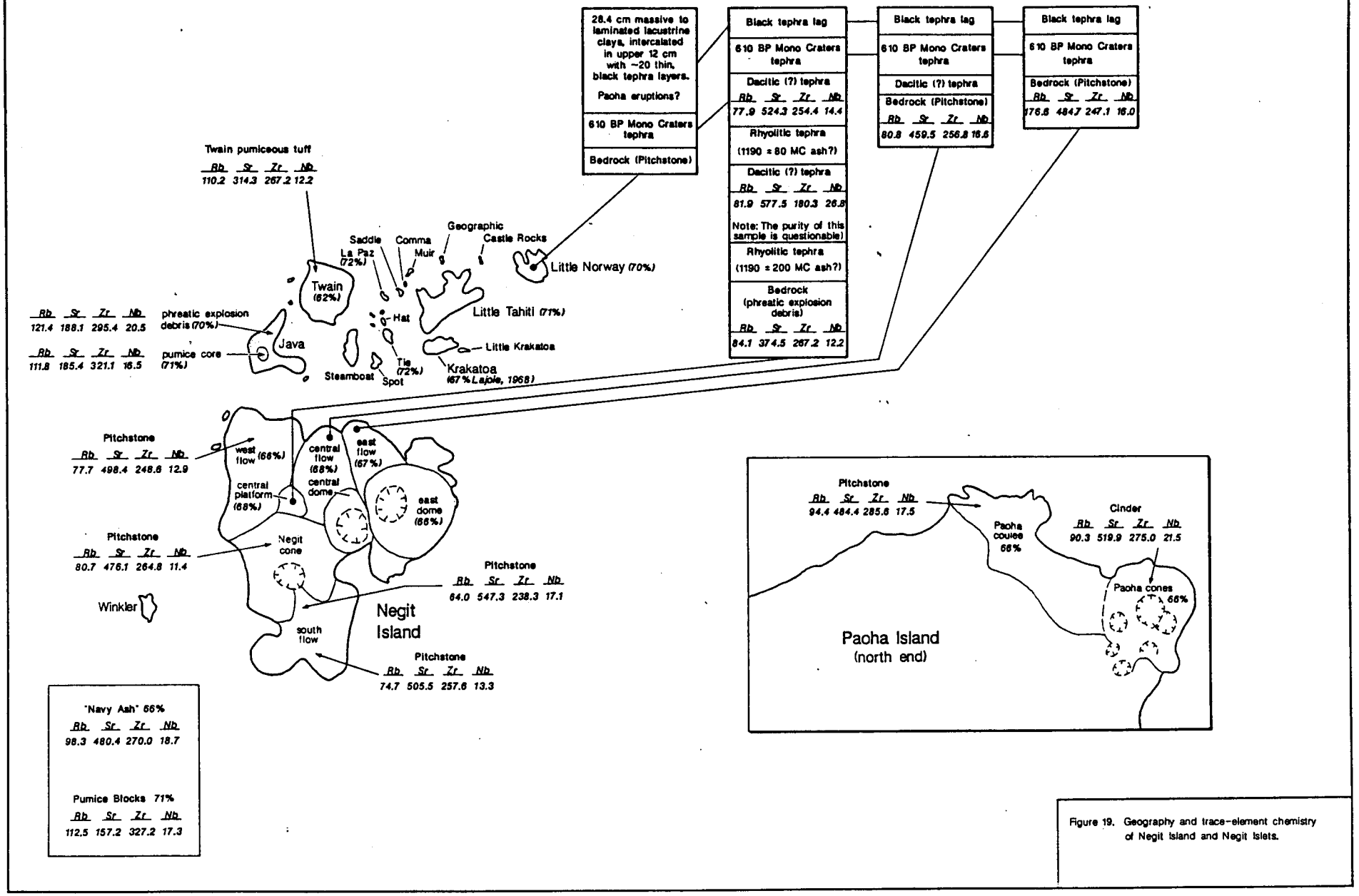


Figure 19. Geography and trace-element chemistry of Negit Island and Negit Islets.

wrote that it consists of "a crater and a lava coulee". Scholl and others (1967) called it a "compound andesitic dome". Wood (1977) described it as "two recent. . .flows and a cinder cone, and a central saddle area of older tuffs", while Lee (1969) ventured that the island "seems to be a single vent for the dacite which flows to the north and east."

The conclusion drawn here from field inspection and examination of aerial photos is that Negit Island is composed of three distinct eruptive centers--a prominent cinder/scoria cone and two domes--that have given rise to at least six lava flows. The cone (here called the Negit Cone) rises 75 m above the lake surface, and constitutes the summit of the island. Its south, east, and west flanks are composed of scoriaceous dacite blocks, while the northern side is mantled with cinder. A meters-wide dike dipping approximately 40° to the south is visible on both its east and west sides. The cone is crowned by a shallow crater, the southern rim of which has been breached by the overflow of lava.

Northeast of the Negit Cone are two deeply fissured dacite domes (the Central- and East-Negit domes) that project 45 m above the surface of the lake. The summits of the two domes have collapsed into shallow craters.

The cone and the two domes are aligned along a series of *en echelon* fractures that trend SW-NE across the island

(Appendix D). When projected beyond the island shores, these fractures join a prominent bathymetric linearity that can be traced along the lake bottom for a distance of approximately 10 km. The linearity is presumably the sublacustral expression of a fault system that has acted as a vent for the volcanics of Negit Island, as well as for the Negit Islets (see below).

Blocky dacite coulees emanate from each of the three eruptive centers (Figures 2 and 19). The largest coulee on the island, the South-Negit Coulee, flowed southward from the crater of the Negit Cone. Only slightly smaller is the West-Negit Coulee, which flowed northward from a source near the northern base of the cone. The Central- and East-Negit domes each produced a stubby, northward-flowing coulee (the Central- and East-Negit coulees); additionally, one minor flow was extruded to the southwest, and another to the northeast, from near the base of the East-Negit Dome.

Lying between and stratigraphically beneath the Central- and the West-Negit coulees is a small platform composed of gently dipping beds of welded phreatic explosion debris (Photo 32d). This rhyodacite deposit (SiO_2 =67.72%), and the West- and Central-Negit coulees, are separated from the Negit Cone by an arcuate declivity that girds the base of the cone on its northern side. A similar though shallower declivity

encircles the base of the East-Negit Dome along its southeastern margin.

The Negit Islets

Associated with the NE- to SW-trending bathymetric linearity that cuts across the northwestern floor of Mono Lake (Scholl, *et al.*, 1967) are spires and domes composed variously of glass, pitchstone, pumice, and tuff, the tops of which protrude from the lake as a linear cluster of islets. These "Negit Islets" are mapped on Figure 19 and pictured on Photo 32; the individual members were named by ornithologists studying the nesting behavior of the California Gull (Larus Californicus) and other aquatic birds that frequent the lake (Winkler, 1983). The Negit Islets are composed of dacite, rhyodacite, and rhyolite, with SiO_2 contents ranging from 62% to 72%.

Russell (1889) believed the islets to be remnants of a single lava flow "which has been mostly removed by erosion". The variation in both age (see below) and chemical composition (Figure 19) of the different islets, however, strongly suggests at least several separate eruptions from a number of distinct vents.

Historically, the number of Negit Islets has ranged from zero at the time of the Historic High Stand (=6428 feet) in

1919, to 20, covering a total of approximately 33 acres, at the time of the Historic Low Stand (=6372 feet) in 1982. The main cluster of islets lies to the north and east of Negit Island; note, however, that two unnamed spires lie adjacent to the tip of the West-Negit Coulee (and become peninsular to that flow at lake levels below about 6420 feet), and that, at a lake level of about 6374 feet, "Winkler Islet" emerges to the west of Negit Island.

Paoha Island

Paoha Island ("the white island") is a broad asymetric dome of lacustrine silt and diatomite, locally invaded by siliceous volcanic intrusions, that lies near the center of Mono Lake (Photo 32a). At present-day lake level (6380 feet) the island measures 3.6 km from north to south, 3 km from east to west, and covers slightly over 2000 acres. The highest elevations (up to 97 m above the present-day lake) occur along a deeply scalloped, NNE-SSW-trending ridge that towers over the southern three-quarters of the island. This ridge parallels, but lies well east of, the island's N-S axis.

Most of the island surface is composed of up-arched lake-bottom sediments that have been sculpted by fluvial, volcanic, and mass-wasting processes into a chaos of huge slump scars, random depressions, irregular heaps of landslide

debris, juvenile badlands of unintegrated drainage channels, and broad steps that conform to the quaquaversal dip of the sedimentary beds.[3] Lajoie (1968), who reconnoitered the island as part of his dissertation work, found most of the lacustrine sediment to be pre-Wilson Creek (pre-latest Pleistocene) in age. Wilson Creek beds persist in only a few small areas on the northern quarter of the island; elsewhere they have been removed by landsliding.

Volcanic rocks protrude from the lake sediments on Paoha Island in three different areas.[4] On the north end of the island, glassy to pumiceous spires and dikes of grey to black rhyolite (~70% silica) crop out in concentric rings, a morphology which suggested to Lajoie (1968) that the volcanic pile may consist of "a large plug dome or flow similar to the extrusions forming the Mono Craters". Highly altered rhyodacitic extrusives are found in association with presently-active fumaroles around "Hot-Spring Cove" on the island's east-central shore (Lajoie, 1968), while at least ten cinder cones and a blocky coulee of dacite (~66% SiO_2) make up the northeastern corner of the island (Photo 33a).

The periclinal structure of Paoha Island suggests broad doming by laccolithic intrusion. The bathymetry of the Paoha "lakemount", however, contradicts this simple interpretation. Sublacustral slopes on the northern, eastern, and southern

sides of the island are steep (from 400 ft/mile to near-vertical), suggesting that it was uplifted along bounding faults. The western slope of the lakemount is gentler, with a mean gradient of less than 200 ft/mile. This sublacustral topography, as well as the eastwardly-skewed placement of the axial ridge, suggests that Paoha Island was uplifted as a "trap door" hinged on the west. It may be, on the other hand, that the mass of slump debris found off the western shore of the island (see below) conceals a steep bounding scarp such as those on the northern, eastern, and southern sides of the island. The upheaval that resulted in the emergence of the island was presumably caused by the shallow intrusion of magma, though a test-well drilled in 1908 to a depth of 1998 feet on the island's southwestern corner failed to penetrate the hypothesized intrusion (Pakiser, et al, 1960, Fig.9; Scholl, et al, 1967; Lajoie, 1968).

The Paoha Islets

The sublacustral topography immediately west of Paoha Island is highly irregular and cluttered. Scholl and his co-workers (1967) surmised that this jumble of peaks and depressions is a landslide deposit that owes its existence to gravity-slumping off the western flank of Paoha Island. The nature and composition of the deposit (fractured, faulted,

and contorted lacustrine silts and diatomites) and the huge slump scars on the island's western flank (Photo 33b) support this interpretation.

In 1962, as the declining surface of Mono Lake neared an elevation of 6394 feet, sharp-crested pinnacles and hummocks of this landslide deposit began to emerge from the lake as tiny islets. By 1982, when the lake reached its Historic Low Stand of 6372 feet, the "Paoha Islets" numbered roughly two dozen (Photo 33c). The rise in lake level that occurred between 1982 and 1986 resulted in the reinundation and the obliteration (see below) of large portions of the Paoha Islets.

Age of the Mono Islands

Introduction

Reliable direct-dating of the Mono islands has met with little success. Hydration-rind analysis (a relatively imprecise method of chronometric control) on Paoha rhyolites by Wood (1977) yielded an age of 800-900 years. Wood explains, however, that this figure has not been calibrated, and that it therefore must be considered only an estimate. The annual rings displayed in cores extracted from the few trees growing on the islands show no obvious signs of volcanically-induced trauma, thus precluding a direct date from a tree-ring chronology. Thalus diameters of several

species of lichens growing on Negit Island were measured in the course of the study and, while they confirm the eruptive sequence derived from other lines of evidence, they cannot yet be used to provide absolute dates. Finally, it should be noted that the oral tradition of the native inhabitants offers no tenable hint of the eruptive history.[5]

With no available means of directly dating the islands, the eruptive sequence must be illuminated through indirect means. Several types of indirect evidence can be used to constrain episodes of island volcanism to time intervals ranging from several centuries to approximately six decades. The purpose here is to consider the history of island volcanism in light of the tephrostratigraphic, geomorphic, dendrochronologic, early historic, and lake-fluctuation records.

Sequence and Timing of Negit Island Volcanism

Tephra from three recent eruptions of the Mono Craters can be found on, and in close proximity to, Negit Island. Stratigraphy of the ashes leaves no doubt that the two youngest of these three geological time lines are the 1245 cal BP tephra of Wood (1977) and the 605 cal BP tephra of Sieh (1984; Sieh and Bursick, 1986); the oldest of the three is believed to be either the 1610- or the 1990(?)-year-old Mono Craters ash. For purposes of

discussion, this lowest ash will be assumed to date from 1610(?) BP; as its age is clarified, so too will be the timing of Negit Island volcanism.

Figure 19 illustrates the distribution of the three rhyolitic ash layers, as well as of three dacitic tephras, found on Negit Island. The generalized tephra stratigraphy shown there is based on roughly two dozen shallow pits that were dug to bedrock on various parts of the island. The longest sequence of ash units on the island mantles the platform of phreatic explosion debris. There, the three Mono Craters ashes alternate with the three dacitic tephras, the rhyolitic ashes making up the lower unit of each rhyolite/dacite pair. The three dacite units are informally designated, from youngest to oldest, dacitic tephras A, B, and C.

The Mono Craters ashes of 1610 BP and 1245 cal BP, as well as dacitic tephra C, are restricted to the platform of phreatic explosion debris, indicating that this feature is the oldest portion of Negit Island, having formed before 1610 BP.

The ash units overlying the Central-Negit Dome and Flow include dacitic tephra B, the 605-year-old Mono Craters ash, and dacitic tephra A (that is, the three uppermost tephra units found on the island). The East-Negit Dome and Flow lack dacitic tephra B, and are therefore judged to be younger

than their central-platform counterparts; they are, however, mantled with both the Mono Craters ash of 605 cal BP, and dacitic tephra A (the two youngest ashes on the island). On the basis of the tephra stratigraphy it is concluded that the East- and Central-Negit domes and flows formed sometime between 1245 and 605 cal BP.[6]

While both the West- and South-Negit Flows are in places peppered with dacitic tephra A, they lack a mantle of the most recent Mono Craters ash, indicating that they were deposited after 605 cal BP. An upper constraining age for the West-Negit Flow can be assigned based on the presence of strandlines of known age. The highest strandline on the flow, and in fact the highest strandline found anywhere on Negit Island, lies at an elevation of 6456 feet--the level of the Clover Ranch High Stand of 290(?) cal BP. This feature takes the form of an erosional notch wherever it is found on the island. Pitchstone blocks lying above the notch are angular, jagged, and characterized by a lustrous sheen. Rocks below the cliffline are typically lackluster, and well- to sub-rounded. Inscribed as it is with the Clover Ranch strandline, and lacking the uppermost Mono Craters ash, the West Negit Flow is judged to have formed between 605 and 290(?) cal BP.

The Clover Ranch strandline encircles almost the entire island. It is absent only on the South Negit Flow. The

highest shoreline on that flow--a conspicuous notch similar morphologically to the Clover Ranch strandline--lies at an elevation of 6445 feet (11 feet below the Clover Ranch strandline); the flow thus post-dates the Clover Ranch High Stand of 290(?) cal BP (though perhaps by only two or three decades), and appears to be the youngest portion of Negit Island.

In summary, the events leading to the development of Negit Island proceeded as follows:

1. Phreatic eruption of rhyodacitic debris, leading to construction of the "central platform" area on Negit Island.

--Ashfall associated with the Mono Craters eruption of 1610 BP

--Deposition of dacitic tephra C--source unknown (see below)

--Ashfall associated with the Mono Craters eruption of 1245 cal BP

2. Formation of the Central-Negit Dome and Flow.

--Deposition of dacitic tephra B--source unknown (see below)

3. Formation of the East-Negit Dome and Flow, and presumably of the tiny flows on the southern and northeastern sides of the East-Negit Dome.

--Ashfall associated with the Mono Craters eruption of 605 cal BP

4. Formation of the West-Negit Flow.

--Lake attains, then recedes from, the Clover Ranch High Stand

5. Formation of the South-Negit Flow, ~270 cal BP.

--Deposition of dacitic tephra A (source: Paoha Is.--see below)

Note that the formation of the Negit Cone is absent from the list. The presence of the youngest Mono Craters ash

within the crater of the cone indicates that the feature formed prior to 605 cal BP. A thorough search of its flanks may reveal the presence of older tephra units. Further work on the trace-element chemistry of the cone, other features of Negit Island, the Negit Islets, and dacitic tephras B and C, may help clarify the sources of these two lowest dacitic tephra units and, consequently, the relative ages of the vents.

Age of the Negit Islets

As previously noted, the tens of thousands of pumice blocks that litter the southwestern half of the Mono shorelands lie stratigraphically between the Marina-age littoral sands and plant detritus dated at 1610 BP. On the basis of both lithology and trace-element analysis (Figure 19), the blocks are judged to be the product of the pumiceous "core" region of Java Islet. The age of the Java core can thus be placed at approximately 1700 BP. While demonstrably older than many of the island volcanics, the Java core is clearly younger than the phreatic explosion debris that it intrudes.

Lajoie (1968) pointed out that the two small spires that protrude just north of the West-Negit Flow are covered with a tufa rind the thickness of which far exceeds that on the flow itself. It is therefore concluded that these two islets predate the West Negit Flow.

Assigning ages to other islets of the Negit Archipelago is problematical. Because the islet summits lie below the elevation of the Clover Ranch High Stand (and, with only a few exceptions, below the Historic High Stand), stranded shorelines cannot be used to fix maximum or minimum ages. Furthermore, most of the islets lack protected embayments in which a tephra sequence might survive obliteration by waves. Only on "Little Norway", so named because of the miniature fiord-like declivity that bisects the islet from north to south (Photo 33d), can a tephrostratigraphic sequence be found. Near the southern end of this narrow, slack-water cove the rhyolite (70.35% SiO_2) that makes up the islet is overlain by sediments that include the Mono Craters ash of 605 cal BP and dacitic tephra A (Figure 19). Lacking the second-youngest Mono Craters ash, Little Norway is accordingly assigned an age of between 605 and 1245 cal BP. The 605-year-old ash lies in direct contact with the bedrock of the island, suggesting that Little Norway formed immediately prior to the last eruption of the Mono Craters.

XRF analyses were conducted on the rhyolite of Little Norway, Tie, Little Tahiti, and La Paz (Figure 19). The results indicate a high degree of similarity from islet to islet, suggesting that they may be the product of the same eruption. If this is indeed the case, the pre-605 cal BP

date inferred for Little Norway is applicable to these other islets, and perhaps to other (yet-unanalyzed) rhyolitic islets of the archipelago as well.

Age of Paoha Island and the Paoha Islets

Absence of the Mono Craters ash of 605 cal BP. A thorough search of Paoha reveals that deposits of Mono Craters tephra are confined to a few highly localized sites on the island's northern quarter. There, the ash occurs as thin beds intercalated within contorted glaciolacustrine silts of the late Pleistocene Wilson Creek Formation. Unlike nearby Negit Island and Little Norway, and the Mono shorelands to the north, east, south, and west, Paoha Island lacks a surface mantle of tephra from late Holocene eruptions of the Mono Craters. Given the well-documented distribution of the tephras of 605 and 1245 cal BP,[7] it is inconceivable that Paoha, had it existed at the time of these eruptions, could have escaped the ashfalls.

Littoral landforms and their bearing on the age of Paoha Island and the Paoha Islets. The distribution of clifflines and wave-cut terraces on the Paoha Island-Complex is equally revealing. Around 1962 (lake level =6394 feet) a few of the islets began to project above the declining lake surface. Aerial photos from 1964 show clearly that the newly-emergent individuals displayed sharp, linear crests that had never

before been subjected to planation by waves. By 1975, when the lake reached 6380 feet, the islets numbered one dozen and covered over 24 acres, and in late December of 1981, at the time of the Historic Low Stand of 6372 feet, the number of islets had increased to 23, with a total area exceeding 35 acres.

During this period of declining lake levels waves sculpted the islets into smooth, rounded, and in many cases steep-sided forms, with flanks that descended to the lake surface in a series of subdued steps, each step corresponding in elevation to a minor, vernal rise of the receding lake. The lake transgression that began in 1982 resulted in wholesale modification of the Paoha Islets. Waves rapidly beat them back, cutting a low-gradient platform that terminated at a vertical cliff (Photo 34). By the summer of 1986 the rising lake had reattained an elevation comparable to that of 1975; islet area, however, had been reduced to less than half of its 1975 value.

It is clear from these figures, and from observations made in 1982, '83, and '84 (Stine, 1984), that a rise in lake level does not simply resubmerge islets composed of easily erodible sediment; rather, the rising lake bevels the islets at waterline, transforming each one into a gently-inclined abrasion platform. Such islets do not survive an episode of resubmergence, and thus cannot have been exposed prior to

their emergence in 1962. When considered in light of the pre-historic lake level curve, this line of reasoning indicates that the Paoha Islets could not have existed 500 years ago during Navy Beach time.

This same conclusion must be drawn from observations made by University of California geologists in 1966. In the summer of that year, when the surface of Mono Lake stood at approximately 6388 feet, Professor Charles Gilbert and his students (Reed, 1972, 1977; Lajoie, 1968; Christensen, *et al.*, 1969) found that Paoha Island sediments newly exposed by the artificially-induced drop in lake level had rapidly oxidized to white, while sediments below lake level remained black and unoxidized. They reasoned that the sediments on the margin of Paoha Island had never before been subaerially exposed, and, consequently, that the lake at the time of the visit was lower than at any time since Paoha Island came into existence. As Reed (1972, 1977) put it, "Mono Lake is now at its lowest level since uplift of Paoha Island", a conclusion in keeping with a post-500 BP date for the Paoha Island-Complex.

Lajoie (1968) and Reed (1972, 1977) also pointed out that, at a mid-1960s elevation of ~6395 feet, Paoha Island lacked a submerged terrace, corroborating their contention that the island had never before seen lake levels as low as those of modern time. Russell's account, on the other hand,

makes it clear that at the time of his visit in 1883, when lake level stood approximately 20 feet higher than that witnessed by Lajoie and Reed, a submerged terrace did exist. On page 305 of his monograph he states that this terrace extended lakeward to a depth of "about 12 feet", while on his bathymetric map the terrace is shown to extend to a depth of 15 feet. It may be concluded from the Russell account that in 1883 the terrace extended lakeward to an elevation somewhere between 6395 feet and 6398 feet--that is, very close to the level of the Pre-Historic Low Stand of roughly 150-250 years ago.

It can thus be inferred from evidence related to past low stands of the lake that Paoha Island did not exist 500 years ago, but that it had come into existence by the time of the Pre-Historic Low Stand some 150-250 years ago. What conclusions can be drawn from evidence related to past high stands? Photos 35 shows that in 1930 the lake, at a level of 6420.7 feet, lay close to, and in fact was in the process of receding from, an abrupt cliffline. Measurement of the cliffline at many points around the island indicates that it corresponds in elevation with the Historic High Stand (6428 feet). A similar photo taken in 1982 shows the broad, wave-cut platform that lies below the cliffline. That the cliffline was cut during the lake transgression of the 19th

and early 20th centuries is made evident in Russell's account of 1883. He wrote that "wherever the shore of the island is composed of lacustral sediments a broad cut-terrace has been formed . . .", and that on the east side of the island the terrace terminated against "bold bluffs, which are being eaten away by the waves". (W.D. Johnson's shaded relief map of the Mono Basin, included as Plate XIX in Russell's monograph, shows this cliff at many points around the island margin.) It is evident from this account, as well as from modern photographs (Photo 33c and 35), that between 1883 and 1919 waves beat Russell's bluffs islandward, broadening the abrasion platform all the way to the level of the Historic High Stand.

Note on these photographs the apparent lack of clifflines and abrasion platforms above the level of the Historic High Stand (6428 feet). The absence of higher strandlines, noted previously by Lajoie (1968) and Lee (1969), was verified in the course of field work on the island. Having established the late Holocene fluctuations of Mono Lake, it must be concluded that Paoha Island was not in existence during Clover Ranch time (290(?) cal BP), nor during the decades that it took the lake to recede from the Clover Ranch High Stand (6456 feet) to 6428 feet.

How long would such a recession require? This, of course, depends on the hydroclimatic conditions that

characterized post-Clover Ranch time. A reasonable minimum duration for the lake decline can be derived by assuming that hydroclimatic conditions during the decades following the Clover Ranch High Stand were less severe those of the most extreme and prolonged drought in the historic record--the "Dust Bowl" years of 1924-1934, when inflow to Mono Lake was only 72% that of modern times (pg. 46). Calculations using the Vorster model (see pg. 360 and Appendix E) show that 25 years of Dust-Bowl-like conditions would be required for the lake to fall from 6456 feet to 6428 feet. The absence of strandlines above 6428 feet, then, indicates that in all likelihood Paoha Island broke the surface of Mono Lake at least 25 years after 290 cal BP--that is, sometime after 1685 AD.

Age of the coulee and cones on northeastern Paoha. AD 1685 must be considered the earliest reasonable date for the emergence of Paoha Island, not only because it assumes extreme and persistent drought conditions for post-Clover Ranch time, but because it presupposes that the lake had dropped only 28 feet below the level of the Clover Ranch High Stand (that is, from 6456 to 6428 feet) at the time the island emerged. In fact, however, Israel Russell's monograph of 1883, as well as the tephrostratigraphic record, make it clear that the formation of at least one portion of Paoha Island--the coulee and cones on its northeastern corner--was

preceded by a significantly greater drop in lake level. Russell's account provides indisputable evidence that in 1883 the volcanic features on the northeastern corner of the island lacked strandlines at elevations higher than the lake margin (~6411 feet in the summer of that year). He wrote, for instance, that the lava coulee "is not covered with lacustral sediments, and is without deposits of calcareous tufa . . . [It] descends into the lake without change of character, thus indicating that the surface of the water at the time of formation may have been lower than now".[8] The adjacent cinder cones, according to him,

> ...do not contain lacustral sediments, and are not scored with beach lines on their outer slopes. The loose, incoherent nature of the material of which they are composed renders it evident that they could not have withstood the action of waves and currents for even a brief period without having evidence of the fact inscribed upon them... [The craters thus] *formed after the lake had fallen at least as low as at the present time* [emphasis added].

Examination of the northeastern corner of Paoha Island confirms Russell's contention that these volcanic features cannot resist littoral erosion. The cinder cones, as well as the lava coulee, are today notched with conspicuous terraces at and below the elevation of the Historic High Stand. Russell's account, then, leaves no doubt that the lake had dropped from the Clover Ranch High Stand (6456 feet) to a level below 6411 feet before the volcanic features on the northeastern corner of Paoha Island had formed.

Tephrostratigraphic evidence confirms the recency of the eruptive centers on northeastern Paoha Island. Sedimentary sections exposed at several sites around the lake include thin layers of ash from the Paoha cones.[9] (This ash was referred to as "dacitic tephra A" in the above discussion concerning the age of Negit Island.) The most instructive of these sections are found on Little Norway (see Figure 19 and Photos 36a and b), at Navy Beach (Plate 5d, and Photos 37a and b), and at South Tufa (Plate 5c), where up to eight thin layers of dacitic ash can be seen lying high above the Mono Craters tephra of 605 cal BP, and close to the modern-day surface.

The sequence of sediments exposed in the research pit at South Tufa is of particular interest because it can be used to define the approximate surface elevation of the lake at the time the eruptions occurred. Note on Plate 5c that the Paoha ashes are intercalated within littoral sands deposited during the latest pre-historic lake recession (the post-1660 AD recession). One of the ash layers, in fact, fills the troughs of oscillation ripples formed by wave-drag over the littoral sands. The occurrence of the Paoha ash in association with the rippled sands demonstrates that the tephra was deposited in shallow (<1 m?) water within the littoral zone of the lake. The elevation of the

tephra-intercalated littoral sands is 6393 feet, suggesting that the lake stood at approximately 6396 feet--that is, near the level of the Pre-Historic Low Stand--at the time of the Paoha eruptions.[10]

The available evidence thus indicates that the interval of time that elapsed between the Clover Ranch High Stand (AD 1660(?)) and the volcanic eruptions that gave rise to the cinder cones on the northeastern corner of Paoha Island was of sufficient duration to allow the lake to fall approximately 60 vertical feet--from an elevation of 6456 feet to roughly 6396 feet. According to the Vorster model, this decline in lake level, under hydroclimatic conditions such as prevailed during the "Dust Bowl" period, would require approximately 63 years. A reasonable lower limit on the age of the Paoha coulee and cones, therefore, is 1723 AD (AD 1660(?) + 63).

It must be understood that the difference between the lower constraining date on the volcanics of northeast Paoha Island (1723 AD) and that on the main island mass (1685 AD) reflects the nature of the available evidence, rather than a real difference in age. While Israel Russell's account and the tephrostratigraphic record make it possible to say that the lake had dropped to a level approximately 60 feet below the Clover Ranch High Stand (6456 feet) at the time the cones and coulee were formed, only a minimum amount of lake decline

(to 6428 feet) can be defined as preceding the emergence of the main island mass.[11] The main island mass is unquestionably older than the cones and coulee (cinder from the cones can be seen to overlie the main island mass at dozens of localities), but the actual difference in age between the island and the earliest of the cones might be a matter of hours, days, or weeks, rather than decades, as the constraining dates suggest.

An upper constraining age on Paoha Island: dendrochronological evidence

An upper limit on the age of the northeast-Paoha volcanics can be defined on the basis of dendrochronological evidence. Here again, it is necessary to draw upon Russell's account from 1883:

> Among the most recent craters [in the Mono Basin] are those on Paoha Island and the one on the south shore of the lake [i.e. Panum Crater]. . . In each of these instances aged cedars and pines are growing within the bowl formed by the violently ejected lapilli, thus proving that the craters could not have been the site of an eruption within at least one hundred years".

A thorough search of the Paoha cones in 1986 and 1987 turned up traces of only one tree.[12] This specimen--a dead pine--grew on the east-facing inner-crater wall of the largest of the Paoha cones. It is still standing, despite

extensive rotting at its base. The tree, pictured in Photo 37, was sectioned in order to obtain a ring-count. Unfortunately it was afflicted with heart-rot, precluding an accurate assessment of age at the time of death.

Without knowing the year of death it is impossible to determine when the tree was established (and thus provide an accurate upper constraining age on the Paoha cones). It may be possible in the future to cross-check the sequence of this tree's annual rings with that from the living, ~350-year-old pinyon pine growing on the East-Negit Dome, and thus derive an estimate of the date of establishment. For now, however, it is possible only to trust Russell's age estimate of "at least 100 years", and conclude tentatively that the Paoha cones were in existence by at least a century before his expedition of 1883. This, together with the tephrostratigraphic and geomorphic evidence cited above, argues that the Paoha cones formed sometime within the sixty-year interval 1723-1783 AD. Since the cones can be shown to be younger than the main island mass (see above), Russell's "aged pine" provides an upper constraining date not only on the northeastern volcanics, but on the rest of the island as well.

Age of Paoha Island--Summary

The presence or absence of known geomorphic,

tephrochronologic, and dendrochronologic "time lines", in combination with assumptions about the behavior of the lake in pre-historic time, can be used to constrain the age of Paoha Island and the Paoha Islets. These constraints, and their relevance to dating the Paoha Island-Complex, are summarized below:

--The island lacks a mantle of tephra from recent eruptions of the Mono Craters, indicating that it did not exist at 605 cal BP.

--The island lacks strandlines below those cut in modern times; this, together with the inabililty of the exposed islets to survive a lake transgression, indicates that the island-complex did not exist at the time of the lowstand of ~500 BP.

--The island lacks strandlines above an elevation of 6428 feet, indicating that it did not exist at the time of the Clover Ranch High Stand (AD 1660(?)), nor during the years that it took the lake to decline from that high stand (6456 feet) to 6428 feet. According to the Vorster model, if the hydroclimatic conditions that prevailed during the decades following the Clover Ranch High Stand were less extreme than those of the period 1924-34, as seems likely, this decline in lake level required more than 25 years. Thus, the island must have emerged sometime after AD 1685.

--In 1883, when Israel Russell visted Paoha, the coulee and cones on the island's northeastern corner lacked strandlines at elevations higher than the 1883 shoreline (6410 feet). This indicates that the coulee and cones did not exist at the time of the Clover Ranch High Stand, nor during the years that it took the lake surface to decline from that level (6456 feet) to 6410 feet.

--The island existed at the time of the Pre-Historic Low Stand (sometime between 150-250 years ago), as evidenced by the

existence of the submerged terrace described by Russell in 1883.

--Tephrochronologic evidence indicates that the lake stood very close to its Pre-Historic Low Stand (6396 feet) at the time the Paoha cones were formed. Assuming that the hydroclimatic conditions that prevailed during the decades following the Clover Ranch High Stand were less extreme than those of the period 1924-34, the decline in lake level must have required more than 63 years. Thus, the eruption of the coulee and cones on northeast Paoha in all probability formed sometime after 1723 AD.

--Based on his estimate of the age of a tree growing in the cones on northeastern Paoha Island, Israel Russell concluded in 1883 that the island was more than 100 years old. This tree has been located and sectioned; future detailed analysis of the sample may provide a more precise estimate of the upper constraining age of Paoha Island.

Uncertainty in the age of the Clover Ranch High Stand: a caveat. As mentioned earlier (pg. 281), and as discussed in more detail on in Chapter 6, there is reason to suspect that the Clover Ranch High Stand, dated on the basis of two radiocarbon assays at 1660 AD, may have actually occurred around 1600 AD. To the extent that this earlier date is the correct one, the lower constraining age of AD 1723 on Paoha Island must be pushed back approximately six decades.

Age of Paoha Island: an alternative hypothesis. Given the stratigraphic position of the Paoha ashes, and the lack of high-standing shorelines on the coulee and cones, it is incontestable that these volcanic features of northeastern Paoha Island post-date by many decades the Clover Ranch High

Stand. That the entire island emerged in post-Clover Ranch time, however, cannot be proven with absolute surety. It is conceivable that the island has been a feature of Mono Lake for many hundreds or thousands of years, and that the existing time lines were, one and all, utterly and completely erased from the entire island by gravity sliding induced by earthquakes associated with the northeast-Paoha eruptions.[13] This possibility seems unlikely, however, since the most recent of the time lines (the Clover Ranch strandline) is absent not only from those portions of the island subject to sliding, but from areas which have clearly not been so affected (i.e. the large areas of outcropping rhyolite and rhyodacite that occur on the northern and eastern sides of the island). In other words, had Paoha existed at the time of the Clover Ranch High Stand, and the entire outer shell of lacustrine sediment on the island was shed during the volcanic activity associated with the formation of the northeastern coulee and cones, one would still expect to find stranded shorelines on those portions of the island margin that are composed of bedrock. (These portions of the island are today etched with a prominant shoreline at the elevation of the Historic High Stand but, as noted previously, lack higher strandlines.) Furthermore, Scholl and his co-workers (1967) argue that the major episodes of gravity sliding from Paoha Island probably occurred during, rather than after, the

process of island building. They reason that sliding would have been favored as the island broke the surface of the lake, since "a constantly increasing unbuoyed load would be placed upon the submerged portions of the sedimentary section as the island emerged." In light of the absence of strandlines above the Historic High Stand on both bedrock and sedimentary portions of Paoha Island, and given the unlikelihood that gravity sliding has effected the entire island since the time it was formed, the possibility that the island existed at the time of the Clover Ranch High Stand must be considered remote.

The Putative Volcanic Events of AD 1859 and 1890

Several accounts from 19th century newspapers suggest that volcanic eruptions have occurred historically in the Mono Basin. Two of these reports concern the Mono Islands.[14] The earliest of the two is found in the February 26, 1881 edition of the Bodie Daily Free Press. It includes this description of Negit Island:

> On the island of the second magnitude [Negit] is a volcanic crater... Twenty-two years ago this volcano was in active eruption, throwing up boiling water, mud, and jets of steam to a height of 20 feet or more above the crater."

Any material that might have been expelled during an eruption in 1859 is not readily distinguishable from ejecta associated

with the Negit eruption of approximately 270 yrs. BP (see above). Field evidence of a mid-19th century eruption is thus inconclusive. Certainly the Negit Cone is capable of activity such as that described in the Daily Free Press, but the fact that the putative eruption is not mentioned by members of the Whitney Geological Survey, who visited the basin within four years of its supposed occurrence, or by Joseph LeConte, who studied the volcanoes (including the islands) of the Mono Basin and interviewed basin residents during the 1870s, makes the account suspect. That the report represents a ploy by local commercial interests to lure sightseers to the Mono Basin must be considered a possibility.

Considerably more attention has been given to the following article from the Homer Mining Index of Lundy, Mono County:

> 1890. August 23; Mono Lake--
> Remarkable earthquake at Mono.-- The southern end of Mono Lake was considerably agitated last Sunday, and dwellers in that shaky locality were much perturbed. Steam was issuing from the lake as far as could be seen, in sudden puffs, and the water was boiling fiercely, while high waves rolled upon the beach and receding left the sand smoking. In a moment the air was thick with blinding hot sulphurous vapor, and subterraneous moans and rumblings made the witness think that the devil was holding high carnival down below. The fences wobbled up and down and sideways.
>
> This appalling fracas lasted about two minutes. Then came a blessed quiet for a moment, followed by a sudden twitch of the earth, as a horse jerks his hide and dislodges a bothersome fly. The shock threw men and animals off their feet with bruising violence.

> It was some hours before the lake ceased to emit columns of steam and the water became very hot. Two springs near the house, long noted for the coldness and purity of their water, changed their character and spouted hot mud for two days, when they flowed cold water again. A stack of 200 tons of hay was moved 70 feet south without disarranging it [Quoted from Holden, 1898].

Holden, who brought this article to the attention of earth scientists in his Catalogue of Earthquakes of the Pacific Coast: 1769-1897 (1898), classified the quake as "extremely severe". Several subsequent workers (Toppozada *et al.*, 1981) consider it to be an exaggerated description of a "small local event".[15] They point out that the shock was not reported in the newspapers of neighboring communities (e.g. Bishop, Bridgeport, Mariposa, or Hawthorne). Other investigators accept the veracity of the account, and interpret it to indicate that in August of 1890 Mono Lake experienced a sublacustrine volcanic explosion (Kilbourne *et al.*, 1980; Christensen and Gilbert, 1964; Chesterman, 1971). Kilbourne and others (1980), in fact, argue that the absence of newspaper accounts from neighboring communities points to a highly local event of the type that one should expect from a volcanically-induced earthquake.

There is little question that portions of the Homer Mining Index article are exaggerated (e.g. the purported movement of hay). Whether the entire account is a fabrication must at present be left to conjecture. It is

interesting to point out, however, that there is field evidence that suggests the possibility of a volcanic eruption on Paoha Island sometime after the Russell expedition of 1883. Russell wrote that the northeast-Paoha coulee is "of later date than the lapilli craters at hand, *as its surface is entirely free from the debris showered on the island when the craters were formed* [emphasis added]". This observation does not hold true today. In July of 1984 the writer, in the company of Professor Spencer Wood of Boise State University, visited Paoha Island. Both observers were struck with the fact that most of the coulee is today unmistakably peppered with tephra from the Paoha cones. If the coulee was in fact free of lapilli in 1883, as Russell states, it must be concluded that sometime after that year (perhaps during the reputed event of August, 1890) a volcanic eruption involving one or more of the Paoha cones showered it with tephra.

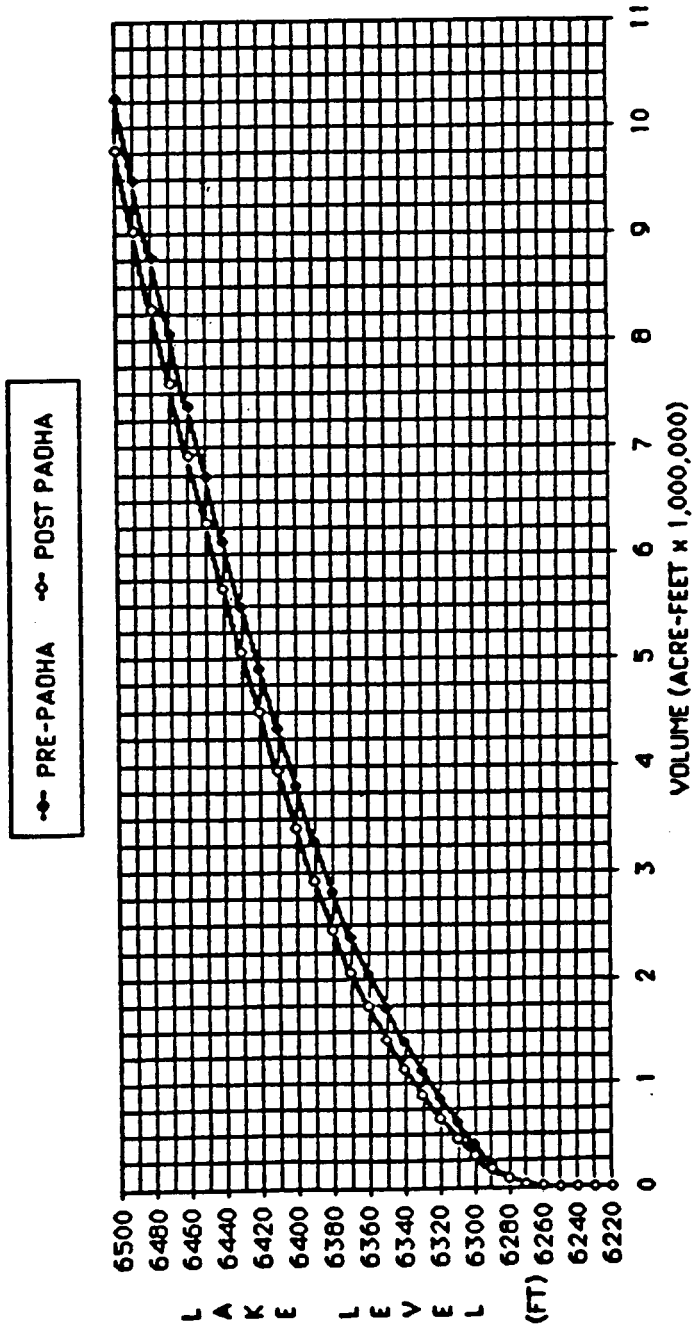
The Effect of Island-Building on the Morphometry of Mono Lake

Evolution of the islands has affected the morphometry of the Mono Lake Basin, altering the relationship between lake level, lake surface area, and lake volume.[16] Most island-building events had only an insignificant affect on these relationships. The totality of Negit Island, for instance, covers on the order of only 200 acres--roughly the same acreage that the lake surface gains or loses due to a

change in surface elevation of one foot. Given that the accuracy of the lake level curve is at best ±1 foot, morphometric changes associated with the formation of Negit Island and the Negit Islets can reasonably be ignored. Paoha Island, on the other hand, has historically covered up to 2200 acres. Note on Figure 20, which compares the lake's stage/volume/area relationships in pre- and post-Paoha times, that the emergence of the island has changed the surface elevation per given surface area by as much as seven feet. Morphometric differences of this magnitude must be taken into consideration when calculating the inflow conditions responsible for past fluctuations of the lake. In the following chapter, therefore, pre-Paoha morphometry will be used to calculate paleohydroclimatic conditions for all lake fluctuations up to and including the Pre-Historic Low Stand; post-Paoha morphometric conditions will be employed for the remainder of the curve.

Figure 20

MONO LAKE STAGE / VOLUME RELATIONSHIP



Footnotes

[1] Mark Twain was apparently in the Mono Basin just one week ahead of the Whitney party. Fascinated by the active fumaroles on the east side of Paoha, he commented that the island still had "some fire left in its furnaces" (Twain, 1972). See Footnote 13 below.

[2] Russell gives a conflicting appraisal of the age of the islands. On page 375, for instance, he wrote that "[Negit Island] is without lacustral deposits and was formed subsequent to the last high-water stage of the lake". He contradicts himself on page 300, however, by stating that during the Pleistocene "the present islands of the lake were deeply submerged."

[3] On two occasions geologists who accompanied me in the field were struck with the abrasion-platform-like appearance of these broad steps. Thinking them at first to be wave-cut, they concluded that Paoha Island must have been hoisted to its present position in a series of separate upheavals. These steps, however, are clearly not wave-cut, but rather are structural features that conform to the bedding planes of the lacustrine sediments that make up the island. The steps slope east when the underlying sedimentary beds dip east, west when the beds dip west, and undulate when the beds undulate.

[4] The relationship between the volcanics and the lacustrine sediments on Paoha Island has been interpreted in two opposing ways. LeConte (1879) observed on the eastern side of the island that "where the diatomaceous earth comes in contact with the basalt [sic], the former always overlies the latter in undisturbed horizontal layers. I conclude, therefore, that the basalt [sic] preceded the formation of the diatomaceous mud, was once entirely covered by the latter, and was subsequently exposed by erosion." This interpretation was echoed by Russell (1889), who noted that on the north side of the island the lake sediments "are resting on the andesite [sic] ... showing that this outflow preceded the last high-water stage of the lake." Lajoie (1968), on the other hand, wrote that "The Wilson Creek Formation [on the northern end of Paoha Island] does not overlie the volcanic material in a regular fashion, but rather occurs in randomly oriented and contorted beds indicating that this lacustrine deposit was intruded and uplifted by the volcanic plug after deposition." My two attempts to resolve this matter were foiled by a thick cover

of snow.

[5] Russell interviewed native and non-native residents as part of study of the Quaternary of the Mono Basin. He used information gained in the course of the discussions to name Paoha (Mono for "diminutive spirits having long, wavy hair, that are sometimes seen in the vapor wreaths ascending fom hot springs"), Panum (Mono for "a lake"), and Negit (Mono for "blue-winged goose"). He attempted to illuminate the history of the young volcanoes in the basin with information gained from Indian legends, but concluded that "the traditions of the aborigines are silent concerning them".

[6] The only tree of any size on Negit Island, a pinyon pine (Pinus monophylla) that grows on the inner flank of the crater rim on East-Negit Dome, was cored at waist height to determine its age. The core, which seems to include the innermost ring of the tree, proved to have approximately 345 annual rings. Growing as it does on a feature overlain by the 605 cal BP Mono Craters ash, the tree adds nothing to an understanding of the age of the island.

[7] Isopach analyses by Sieh and Bursick (1986) indicate that between 350 and 550 mm of ash fell in the region presently occupied by Paoha Island during the most recent eruption of the Mono Craters. The 1245 cal BP Mono Craters ash of Wood (1977) is found widely around the lake, and on Negit Island.

[8] A photograph of the coulee taken by Russell in 1883 is available at the USGS archives in Denver (Russell Photo 66). Though the coulee was at a considerable distance from the camera, the picture seems to confirm the absence of strandlines above the lake margin.

[9] The dacitic ashes encountered in sections around the Mono shorelands are similar chemically to the Paoha cinder cones, as well as to several of the different dacites on Negit Island. Because the ash is far thicker on Paoha Island than it is on Negit, and because the Paoha cones seem a more likely source than the vents on Negit, it is concluded that the ashes were derived from Paoha Island.

[10] In the pit at Navy Beach at 6381 feet, the Paoha ashes are intercalated in biogenic clay, indicating that at the time of the eruptions the lake stood above ~6384 feet; at both Navy Beach and South Tufa the Paoha ashes cannot be found in sedimentary sections above 6397 feet, presumably because they fell on land, and were reworked either by wind, or by waves and littoral currents as the lake rose in immediately

pre-historic, and earliest historic, times.

[11] While Russell was explicit about the absence of strandlines on the Paoha cones and coulee, he said nothing about either their presence or absence on the main island mass. It is possible that in 1883 the main island mass was ringed with strandlines within the elevation range 6410-6428 feet, and that these features were undercut and destroyed by waves as the lake rose toward the Historic High Stand. But given a) Russell's explicit statements concerning the absence of stranded shorelines on the Paoha coulee and cinder cones, b) the fact that he did observe and discuss the shorelines that stood above the 1883 lake margin on Negit Island, and c) that any stranded shorelines that might have existed on the soft lacustrine sediments that make up most of Paoha Island would have been highly conspicuous, it seems likely that Russell would have described any higher shorelines on Paoha and discussed their significance in relation to the age of the island. A case can thus be made that there were no stranded shorelines on Paoha Island at the time of the Russell expedition, and, therefore, that the lake had declined from the Clover Ranch High Stand to an elevation somewhat below 6410 feet at the time Paoha Island broke the surface of the lake. This, of course, would mean that the emergence of the main island and the formation of the northeastern coulee and cones were separated by a much smaller interval of time than is suggested by the dates of 1685 and 1723 AD. Without incontestable statements by Russell or other observers concerning stranded shorelines on Paoha, however, 1685 must remain the lower constraining date on the emergence of the main island mass.

[12] Russell's Paoha Island pine is not to be confused with the pine tree described by Mark Twain during his visit to the island in 1863. Twain found what he incorrectly believed to be "the only tree on the island" growing near the fumaroles on the knob of rhyodacite above Hot Springs Cove. The tree, according to him, was "a small pine of most graceful shape and almost faultless symmetry; its color was a brilliant green, for the steam [emanating from one of the nearby fumaroles] drifted unceasingly through its branches and kept them always moist." In 1983, during my first trip to the island, I found the toppled remains of four dead pines that had grown amongst the fumaroles. According to Keenan Lee (1969) two of the pines were alive during the late 1960s. David Gaines (personal communication, 1987) observed that these two trees (a jeffrey pine and a pinyon pine) were "barely living" in the early summer of 1976. They thus died between 1976 and 1983.

These pines were sectioned to determine their age at the time of death; the oldest tree suffered heart rot, thus precluding an accurate ring count. An estimate of the age of this tree was made by extrapolating from the innermost existing ring (ring 94) to the hypothetical center. This provides an age estimate of 127 years at the time of death. It is therefore concluded that the tree was established on Paoha around 1853--just 10 years before Twain's journey to the island.

[13] Gravity sliding in times following the emergence of the island would have to account for the complete removal of one or more of the following: the Clover Ranch strandline, the terrace and cliffline associated with the lowstand of ~550 BP, the Mono Craters tephra of 605 cal BP, the terraces and clifflines associated with the lowstands of ~700 and ~1000 BP, the Mono Craters tephra of 1245 cal BP, the ash associated with the Mono Craters eruption of 1610 BP, the terrace and cliffline associated with the lowstand of ~1820 BP, and the Dechambeau Ranch strandline.

[14] The third report, published in the January 29, 1881 issue of the Homer Mining Index, concerns the Mono Craters:

> Is it a volcano?
> One of the three old craters at the south end of Mono Lake has been industriously smoking for a week past, at intervals sending up dense columns of vapor, smoke, or something else. As the country about here has been turned topsy-turvy by volcanic action, it would not be at all strange if we were treated to the spectacle of an active eruption.

[15] Townley and Allen (1939) question the accuracy of this report on several grounds, including their contention that "August 23, 1890, was not Sunday as stated [in the article], but Saturday." Without taking a stand on the veracity of the account, it should be pointed out that the article never states that August 23, 1890 is a Sunday, as Townley and Allen contend; rather, it refers to an earthquake that took place on the Sunday before Saturday, August 23, 1890 (i.e. on Sunday, August 17, 1890).

[16] Pre-Paoha volume/stage relationships were derived by planimetering the bathymetry of Scholl, et al (1967). For this purpose the broad, relatively featureless plain that constitutes the present-day central-lake bottom on the west, east, and south, was projected over areas whose topography has been disturbed by uplift of, and subsequent gravity sliding from, the Paoha block. This provides an estimate of

lake volume under conditions in which the central-lake bottom is entirely free from volcanic disturbance. While there are no grounds for assessing the bathymetry that existed in pre-Paoha time, it is felt that this approach furnishes a more accurate estimate of pre-Paoha lake volume than would be the case if no adjustment were made.

In any case, from the standpoint of understanding the hydroclimatic conditions responsible for the past fluctuations of Mono Lake, volume changes brought about by island building are important only insofar as they affect the salinity of (and therefore the evaporation rate from) the lake. The problem of defining past salinity (and thus past evaporation-rate) is greatly complicated by the fact that unknown quantities of salts were belched into the lake at the time of the sublacustrine eruptions. No attempt was made to grapple with the question of how salinity might have changed due to episodes of volcanically-induced injection of solubles. It will thus be assumed in Chapter 6 that total dissolved solids remained constant during the past 4000 years, and that lake salinity fluctuated simply as a function of lake volume.

CHAPTER 6

PALEOHYDROCLIMATIC IMPLICATIONS OF THE LAKE FLUCTUATION CURVE

Introduction

As Israel Russell pointed out in 1883, the late Pleistocene shorelines that encircle the Mono Basin have been warped and tilted westward by tectonic forces. Measurement of the late Holocene strandlines indicates that little if any of this deformation occurred during the past four millennia. The slightly (5-foot) higher elevation of the Dechambeau Ranch strandline east of the Simon's Springs fault may well be due to measurement imprecision or wind-induced surge on the windward shore, rather than to faulting. Even if the difference can be attributed to tectonic displacement, it is minor and local rather than regional. The changes in lake level discussed in Chapters 1-3 are clearly real changes, rather than apparent changes attributable to basin tilting.

Several factors might be implicated in explaining the fluctuations in lake level. There can be no denying that the slow and steady accumulation of sediment on the lake floor during late Holocene time has had some effect on lake elevation, though at a sedimentation rate of roughly 50-80 cm

per 1000 years the magnitude of the change is clearly trivial and undetectable.[1] Deposition of tephra during the Mono Craters eruptions may have caused a discernible rise in lake level, though the magnitude of the rise instigated by any single eruptive event could not exceed 1-2 feet. Displacement of lake water due to the extrusion of magma (such as the events that formed the Negit Archipelago) is likewise minor; indeed, if, with the lake standing at 6400 feet, Negit Island and all of its islets had formed at the same instant in time, the lake surface would have risen less than a foot. Even the uparching of the lake bottom that created Paoha Island, the only sizable disturbance on the lake floor, displaced a mere ~350,000 acre feet of water--enough to force a rise in lake level of just five to six feet. These factors obviously cannot be evoked to explain the fluctuations in lake level graphed on Figure 16--fluctuations that span an elevation interval of 130 feet. Rather, the fluctuations in lake level are attributable to changes in the balance between inflow and outflow.

Like all closed water bodies, Mono Lake expands when inflow exceeds outflow, and contracts when the relationship is reversed. Since both inflow and outflow are functions of climate, the late Holocene fluctuation curve for Mono Lake can be used as a proxy indicator of hydroclimatic change. Indeed, for reasons discussed in the introduction to this

work, Mono Lake is in many ways the best of the Great Basin terminal lakes for paleohydroclimatic reconstruction. This chapter examines the paleohydroclimatic implications of the late Holocene lake fluctuation curve.

Theory

Lake expansion and contraction occur due to an imbalance between inflow and outflow. In general terms, this imbalance is expressed by the continuity equation

$$I - O = \Delta S \qquad (1)$$

where I = inflow, O = outflow, and ΔS = change in storage, with all three terms expressed in acre feet. Lake stabilization (where ΔS = zero over some specified period of time) occurs when the inflow equals the outflow over that time period.[2] Since outflow from the lake is the product of an evaporation rate (E, in feet) times a lake surface area (A, in acres), lake stabilization occurs when

$$I = (E \cdot A) \qquad (2)$$

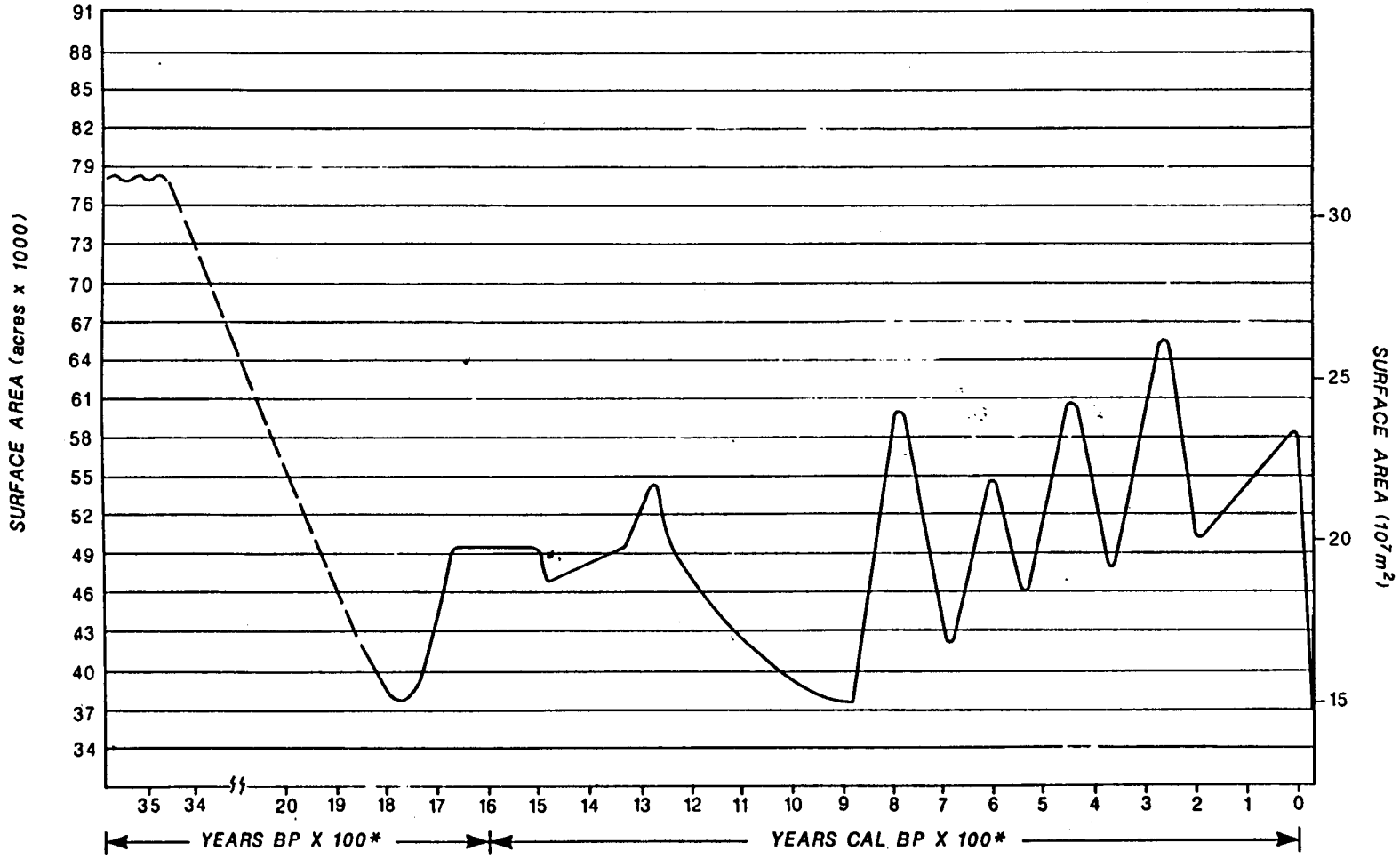
or, in other terms, when

$$A = {}^{I}/_{E} \qquad (3)$$

Thus, for every set of variables I and E, there is a single value A at which lake stabilization occurs. In other words, given a set of hydroclimatic (inflow and evaporation) conditions, a lake will stabilize when its surface area attains a value such that evaporative loss equals inflow.

Lake *level* vs. lake *area*. Thus far, the late Holocene fluctuations of Mono Lake have been expressed in terms of changes in surface level. It is apparent from the discussion above, however, that, for the purposes of defining past changes in the relationship between lake inflow and outflow, surface level, *per se*, is all but inconsequential. The nature of the hydroclimatic variations that underlie the fluctuations of a terminal lake can be understood only in terms of changes in lake surface area.

Using the area/stage curves illustrated on Figure 20 the elevation of each of the high stands and low stands on the late Holocene lake level curve was converted to an area value and plotted against time. The resultant "late Holocene lake area curve" is shown on Figure 21. Note that in constructing Figure 21 changes in insulosity,[3] due both to fluctuations in lake level and to the emergence of Paoha Island, were taken into account. The curve thus expresses the area of the



* see Stuiver & Pearson, 1986, and Pearson & Stuiver, 1986.

Figure 21. Late Holocene fluctuations in the surface area of Mono Lake.

lake's water surface, rather than simply the total area (water + islands) contained within the shoreline contour. In addition to forming the basis for paleohydroclimatic assessment, then, the late Holocene lake area curve provides a single standard for comparing lake behavior in times prior to, and following, the emergence of Paoha Island. Notice in this regard that, relative to the fluctuations that occurred in pre-Paoha time, the lake expansion of the early 20th century is an event of lesser magnitude than might be inferred from the lake *level* curve, and that the diminished surface area associated with the artificially-induced low stand of 1981 is without late Holocene precedent.

The Limits To Interpretation

All proxy records of climatic change are subject to interpretive constraints. These constraints must be recognized if misinterpretation of the proxy record is to be avoided. In addition to the problems of dating and resolution discussed earlier, the following three constraints are of particular importance in inferring paleohydroclimatic conditions from a lake fluctuation curve.

1. A lake fluctuation curve cannot be used to differentiate changes in climate that alter the inflow term from those that alter the outflow term. Expansion or contraction of a terminal lake formerly in equilibrium with a

given set of hydroclimatic conditions can be induced by either a change in inflow, a change in evaporation, or a simultaneous but incommensurate change in both inflow and evaporation. The lake fluctuation record provides no basis for determining the precise combination of inflow and evaporation values that instigated the expansion or contraction; in other words, it is impossible to distinguish a lake expansion wholly attributable to an increase in inflow, from one caused solely by a decrease in evaporation, or, for that matter, from one instigated by an increase in inflow that was accompanied by a decrease (or an incommensurately small increase) in evaporation. It is possible only to identify an infinite set of inflow/evaporation combinations that result in the expansion or contraction in question; these combinations, in turn, can be simplified to produce an index of "effective inflow" or EI (see below), in which the evaporation rate is treated as a constant and lake fluctuations are attributed solely to changes in the inflow term.

2. In the absence of precise chronometric control, rising segments of the lake fluctuation curve can be used only to define a minimum possible value for effective inflow; declining segments of the curve can be used only to define a maximum possible value for effective inflow. A doubling of lake-surface area in, say, one decade, obviously requires a

higher EI than the same doubling spread over a century. In order to assess the EI that forced a particular fluctuation of a lake, then, it is essential to know within reasonable limits the duration of the fluctuation. If the duration cannot be specified it becomes possible only to assign a value of the "effective stablization inflow" (ESI) for each point on the curve--that is, it may be concluded only that EI was *at least* great enough to *stabilize* the lake at a given point on a rising segment of the curve (or at a high stand), leaving open the possibility that it *exceeded* the amount necessary to stablize the lake at the surface area in question; similarly, it is possible to conclude only that EI was *at most* the amount required to *stabilize* the lake at a given point on a declining segment of a fluctuation curve (or at a low stand), again entertaining the possibility that it was less than the amount required to stabilize the lake at that surface area.

Consider, for example, the rise to Mono Lake's Historic High Stand. Knowing that the lake rose from 6410 feet to 6428 feet during the 35 years prior to 1919, it is possible, using the Vorster Model (see below), to estimate that EI during that period was approximately 112% of the average value for the modern period (1937-79). If the duration of this lake transgression was unknown, however, it could be concluded only that the effective inflow was at least 98% of

normal--that is, the amount of inflow required to stabilize the lake at 6428 feet.[4]

3. The level to which a lake ultimately rises (falls) in the course of a transgression (recession) is related to more than simply the severity of the hydroclimatic conditions; thus, in the absence of precise chronometric control, it cannot be assumed, ipso facto, that the hydroclimatic conditions that drove the lake to an extreme high stand (low stand) were more severe than those which gave rise to a less extreme high stand (lowstand). The level to which a lake rises (falls) during a transgression (recession) is a function of three factors: the severity of the causal hydroclimatic conditions, the length of time that those conditions persist, and the level of the lake at the time the causal hydroclimatic conditions commence. As noted above, without knowing the precise duration of a lake fluctuation, it is impossible to determine, beyond an estimate of ESI, the effective inflow that forced that fluctuation. This precludes paleohydroclimatic comparisons based simply on the relative elevations of high stands or low stands. It would be erroneous, for instance, to conclude that the effective inflow that resulted in the Mono High Stand (6499 feet) approximately 3500 yrs BP was necessarily greater than that which forced the lake to rise to the appreciably lower level of 6456 feet some 220 yrs BP; the difference in elevation of

the two high stands might well be due to the relative duration of the causal hydroclimatic conditions. Indeed, had the conditions leading to the high stand of 220 BP persisted for many centuries the lake might eventually have exceeded the Mono High Stand.

Simple comparisons such as this are further misleading because they do not take into account the level of the lake at the time a fluctuation commenced. In simplest terms, the level to which a lake rises or falls after, say, 50 years of a given set of hydroclimatic conditions, is dependent on the elevation of the lake surface at the time of the onset of those conditions. (This is true, of course, only if the duration of the hydroclimatic conditions, arbitrarily assumed in this example to be 50 years, is less than the amount of time required for the lake to come into equilibrium with those conditions.)

An Index of Effective Inflow

Because it is impossible to know the precise combination of inflow and outflow conditions that forced the surface fluctuations of late Holocene Mono Lake (see constraint #1 above), it is necessary to combine the two terms into a single measure. This is reasonably accomplished by treating either the inflow rate or the evaporation rate as a constant, and attributing all lake fluctuations to changes in the

variable term.

It seems most realistic to treat the more conservative term (the term that varies least with time) as the constant. Throughout the arid and semi-arid west the annual evaporation rate has, at least historically, been subject to far less year-to-year variation than annual inflow. According to Harbeck (1966), the coefficient of variation for annual runoff within watersheds of the western United States can be as high as 100 percent, while the coefficient of variation for annual evaporation "is almost always less than 10 percent, and probably less than 5 percent for most lakes and reservoirs." The Mono Basin is no exception in this regard. Annual measured inflow over the period 1935-1985 has varied from as high as 192% of the mean to as low as 41% of the mean. In comparison, variation in evaporation has been slight. Measurements in the vicinity of the Mono Basin indicate that evaporation from test pans has varied from 89% to 113% of normal during the period of record (1944-1983) (Vorster, 1985); evaporation from the lake surface itself can be expected to vary even less than pan evaporation. On the basis of this disparity it makes sense to hold the evaporation rate constant, and, for the sake of characterizing hydroclimatic conditions, to treat all the late Holocene fluctuations of Mono Lake as though they were caused by changes in inflow. This provides an index of

effective inflow (EI).[5]

In the analyses described below the evaporation rate will be held constant at the average annual value (45 inches) determined by Vorster (1985) for the period of record (1944-1983).[6] EI (and, similarly, ESI) will be expressed as a percentage of the average annual unimpaired inflow to the groundwater basin (the inflow that would have occurred in the absence of irrigation and trans-basin water diversions) for the period 1937-79 (= 227,970 acre-feet).

Modeling Effective Inflow

Introduction. At least 14 water-balance models for the Mono Basin have been produced in the past half-century. These differ substantially in their methodology, in the number and nature of inflow, outflow, and storage-change components, and in the values assigned to those components. The most recent model was produced by Vorster (1985) as a master's thesis; his work includes a critical and thorough review of all previous water balances of the Mono Basin. The writer worked closely with Vorster on the thesis, served as signatory on his committee, and helped modify the model in such a way as to make it applicable to early- and pre-historic hydroclimatic and morphometric conditions.

The Vorster model was systematically derived using a

four-phase process of formulation, calibration, verification, and application. These four phases are discussed briefly below, and in Appendix A.

Formulation. The model's "free body" (the body to which all inflows and from which all outflows occur) is the Mono Groundwater Basin, defined by the contact between the unconsolidated sediments of the basin floor and the surrounding bedrock (or glacial till). The "time period" employed in the model (that is, the unit of time used for a single execution of the water balance equation) is one "water year", from October 1 to September 30. The "base period" (the time period for which the model components are quantified from records) is 1937-1983.

The model includes 19 inflow, outflow, and storage change components. Following the approach prescribed by Winter (1981), Ferguson (1981), and Sokolov and Chapman (1974), the value of each component was derived independently, rather than as a residual. The components, the basis for computing component values, and information related to the calibration and verification of the model are given in Appendix A.

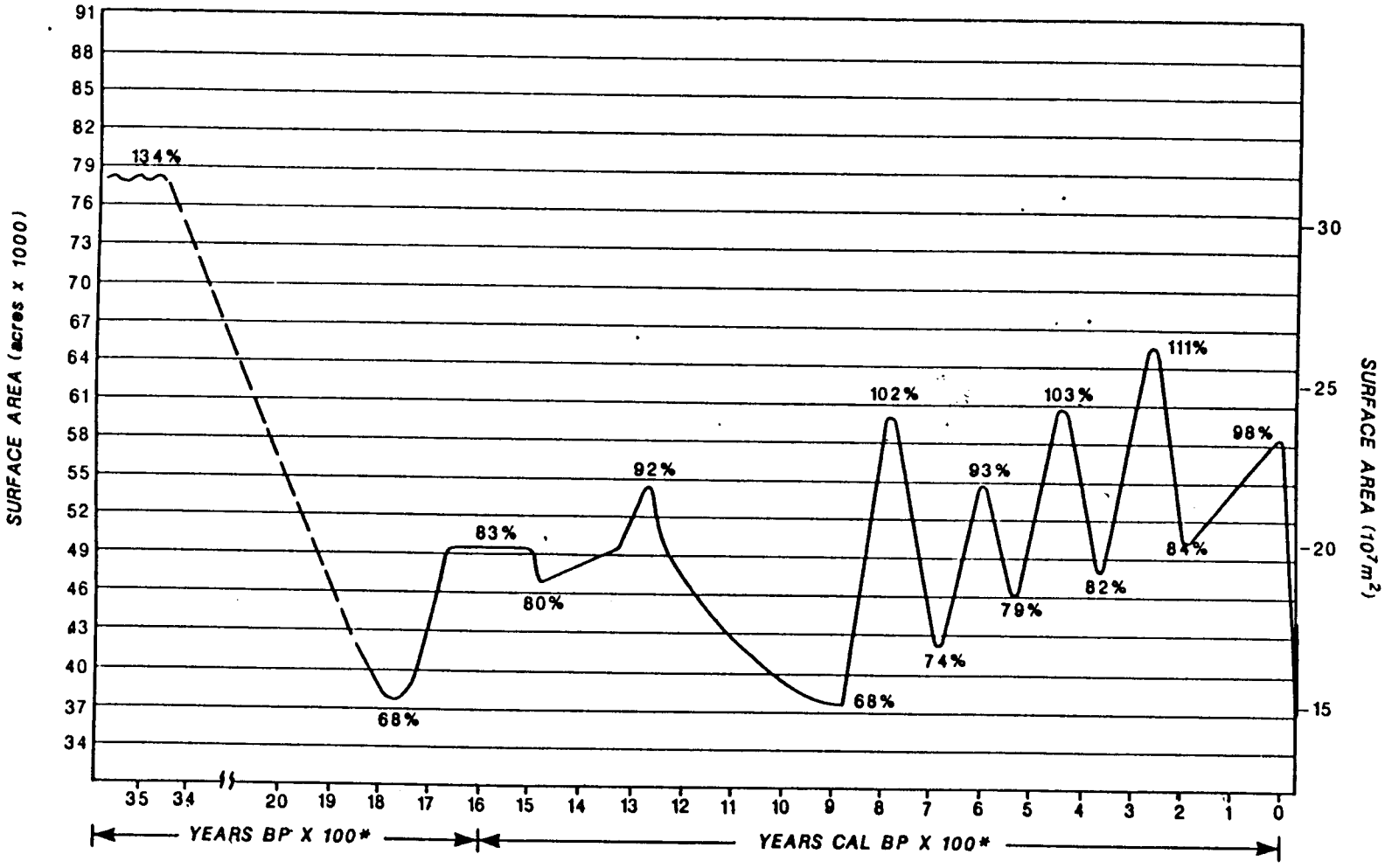
Application. Vorster's water balance forecast model was constructed with two primary applications in mind: first, to predict and retrodict the response of the lake to real or hypothetical hydroclimatic conditions (this application was

used in previous sections to evaluate the lake response to drought conditions during post-Clover Ranch time (pg. 329)); and secondly, to assess the hydroclimatic conditions responsible for the lake fluctuations of the pre-historic past. Results of applications of this second type are presented below.

Results

The model was first applied to determine ESI for points of inflection on the pre-historic fluctuation curve. Results are given on Figure 22. Note there that ESI over the past 3490 radiocarbon years has ranged from 134% of modern inflow (for the Mono High Stand) to 68% of the modern value (for the Lee Vining Creek and Mono low stands).

It should be stressed that these ESI values represent the amount of effective inflow that would be required to *stabilize* the lake at the extremes of the elevation interval occupied by Mono Lake in late Holocene time. In all probability the hydroclimatic conditions that forced the lake to these stands were more extreme than the figures would indicate. The tendency for ESI to understate the severity of paleohydroclimatic conditions is clearly shown on Figure 22. Note there that during the period between 866 cal BP and 1919 AD (an interval spanning approximately 835 sidereal years), the lake underwent five transgressions and four recessions.



* see Stuiver & Pearson, 1986, and Pearson & Stuiver, 1986.

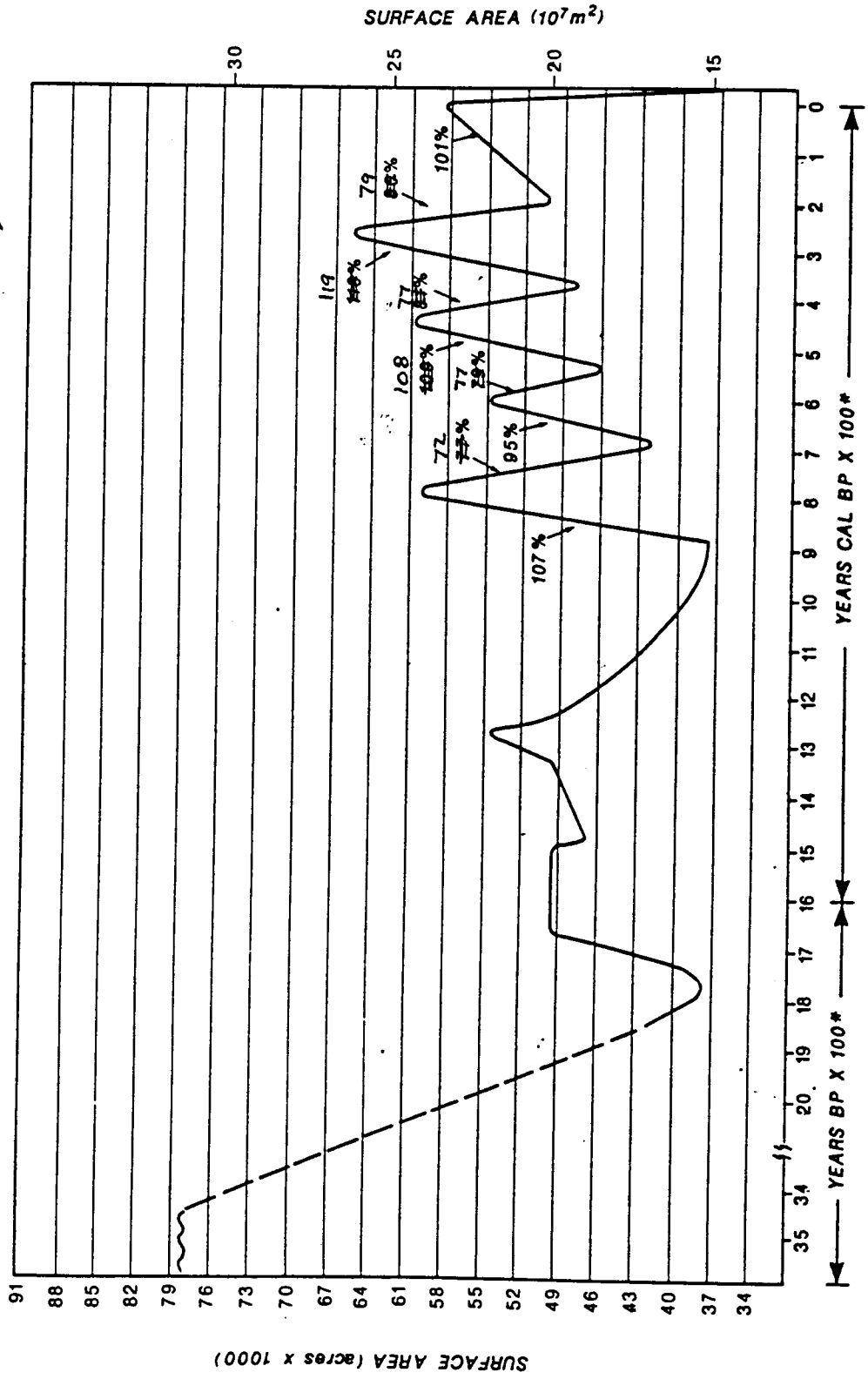
Figure 22. Effective stabilization inflow for points of inflection on the Mono Lake fluctuation curve. See text for definitions.

Under ESI conditions these nine fluctuations would require a total of some 2088 years--that is, well over twice the amount of time actually available. For this portion of the fluctuation curve, then, ESI grossly underestimates the severity of the causal wet and dry periods.

ESI is the only approach available to assess effective inflow for the first three-quarters of the fluctuation curve. This portion of the curve lacks the chronometric precision necessary to estimate EI. For the last 900 years of the curve, where chronometric control is relatively precise, the duration of the transgressions and recessions (and thus EI) can be estimated within reasonable limits. Within the constraints of the available radiocarbon dates, it appears that each of the nine transgressions and recessions of the period 866 cal BP to 1919 AD lasted an average of approximately one century (835 dendro-years ÷ 9 = 93 years); for the sake of estimating EI, then, it will be assumed that each of these fluctuations took 100 years. Results of calculations made under this assumption appear on Figure 23. Note there that the effective inflow necessary to account for these century-long fluctuations ranges from 77% to 118% of modern (1937-79) inflow.

There is evidence to suggest that the relatively hydric periods responsible for the lake transgressions of the past millennium were of shorter duration than the relatively xeric

changes based on corrected model runs 6
2/88.
S.S.



* see Stuiver & Pearson, 1986, and Pearson & Stuiver, 1986.

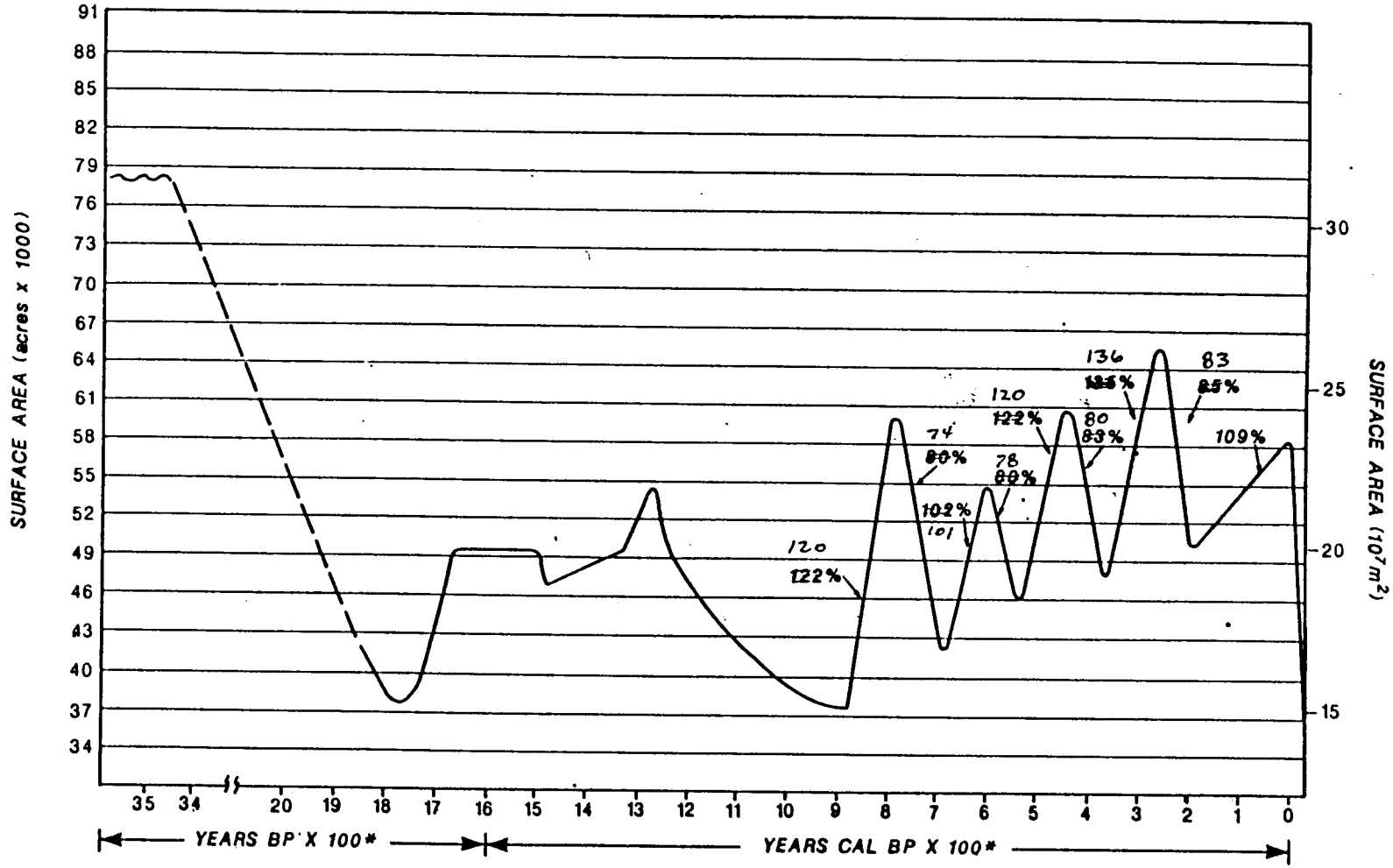
Figure 23. Inflow required to explain lake behavior during the past millennium, assuming that each rise and each fall took 100 years.

periods that forced the recessions. LaMarche's 1160-year-long bristlecone pine tree-ring record from the nearby White Mountains shows a half-dozen "spikes" in precipitation (which arguably correlate with transgressions and high stands of Mono Lake--see below), each of which seems to persist for only a half-century or so. It may be more realistic, therefore, to assume that the transgressions of the past nine centuries each took place in an average of 50 years, while the lake recessions required an average of 150 years each. Results of the computations made under this set of assumptions are shown on Figure 24. In this analysis EI since 866 cal BP ranges from 80% to 134% of the modern value.

Discussion. It must be stressed that just as the lake fluctuation curve itself ignores the stillstands and reversals that must have punctuated individual transgressions and recessions, so too do the analyses of EI ignore these fluctuation intricacies. During any given transgression or recession shown on the lake fluctuation curve EI undoubtedly varied from year-to-year and decade-to-decade, at times attaining values higher, and at other times lower, than the calculated value. Each of the calculated EI values shown on Figures 23 and 24, then, reflects the average effective inflow that prevailed during a particular fluctuation of the lake.

It is also important to appreciate that the EI values

changes based on corrected model runs of 2/88 S.S.



* see Stuiver & Pearson, 1986, and Pearson & Stuiver, 1986.

Figure 24. Inflow required to explain lake behavior during the past millennium, assuming that each rise took 50 years and each fall took 150 years.

calculated for the past nine centuries are based on the assumption that all transgressions and all recessions are of approximately average length (that is, 100 years per fluctuation in the first EI analysis; 50 years per transgression and 150 years per recession in the second EI analysis). Thus, in cases where the actual duration of a transgression was greater than the assumed duration (or, similarly, in cases where the actual duration of a *recession* was *less* than the assumed duration) the calculated EI is an underestimate of the actual EI; likewise, in cases where the actual duration of a transgression was less than the assumed duration (or, similarly, in cases where the actual duration of a recession was *greater* than the assumed duration) the calculated EI is an overestimate of the actual EI.

Summary

Paleohydroclimatic interpretation of the Mono Lake fluctuation curve is hindered by the imprecision of the chronometric control. Without the ability to pinpoint the duration of a given fluctuation of the lake it is impossible to determine precisely the effective inflow that forced that fluctuation. In cases where there is no basis for estimating the duration of a transgression or recession, it is possible only to define the effective stablization inflow. Calculations of ESI indicate that, for prolonged

(half-century or more) periods within the past 3490 radiocarbon years, effective inflow to Mono Lake has ranged from greater than 134% of the modern (1937-79) value to less than 68% of the modern value.

Chronometric control over the past 900 years is such that the duration of lake fluctuations (and thus the effective inflow) can be estimated with reasonable precision. If it is assummed that each of the fluctuations that occurred during this period of time lasted approximately 100 years, then EI during these century-long spans can be estimated to have ranged from 77% to 118% of the modern normal; if it is assumed that the transgressions of this period took place in 50 years, effective inflow can be estimated to have ranged from 80% to 134% of normal.

It must be borne in mind that the index of effective inflow incorporates both the inflow and the evaporation terms. While there is reason to believe that the inflow term is of greater importance in accounting for the lake fluctuations inferred for late Holocene time (see pgs. 358-59, and Footnote #4 of this chapter), evaporation nevertheless plays a role that cannot be ignored, working either in concert with, or in opposition to, changes in inflow.

Conclusions

There is no shortage of examples in the historic record of years in which the inflow to Mono Lake matched or exceeded in severity the hydroclimatic conditions necessary to account for the extremes of the late Holocene fluctuation curve. The years 1938, '52, '67, '69, '80, and most recently 1982 through '83, furnished inflow that would, if perpetuated, force an expansion of the lake surface to areas greater than any it attained during the past 3490 radiocarbon years. Likewise, the inflow conditions that characterized the years 1924 through '31, 1933 through '34, 1954 through '55, 1959 through '61, and most recently 1976 through '77, would, if they persisted, draw the lake to a surface area smaller than any attained during late Holocene time. It is thus necessary to look no farther than the historic record to gain an appreciation for the nature of the inflow conditions responsible for the extremes of the late Holocene fluctuation curve.

It is of special interest to compare the hydroclimatic conditions of the modern period with those of pre-historic time. As previously stated, under natural conditions (no irrigation, no trans-basin water diversions) perpetuation of 1937-79 inflow at average, present-day evaporation rates, would ultimately stabilize Mono Lake at a surface area of 60,000 acres (corresponding to a surface elevation of 6432 feet). In both lake level and lake area this figure is

almost precisely half way between the extreme high stand and the extreme low stand experienced during the past three and one-half millennia. In this context, the 1937-79 "normal" inflow might be considered to represent the average inflow condition of the past 3500 radiocarbon years. Note that this simple comparision does not pretend to speak to the amount of time that the lake spent at different elevations during late Holocene time.

Well-founded concern over future changes in climate dictates that proxy records such as the Mono Lake fluctuation curve be used to help define the range of climatic conditions to which a region has been (and by inference, might in the future be) subjected. Note in this regard that, in the absence of water diversions, Mono Lake would today be in the process of a rise that began in approximately 1966. How long the hydroclimatic conditions favoring lake expansion will continue is impossible to predict. What hydroclimatic conditions lie beyond the next would-be high stand of the lake is a question of even greater importance. In this regard it is well to point out that not since pre-Gold Rush time has the Mono Basin, and by extension central California, experienced drought conditions of the severity and duration necessary to force Mono Lake to the low levels that characterized half or more of the past thousand years, and most if not all of the previous millennium. Viewed in the

context of the past 2000 years, then, the urban, agricultural, and industrial development of central California must be seen to have occurred during a period of unusually favorable (hydric) climatic conditions. Based on the lake fluctuations of the past millennium, one might venture that, anthropogenic modification of the atmospheric system aside, a drought sufficiently xeric and prolonged to diminish today's equilibrium surface area of Mono Lake (60,000 acres) by a third or more might lie just a few years or decades in the future.

Footnotes

[1] On the other hand, the accumulation of sediment is of importance in understanding long-term (1000s of years) changes in the relationship between elevation, volume, and salinity of the lake. Assuming a sedimentation rate of 77 cm per millinnium, for example, the lake 5000 years ago, standing at an elevation of 6368 feet, had a volume equal that of today's (pre-Paoha) lake at an elevation of 6380 feet.

[2] A terminal lake spends an infinitesimal amount of time in equilibrium with climatic conditions. Any true "balance" that is struck between inflow and outflow is only momentary. Whether it be on a daily, seasonal, annual, or secular level, the lake is almost always shrinking (in response to a negative change in storage), or swelling (in response to a positive storage change).

[3] "Insulosity" is defined by Hutchinson (1957) as the precentage of the area within the shoreline contour that is occupied by islands.

[4] The disparity between these EI and ESI values results from the fact that in 1919, when the rising lake reached its Historic High Stand, it had not come into equilibrium with the hydroclimatic conditions that forced the transgression. Using the Vorster model (see pg. 360) it can be shown that, had these hydroclimatic conditions persisted indefinitely, the lake would have continued its rise to the present day and beyond, ultimately stablizing in the year 2202 at an elevation of approximately 6463 feet.

[5] Annual variation in evaporation from the surface of Mono Lake almost surely falls within ±10% of the mean modern value. Even if the long-term mean evaporation were to change to the assumed upper or lower limit of the modern range, the resultant changes in lake level would be of relatively small magnitude and would require long periods of time. It can be demonstrated using the Vorster model that with the lake surface in equilibrium with modern hydroclimatic conditions (thus, standing at an elevation of 6432 feet), a 10% increase in evaporation would draw the lake to an equilibrium level of 6409 feet in 244 years; a 10% decrease in evaporation would force a rise to an equilibrium level of 6466 feet in 429 years. Thus, even at the assumed extremes of the modern range, evaporation can not, in and of itself, account for the range of lake fluctuations that have occurred during late Holocene time. The inflow conditions necessary to account for the magnitude and duration of the late Holocene lake fluctuations, on the other hand, do fall well within the range of modern conditions (see discussion, pg. 370). This constitutes further justification for using inflow as the variable term.

[6] Forty-five inches is the average *freshwater* evaporation rate for the Mono Basin. In computing effective inflow, this rate must be corrected for fluctuations in the salinity of the lake. See Vorster, 1985.

CHAPTER 7

CORRELATIONS

Introduction

From a Quaternary paleoclimatic perspective, the west-central Great Basin (including the eastern Sierra Nevada) is one of the most provocative regions in the world. Here, changes in climate are expressed not only in the fluctuations of closed lakes, but in varying degrees of glacial activity, in changing distributions of plant species, and in the lengthy tree-ring record of the bristlecone pine (Pinus longaeva).

Past attempts to correlate the paleoclimatic records derived from these different proxy indicators have resulted in considerable confusion; non-corroboration is common, while contradiction is not rare. Much of this confusion stems from differences in the response time, the response thresholds, and the degree of resolution of the various indicators; from problems inherent in dating the different records; and from outright misinterpretation of the records. With these problems in mind, the following discussion examines the various proxy indicators of late Holocene climatic change in the west-central Great Basin, and

tentatively correlates these proxy records with the fluctuations of Mono Lake.

Correlation With Other Lakes

Theory. The manner in which a lake responds to a given change in hydroclimatic conditions depends on a variety of factors. A shallow lake that occupies a broad, flat-floored basin adjusts its surface area faster, and with smaller changes in volume and surface elevation, than a deep lake nestled against steep mountain walls, all other factors being equal. This difference in response time can lead to confusion in comparing two or more lacustrine records: a brief period of extremely hydric conditions can cause a monumental expansion of the shallow lake, while having only a minor effect on the deep lake; a prolonged period of moderately hydric conditions, on the other hand, provides the deep lake with time to substantially increase its surface area, while forcing the shallow lake to expand rapidly to only a moderate size. Thus, under the hypothetical climatic sequence described here the two lakes would attain their respective highest stands at different times, even though they were subjected to the same hydroclimatic conditions and changes.

Other factors that influence the response of a closed lake to a hydroclimatic change include its susceptibility to

desiccation and/or overflow, the type and density of the surrounding vegetation, the aquifer characteristics of surrounding substrates, the ratio of lake-area to basin-area, and the degree to which it is influenced by threshold responses that abruptly increase or decrease inflow (consider, in this last regard, the Tahoe-Pyramid relationship described on pg. 4). Because of these types of basin-to-basin differences, each closed lake must be expected to respond to a given hydroclimatic change in a manner peculiar to that lake. Thus, even if it is assumed that the climatic conditions affecting the closed lakes of the western Great Basin over a period of some thousands of years have been the same, and that the lakes are fluctuating solely because of these changes, differences in their behavior must be expected. With this in mind, and in the absence of a hydrological model for each of the closed lakes in question, only the broadest correlations can realistically be attempted.

One further impediment to correlating the Mono fluctuations with those of other lakes must be noted. The behavior of the lakes considered here--Searles, Pyramid, Walker, and Carson--have been studied only in general terms. Indeed, these water bodies lack "curves" as such; fluctuation records consist in many cases of dates on recognized highest and/or lowest stands. The discussion that

follows, therefore, compares the timing of the recognized high and low stands at other lakes with the Mono Lake record.

Searles Lake. Searles Lake lies between the Sierra Nevada and Death Valley, approximately 200 miles to the south of Mono Lake. Historically it has contained water only in the wettest years, when it received runoff from the small intermittent streams of the surrounding desert ranges. It becomes a large and persistent feature only when Owens and China lakes overflow, permitting the Owens River to reach its shores.

G.I. Smith's classic work (1979) on the late Cenozoic fluctuations of Searles Lake includes only a generalized and fragmentary history of late Holocene time. The only reliable radiocarbon date from the Holocene portion of the section (3590 ±190 yrs BP) lies within muds that indicate the presence of a lake at that time. The correspondence between this high stand of Searles Lake and the Mono Lake High Stand (3490 ±90) is striking.

Pyramid Lake. Pyramid Lake, Nevada (see also pg. 4) lies 140 miles to the north of Mono Lake. It receives the bulk of its inflow from Lake Tahoe by way of the Truckee River. When Tahoe drops below its lip, as it has on several occasions during the period of historic record, Pyramid Lake is deprived of the bulk of its inflow. When Pyramid rises to above 3863 feet, it "shares" the Truckee with Winnemucca

Slough.

The late Holocene fluctuations of Pyramid Lake have yet to be described in detail, though Born (1972), Davis (1982), and others have provided information on its surface elevation at certain points in late Holocene time. Born's curve includes a rise in lake level beginning about 3500 BP, followed by a recession that culminates about 2000 BP (this transgression/recession constitutes Born's "Cycle II"). According to him the lake remained relatively low until sometime after 670 BP, when it reached another high stand. At the level of generalization that characterizes Born's curve, the fluctuations of Pyramid Lake correlate well with the most striking features of the Mono Lake curve. Indeed, this generalized interpretation of the late Holocene portion of the Pyramid record could just as well be applied to the generalities of the Mono curve.

Walker Lake. Paleoclimatic interpretation of the surface fluctuations of Walker Lake (north of Hawthorne, Nevada, between Mono and Pyramid lakes) is complicated by the tendency of the Walker River to shift course at times and flow into the Carson Sink (see pg. 4). To the extent that the Walker River has been tributary to Walker Lake over the past 3500 years, broad correlations between the Mono curve and the Walker and Carson curves should be expected.

Benson's (1978, 1981) date of 2970 ±85 BP on tufa lying

at 1252 m (five meters above Walker Lake's historic high stand) indicates that 3000 years ago its surface was at a relatively high level. (Benson does not maintain, however, that this date represents the late Holocene high stand of Walker Lake.) Other tufa dates of Benson (2185 ± 80 at 1,211 m; 1720 ± 80 at 1222 m; 1335 ± 75 at 1216 m; 1205 ± 75 at 1229 M), as well as a tufa date collected by Mark Newton of the University of Southern California (2135 yrs at 1243.5 m; personal communication, 2/2/87) suggest that from 2185 BP to at least 1205 BP the lake spent much time significantly (to 41 m) below its historic high stand. Indeed, Benson believes that the lake may have dried completely around 2000 years ago (personal communication, 9/22/86). Here again, then, there seems to be general correlation with the Mono Lake's Dechambeau Ranch High Stand, as well as with the Marina Low Stand and the moderate to low levels that characterized Mono Lake during the millennium from 2000-1000 years ago. No known information is available on the pre-historic fluctuations of Walker Lake for the past millennium.

Carson Lake. The late Holocene fluctuations of Carson Lake, between Walker and Pyramid lakes in western Nevada, have been described by R.B. Morrison (1965). During the past 3500 years, according to him, Carson Lake attained five high stands, each of which was followed by a period of near- to total desiccation. The lacustrine deposits associated with

these lake transgressions and recessions constitute his Fallon Formation.

Morrison dates the earliest (also the highest) of the high stands at 3500 to 3200 years ago. The onset of this high stand coincides with that of the Mono High Stand. The most extreme of the desiccation phases at Carson Lake occurred "between the second and third Fallon lakes during the 13th century AD", a time when Mono Lake was also low. Unfortunately Morrison does not provide dates on any of the other pre-historic fluctuations.

Other lakes. In addition to these closed lakes are several other water bodies whose behavior can be used to illuminate climatic conditions in and near the western Great Basin during late Holocene time. Batchelder (1970a and b) inferred the Holocene dynamics of Black Lake, 25 miles to the southeast of Mono Lake, on the basis of sediment chemistry, fossil molluscs, and microfossils of aquatic vegetation. Hall (1983) interprets the Black Lake record to the effect that "relatively more moist conditions are apparent 3600-2100 BP". He further notes that the lake may have been nearly dry after 2100 BP. This interpretation is in obvious agreement with the Mono curve, as well as with the lake level records from Searles, Pyramid, Walker, and Carson lakes.

Information confirming the existence of relatively xeric conditions near the turn of the last millennim, when Mono

Lake reached extremely low levels, comes from near the north-central Sierran crest. Sercelj and Adam (1975) note that Osgood Swamp (a few miles south of Lake Tahoe) dried at this time, permitting colonization of the site by trees. One of the stumps at Osgood yielded a radiocarbon date of 910 ±85 BP, virtually identical to the date on stumps that grew low on Mono shorelands during the Lee Vining Creek Low Stand.

At nearby Ralston Ridge Bog (~10 miles southwest of Lake Tahoe) these same authors found a succession of four horizons, marked by the roots of trees and ericaceous shrubs, in sediments that represent the period from approximately 2000 to 1000 yrs BP. According to them, the root horizons (the upper two of which have been dated at 1150 and 1350 BP) represent times of bog desiccation, when woody vegetation colonized what is today a paludal environment. The presence of these root horizons, like the lack of glaciation in the Sierra, and the low levels that persisted at Walker, Mono, and Pyramid lakes, point to relatively xeric conditions during the last millennium.

Correlation With the Glacial Record

Theory. The late Holocene glacial record is a potentially valuable source of paleoclimatic information. Interpreted correctly, it can be used to define, in a general way, times when climatic conditions favored snow accumulation

and ice advance.

Like any proxy indicator of climatic change, however, the glacial record is afflicted with interpretive constraints that must be appreciated if meaningful correlations with other paleoclimatic indicators are to be made. These constraints have recently been discussed by Porter (1981, 1982). He notes that because of problems related to the dating of glacial deposits, to the incompleteness of the glacial record due to obliteration of older deposits by subsequent ice advance, and to definition of the relationship between climatic change and glacier response (including lag time, accumulation and wastage thresholds, and non-stable responses such as calving and surging), "paleoclimatic interpretations based on glacial-geologic data are likely to be imperfect and generally qualitative in nature" (Porter, 1981).

The neoglacial record of the east-central Sierra Nevada. On the basis of morainal form, topographic relationships, and boulder-weathering ratios, Birman (1964) recognized deposits associated with three post-Tioga glacial advances in the central Sierra Nevada: the Hilgard (oldest), the Recess Peak, and the Matthes (youngest).[1] In the absence of absolute dates, he considered these deposits to be late Holocene (post-"Thermal Maximum") in age. Subsequent workers, however, regard only the Matthes and Recess Peak

advances as products of the late Holocene, and tentatively assign the Hilgard advance to latest Pleistocene or earliest Holocene time (e.g. Curry, 1969, 1971; Morrison, 1965; Bateman and Wahrhaftig, 1966; Gillespie, 1982; Burke and Birkeland, 1983). Work by Curry (op cit; see also Burke and Birkeland, op cit) suggests the presence of another, yet unnamed, late Holocene glacial advance that lies between the Recess Peak and Matthes glaciations.

The ages of these late Holocene deposits were estimated by Curry (op cit) on the basis of lichenometric analysis. He found that the Matthes moraines typically consist of three separate crests, the outer of which is colonized by lichens whose diameters suggest an age of approximately 620 years; lichens on the middle crest provide an age of approximately 330 years, while those on the inner crest yield an estimate of 250 years. The Recess Peak moraines display an outer and an inner crest, which provide lichenometric dates of approximately 2600 years and 2000 years, respectively. Analysis of the lichen cover on deposits associated with Curry's unnamed glacial advance yield an age of approximately 1100 years.

It is clear from Curry's and Birman's work that during late Holocene time glacial advance has been the exception rather than the rule. The record of glaciation from the Sierra Nevada is thus discontinuous, with glacial pulses

alternating with periods of ice-free conditions. In a paleoclimatic sense the late Holocene glacial record from the Sierra Nevada is analagous to a fluctuation curve for a lake that contains water only in the most hydric times.

Correlation. In comparing the late Holocene glacial chronology of the Sierra with the Mono Lake fluctuation curve, it is initially necessary to take account of several problems related to dating. First, because of uncertainties in his lichenometric growth curve, Curry considers the dates on the Matthes deposits to be accurate only to within 50 to 100 years; according to him the dates on the Recess Peak and "unnamed" deposits are less accurate, perhaps to within 100-300 years. Secondly, whereas the Mono fluctuation curve is based on radiocarbon dates, Curry's lichen curve is based on both radiocarbon and tree ring dates; differences in the dendro- and radiocarbon time scales of 100 years or more must be expected. Finally, and most importantly, the relationship between the lichen dates and the climatic chronology has been misconstued by most workers in the Sierra Nevada. Lichens colonize a moraine only after the deposit has stablized--that is, after the ice has receded from its terminal position. Colonization typically commences about one to five decades after stablization. Thus, the lichen dates on the Sierran moraines do not represent the onset of ice advance, or the glacial maximum, as some workers have inferred,[2] but rather a

time some decades after the termination of the glaciation. In short, a lichenometric date marks a time of change to non-glacial climate, rather than the beginning or peak of a climate conducive to ice advance. Lichens cannot be used to date the onset of glacial conditions; such information must be inferred from other proxy indicators of climatic change.

Even in light of the dating limitations outlined above, the similarities between the Mono Lake curve and the glacial record are marked. The three stades of Matthes glaciation--the terminations of which are lichenometrically dated at within 50-100 years of 620, 330, and 250 yrs. BP--are reasonably correlated with the lake transgressions that culminated approximately 605 cal BP, 460 cal BP, and 290 cal BP. It is tempting to correlate Curry's unnamed glaciation (termination date = approximately 1100 ± 300 yrs ago) with the lake high stand that ended shortly after 866 cal BP. The apparent lack of glaciation during the period between 2000 to 1000 years ago[3] is what one would predict based on the consistently moderate-to-low levels that characterized Mono Lake during that millenium. The earliest stade of Recess Peak glaciation, which, incidently, is the most extensive of the late Holocene glaciations of the Sierra Nevada, may well have begun around 3490 years BP, as Mono Lake was rising to its Holocene High Stand. The lack of a lake level correlate for the final stade of the Recess Peak

glaciation--the termination of which is lichenometrically dated at 2000 ± 300 years--may be attributable to the discontinuity of the lake fluctuation curve during this time period.

Correlation With The Pollen Record

Theory. The study of fossil pollen has been of tremendous importance in illuminating the nature and timing of Quaternary changes in vegetation (and by extension, changes in climate). Because of the widespread distribution of environments in which pollen accumulates, palynology can be applied to more of the earth's terrestrial surface than perhaps any other method of paleoclimatic reconstruction. The technique is made all the more attractive by the often-continuous nature of the record that can be extracted from such sites.

Palynoclimatology is particulary valuable when applied to questions of medium- and long-term changes in climate (i.e. changes that occur on the scale of thousands or tens of thousands of years). The technique is not ideally suited, however, for detecting climatic changes that occur on the scale of decades or centuries, even when these changes are of greater magnitude than those of the longer term. This is because the response time of a climate-induced vegetation

change (including both the initial reaction time, and the time required to progress to an equilibrium state) is typically longer than decades or centuries. M.B. Davis (1982), for instance, notes that climatic changes such as the 0.3°C drop in temperature that characterized the period 1950-1970, and the 0.6°C temperature rise of the period 1880-1950, are not represented in the pollen record from the central and eastern United States; furthermore, according to her, the more pronounced drop in temperature (1°-1.5°C by her estimate) that characterized the 400-year-long period from around AD 1450 to 1850 shows itself in the pollen record "only in a small proportion of sites" in those sections of the continent. Any attempt to correlate the pollen record with the fluctuations of a closed lake, therefore, must take cognizance of the inherent incomparability of the two proxy indicators that derives from differences in response time.[4]

It must also be noted that dating climatic changes from the pollen record is typically imprecise, not only because of the relative shortage of radiocarbon dates and the resultant dependency on interpolation that assumes a constant rate of sedimentation over periods of hundreds and even thousands of years, but because of the time lag associated with the response of the vegetation to a change in climate. This too must be taken into consideration in correlations.

Pollen diagrams from within or near the western Great

Basin are few in number and, for reasons discussed above, low in resolution relative to the Mono Lake curve. Adam (1967), for example, in his study of Osgood Swamp, lumps the past ~2900 radiocarbon years into just one pollen zone, and associates it with the neoglacial period. A similar scheme was used by Davis and others (1985) in their work west of the southern Sierra crest; they designate the past 3000 years as the "Abies Zone", and associate it with a "cool, moist climatic regime" that, according to them, continues to the present day. It is important to realize that in both of these studies the vegetation had changed sufficiently by 2900-3000 years ago to warrant designation as a separate pollen zone. Neither study addresses the question of the specific time of the climatic change that forced the vegetation response. Was it several decades, a century, or five centuries prior to 3000 years ago?

A third pollen study, from Ralston Ridge Bog, spans only the last 2600 radiocarbon years. The authors (Sercelj and Adam, 1975) recognize a "major break" in the record, from relatively hydric vegetation to relatively xeric types, at a level coinciding with an age which they estimate at approximately 2000 yrs BP--close to the time when Mono Lake reached its late Holocene low stand.

The published interpretation of the middle portion of the core seems contradictory: of the four root horizons

mentioned above which, according to the authors, represent periods of bog desiccation, only the upper two (dated at 1150 and 1350 BP) occur in association with xeric pollen types. The authors disregard the lower two root horizons in their paleoclimatic interpretation, however, inferring relatively hydric conditions from the pollen collected at these same levels.

Pollen from the upper portion of the core is interpreted and dated on the basis of correlation with the Osgood Swamp record. I prefer to postpone any attempt to correlate this portion of the Ralston Bog record with the Mono curve until the intricacies at Ralston have been independently evaluated.

In conclusion, it seems that the pollen record and the Mono Lake curve are, except on the broadest level of generalization, incompatible indicators of climatic change. A change that causes a detectable rise or fall of Mono Lake may be so short lived that the vegetation response, as reflected in the pollen rain, is miniscule or non-existent. In regard to these short-term changes palynologist David Madsen (1985) states that "it is probably more appropriate to use physical data such as geomorphological features [associated with glaciers and lakes] or mineralogical/isotope changes [e.g. associated with sediments extracted from closed lakes] . . . than it is to use less sensitive proxy data such as the nature and distribution of past plant communities."

Correlation With The Bristlecone Pine Tree-Ring Record

Introduction. Dendroclimatology is, in many ways, an ideal proxy indicator of climatic change. Analysis of the width of annual rings selected from trees of demonstrable climatic sensitivities can provide accurate, unbroken, and precisely-dated information on the timing and magnitude of changes in climatic conditions. Depending on the statistical method used in analysis, the technique can produce a record of extremely high resolution, showing variations in climate on the scale of a decade or less. For these reasons it has the greatest potential for providing a "check" on the Mono Lake fluctuation curve.

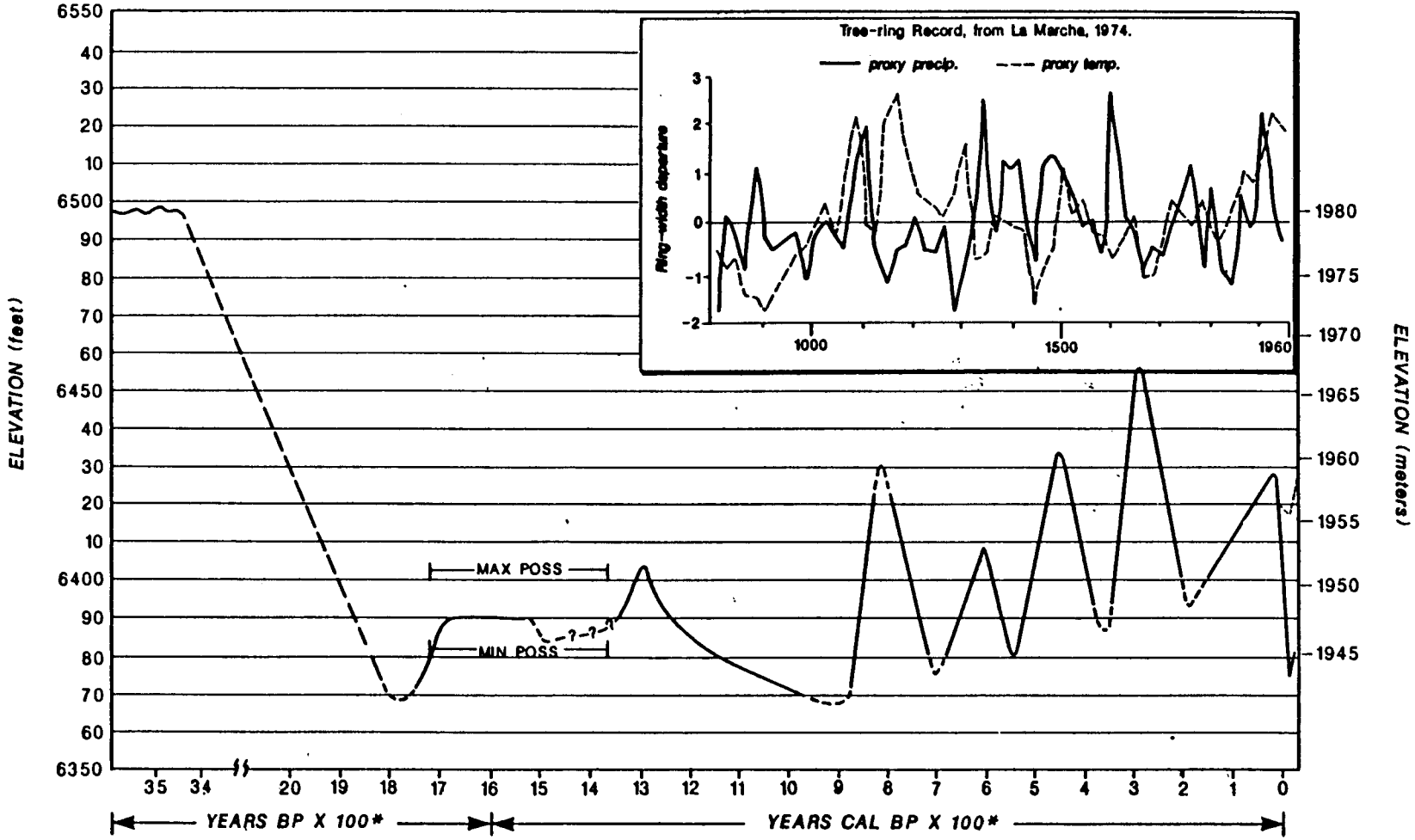
Correlation. Dendroclimatological information derived by LaMarche and his co-workers from bristlecone pine trees (Pinus longaeva Bailey) in the White Mountains of east-central California is particularly applicable here because of the length of the record and the close proximity of the study site to Mono Lake (~50 miles to the southeast). It is of further interest because it includes independent records of changes in both temperature and precipitation. LaMarche produced two tree-ring indices from the White Mountains--the first, a 1160-year-long record based on 20-year running means (LaMarche, 1974); the second, a sequence spanning between 5000 and 6000 years that was

constructed using 100-year running means (Lamarche et al, 1974). The use of a relatively large running mean in the second sequence masks many of the spikes that seem to correspond to the fluctuations of Mono Lake. For this reason the 1160-year-long sequence is a higher-resolution record, and is thus preferred for correlation with the Mono Lake fluctuation curve. It is reproduced here for comparison with the lake fluctuation curve as Figure 25. Note on Figure 25 that the dashed curve, representing the rings of trees selected from the moisture-sensitive lower tree line, indicates changes in precipitation, while the solid curve, based on analyses of trees at the cold-sensitive upper tree line, is indicative of changes in temperature.

Note the striking correspondence between the precipitation curve and the fluctuations in lake level. The periods of abnormally wet and dry periods shown on the tree-ring curve, and likely correlates from the Mono Lake curve, are listed below:

--a period of persistant drought extending, with minor deviations, from before 800 AD to ~1070 AD. As would be predicted from the tree-ring record, Mono Lake is low (ranging from 6390 feet to the Lee Vining Delta Low Stand at 6368 feet) during this entire period.

--a spike indicating a sharp increase in moisture availability from ~1070 to ~1120 AD. Mono Lake begins an



* see Stuiver & Pearson, 1986, and Pearson & Stuiver, 1986.

Figure 25. Tree-ring vs. lake level curves.

abrupt transgression just prior to 1084 (±9) AD, reaching the Post Office High Stand shortly (a half-century?) thereafter.

--persistently dry conditions between ~1120 and ~1285 AD. Mono Lake is declining or low throughout this period of time, reaching a low stand (the Simis Ranch Low Stand) just prior to 1285 (±4) AD.

--an abrupt increase in precipitation between AD ~1285 and ~1340. Coincides with a rise in lake level between 1285 (±4) AD and 1345 (±20) BP that culminates in the Rush Delta High Stand.

--a period of decreased precipitation, persisting from ~1340 AD to ~1380 AD. Coincides with a decline in Mono Lake to the 10-Mile Road Low Stand between 1345 AD and several years prior to 1400 AD.

--A wet period persisting, with a brief interuption of drought, from AD ~1380 to ~1480. The transgression of Mono Lake that began just prior to 1400 AD coincides reasonably well with the initial increase in precipitation; the Danberg Beach High Stand, estimated to have occurred around 1490 AD, is in close agreement with the end of this wet period. No evidence can be found in the Mono record, however, for the intervening drought suggested in the tree-ring record. This may be due in part to the shortness of the dry spell (persisting, according to Lamarche's curve, for only about 20 years), and/or to the fact that the temperature conditions that characterized this short-lived dry period were (according to Lamarche's curve) cooler than at any time during the past 12 centuries, a fact that would have mitigated a shrinkage of the lake.

--decreasing precipitation beginning ~1480 AD, and reaching a minimum at ~1590 AD. This portion of the lake curve is dated only through interpolation. The Navy Beach Low Stand, estimated to have occurred around AD 1575, may well have actually occurred closer to AD 1590. A more meaningful comparison awaits radiocarbon dating of the Navy Beach Low Stand.

--a precipitation maximum, beginning in AD ~1590 and peaking at ~1620. Mono Lake rises during this interval (the Clover Ranch transgression), but, according to the available radiocarbon dates, reaches the Clover Ranch High Stand some 40 years after the time that would be predicted from the tree-ring record. Further dates on the Clover Ranch High Stand may help explain this apparent discrepancy.[5]

--a period of below-normal precipitation extending, with slight deviations, from AD ~1640 through ~1840. Coincides with the lake recession of immediately pre-historic time.

--an increase in precipitation, beginning approximately AD 1840 and continuing through approximately 1920. Coincides with the rise to the Historic High Stand in 1919 AD.

..in addition, the bristlecone pine record, being of higher resolution, provides corroboration for the Mono curve.

Conclusions

The relatively low resolution of the pollen and glacial records, and the discontinuous nature of the fluctuation records from nearby lakes, provides little basis for corroborating the intricacies of the Mono Lake curve.

Nevertheless, these relatively low resolution records do provide reason to believe that the climatic changes reflected in the Mono curve operate regionally, rather than simply locally.

The bristlecone pine tree-ring record is the most accurately dated, and the highest resolution proxy indicator of climatic change available for the western Great Basin. As such, it can be used to "check" the Mono Lake fluctuation curve. Over the past 1200 years, at least, the sign--and within the constraints of radiometric accuracy, the timing--of fluctuations in lake level can, with one possible exception, be predicted from the growth-ring record of precipitation-sensitive trees. This one exception involves the Clover Ranch High Stand, radiocarbon dated at 290 ±20 cal BP (AD 1640-1680). Based on the tree-ring record one would infer a high stand of the lake around AD 1620, with a decline in lake level during the ensuing decades. The critical importance of this abnormally high lake level, both to understanding the causal climatic conditions, and to dating the emergence of Paoha Island, demands that new radiocarbon dates be run on lake-transgressive deposits of Clover Ranch time. With resolution of this apparent discrepancy in mind, rooted stumps, believed to have been killed during the Clover Ranch Transgression, have been collected from the "post-400 BP soil" on the Rush Creek "Downclover cut" (Plate 2C), and

from an analogous position on Lee Vining Creek.

It is important to realize that while the tree-rings provide an inherently higher resolution record than the Mono Lake fluctuation curve, the lake curve is arguably a simpler and more straight-forward reflection of climatic change, incorporating both temperature and precipitation into a single response that reflects overall water availability for the east-central Sierra Nevada. With additional radiocarbon dates on the lake fluctuation curve, and a longer tree-ring record produced with 20-year running means, it may eventually be possible to combine the two indices to produce a precisely dated history of changes in moisture availability for the west-central Great Basin.

FOOTNOTES

[1] Rahm (1964), working in the Bishop area of the eastern Sierra Nevada, likewise identified three Holocene glaciations--the Wonder Lakes (oldest), Basin Mountain, and Gilbert. No known attempt has been made to extend this sequence beyond the Bishop area, or to correlate it with the better known scheme of Birman.

[2] In correlating various indicators of Holocene climatic change, for instance, Morratto, King, and Woolfenden (1978) use Curry's 2600- and 2000-year dates to mark the beginning and end, respectively, of the Recess Peak glaciation. J.O. Davis (1982), interpreting Curry, states that as late as 3200 years ago neoglaciation had not yet begun in the Sierra Nevada, a conclusion that cannot be drawn from Curry's lichen dates. Hall (1983) also cites Curry's dates as indicating the onset and close of glaciation, but wisely grapples with the apparent contradiction between these dates and those of other indicators of climatic change.

[3] Any glaciers that might have formed during this millennium were so small that their moraines were obliterated by the tiny Matthes glaciers beginning approximately 600 years ago.

[4] In this sense, the pollen record might be thought of as being similar to a terminal lake enclosed by extremely steep sides, responding sluggishly to changes in climate.

[5] Wood from trees and shrubs killed by the Clover Ranch Transgression has been collected from sections exposed along Lee Vining Creek and from the Rush Creek "Downclover cut" (Plate 2c). These samples should provide accurate dates on the transgression.

CHAPTER 8

THE LATE HOLOCENE FLUCTUATIONS OF MONO LAKE-- THE QUESTION OF CAUSALITY

Early in the history of radiocarbon dating it was recognized that the ^{14}C content of tree rings varies in a manner that is both systematic and time-dependent (deVries, 1958). Long-term variations (with a period of approximately 10,000 years) appear to be due to changes in the earth's dipole moment (Suess, 1968, 1970; Bucha, 1969, 1970). Variations of medium frequency (the "deVries effect", with a variable period of perhaps 100 to 400 years) are related to changes in solar activity (Stuiver, 1961, 1965; Suess, 1965, 1970; Stuiver and Quay, 1980).

The deVries-type variations, which are the concern here, result in the following way: radiocarbon is produced in the earth's upper atmosphere when cosmic radiation bombards ^{14}N. The earthward flux of this radiation is modulated by magnetic fields associated with the solar wind. During times of high solar wind (associated with a period of high solar activity, and reflected in but not caused by a large number of sunspots) a relatively large portion of the cosmic stream is deflected around the planet. Periods of high solar activity are thus periods of low ^{14}C production, and vise versa

(Stuiver, 1961, 1965). Because of this relationship changes in the radiocarbon content of tree rings are a useful proxy indicator of past solar activity (Stuiver, 1961, 1965; Damon, 1968; Bray, 1968, 1970).

In the mid-1970s astronomer John Eddy (1976, 1977) rediscovered and corroborated long-forgotten evidence from historic records indicating the near-absence of sunspots between AD 1645 and 1715. He called this period of anomalously low solar activity the "Maunder Sunspot Minimum", and noted that it coincided with a positive ^{14}C anomaly in the tree-ring record. Eddy's work helped confirm the relationship between solar activity and ^{14}C production, and provided a basis for evaluating the duration of the time lag that exists between the beginning of a solar anomaly and the manifestation of that anomaly in the ^{14}C record from tree-rings. (This lag was found to be on the order of a few years to a few decades--see also Stuiver and Quay, 1980).

Eddy, like others before him, inferred several other sunspot anomalies from the tree-ring record. He named these the Sporer Minimum (from AD ~1400 to ~1510), the Medieval Minimum (from AD ~640 to ~710), the Medieval Maximum (from AD ~1120 to ~1280), and the Roman Maximum (from BC ~20 to AD ~80). Further work on the tree-ring record led Stuiver and Quay (1980) to add to this list of sunspot anomalies the Wolf

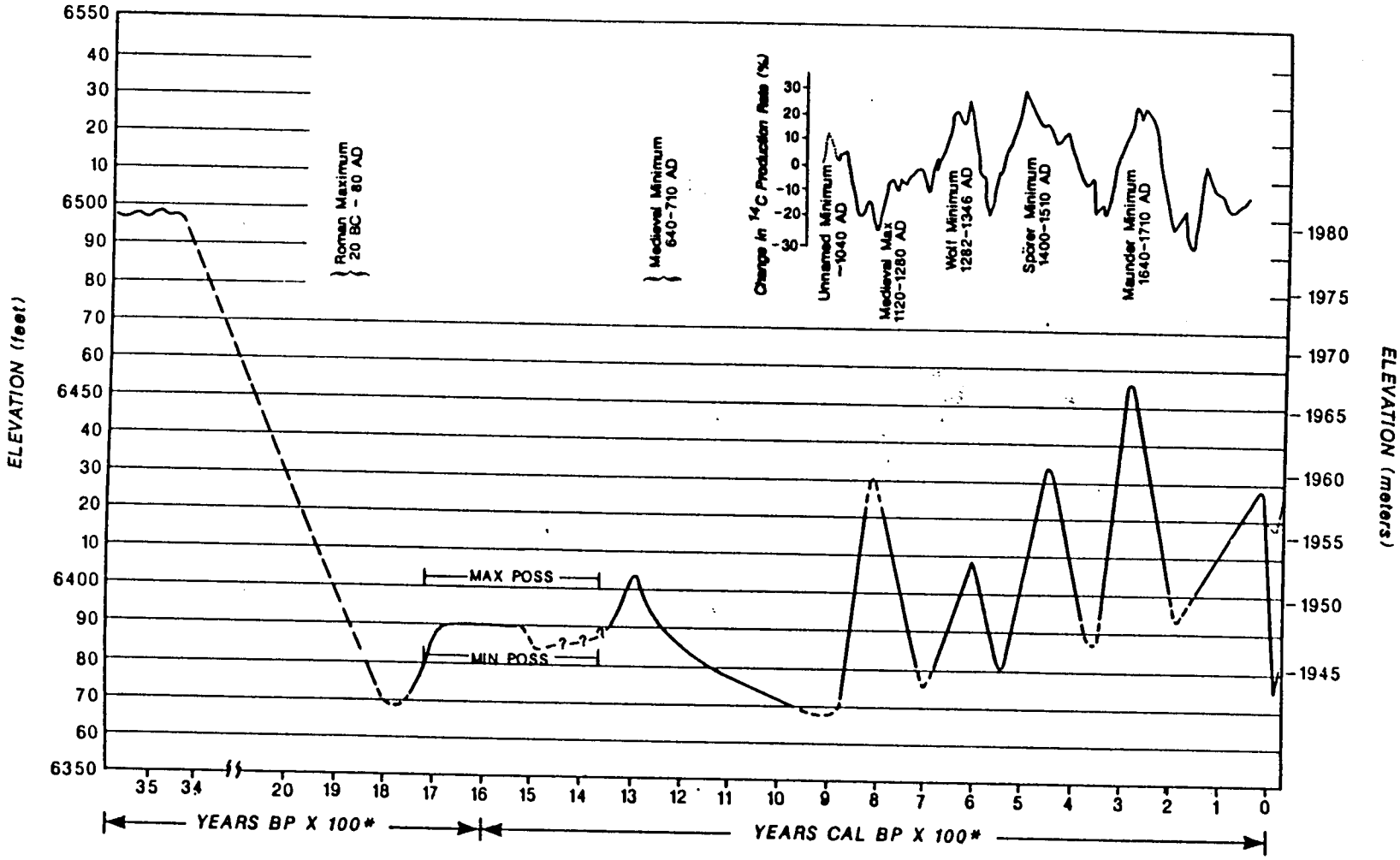
Minimum (from AD 1282 to 1342), a yet unnamed maximum around AD 1375, and an ill-defined and yet unnamed minimum centered on approximately AD 1040.

Scientists were quick to seek evidence of climatic changes corresponding to these minor variations (up to ± approximately 3%) in solar output (Suess, 1968, 1965 [see also Damon, 1968]; Denton and Karlen, 1973; Siscoe, 1978; Eddy, 1976, 1977; Willett, 1977). They pointed out, for instance, that the "Little Ice Age" coincided with the sunspot anomalies now called the Maunder and Sporer minima, and that the "Little Optimum" of the 11th through 13th centuries coincided with the Medieval Sunspot Maximum. More rigorous analysis by Stuiver (1980) casts doubt on any relationship between the sunspot anomalies and climate over large geographical areas during the last 1000 years. Locally, however, the anomalies are of demonstrable climatic significance. On Campito Mountain in the White-Inyo range, just 50 miles south of Mono Lake, for instance, there appears to be a statistically sound relationship between air temperature and solar activity (as determined from the ^{14}C record derived from bristlecone pine tree-rings) during the period since around 3400 BC (Suess and Sonnet, 1984).

The Mono Lake record would seem to provide further evidence of a climatic manifestation of deVries-type solar variations. Figure 26 compares the surface fluctuations of

Mono Lake with Stuiver and Quay's (1980) graph of changes in the ^{14}C production rate for the period AD 1020-1900; also delineated are Eddy's Roman Sunspot Maximum and Medieval Minimum. Note on Figure 26 that the agreement between the lake and ^{14}C-production graphs is close if not perfect, with periods of decreasing ^{14}C production (= increasing solar flux) generally conforming to declining lake levels and low stands, and periods of increasing ^{14}C production (= decreasing solar flux) generally corresponding to rising lake levels and high stands.[1] Specifically, the Maunder Minimum corresponds with the Clover Ranch High Stand, the Sporer Minimum with the Mill Creek High Stand, the Wolf Minimum with the Rush Creek High Stand, and the Medieval Minimum with the Marina High Stand; the Roman and Medieval maxima correspond with the Mono Lake and 10-Mile Road lowstands, respectively.

Slight discrepancies between the two records do exist, though these might be expected, since the lake does not respond directly to variations in solar flux, but rather to atmospheric changes instigated by such variations. Given the tendency for atmospheric changes to be geographically non-uniform and asynchronous, and time-transgressive, there is no reason to believe that Mono low stands should conform precisely with the absolute highest number of sunspots within



* see Stuiver & Pearson, 1986, and Pearson & Stuiver, 1986.

Figure 26. Sunspot maxima and minima vs. lake fluctuations.

a given maximum, or that high stands should conform precisely with the absolute lowest number of sunspots within a given minimum; likewise there is no reason to believe that a ^{14}C-production anomaly that persists for a relatively long period of time should produce a higher high stand, or a lower low stand, than one of shorter duration, or that ^{14}C production should have to reach some critical high or low value before hydroclimatic conditions at Mono Lake are affected. It may simply be the *shift* from relatively high to low (or low to high) solar activity, rather than the attainment of some critical value of solar flux, that instigates the atmospheric changes that result in fluctuations of Mono Lake.[2] With this in mind, note on Figure 26 that during the time represented by the Lee Vining Creek Low Stand the ^{14}C production rate apparently did not reach a value low enough to be designated a sunspot maximum. Nevertheless, the low stand does lie between two designated sunspot minima; the onset of the lowstand thus corresponds with a shift to increased solar activity, and its termination with a shift to decreased solar activity.

The close correspondence between the ^{14}C and lake records strongly suggests a cause/effect relationship. Proof of such a relationship must await more precise dating, and a lengthening, of the Mono fluctuation curve. For now, the

correspondence between the two records is provocative enough to encourage further investigation of the possible link between solar activity and medium-term (100-400 year) climatic changes. With the close correspondence between the two records in mind, and tempered with the realization that future artificially-induced atmospheric changes might undermine the predictive value of the clima-geologic record, it would seem wise to treat future deVries-type changes in solar output as harbingers of climatic change in central California.

FOOTNOTES

[1] Three factors should be taken into account in comparing the records. First, the graph of ^{14}C-production rate does not take into consideration the lag time that exists between the change in solar activity and the manifestation of that change in the tree-ring record; since the actual solar changes occurred slightly before they appear in the tree-ring record, the ^{14}C-production graph should, in the mind's eye, be displaced the equivalent of 1-2 decades to the left. Secondly, the lake high stand shown at 460 cal BP may actually have occurred either several decades before, or several decades after, that date; analysis of datable materials killed in the course of this transgression will resolve the timing of this high stand. Finally, as previously discussed, the Clover Ranch High Stand has been placed at 290 cal BP, in accordance with radiocarbon dates derived from deltaic sediments. Based on the bristlecone pine record, this date is considered suspect.

[2] It is tempting to speculate that this climatic signal may involve a simple expansion (in response to global cooling) or contraction (in response to global warming) of the circumpolar vortex, either increasing (in the first instance) or decreasing (in the second) the incidence of frontal passage across central California.

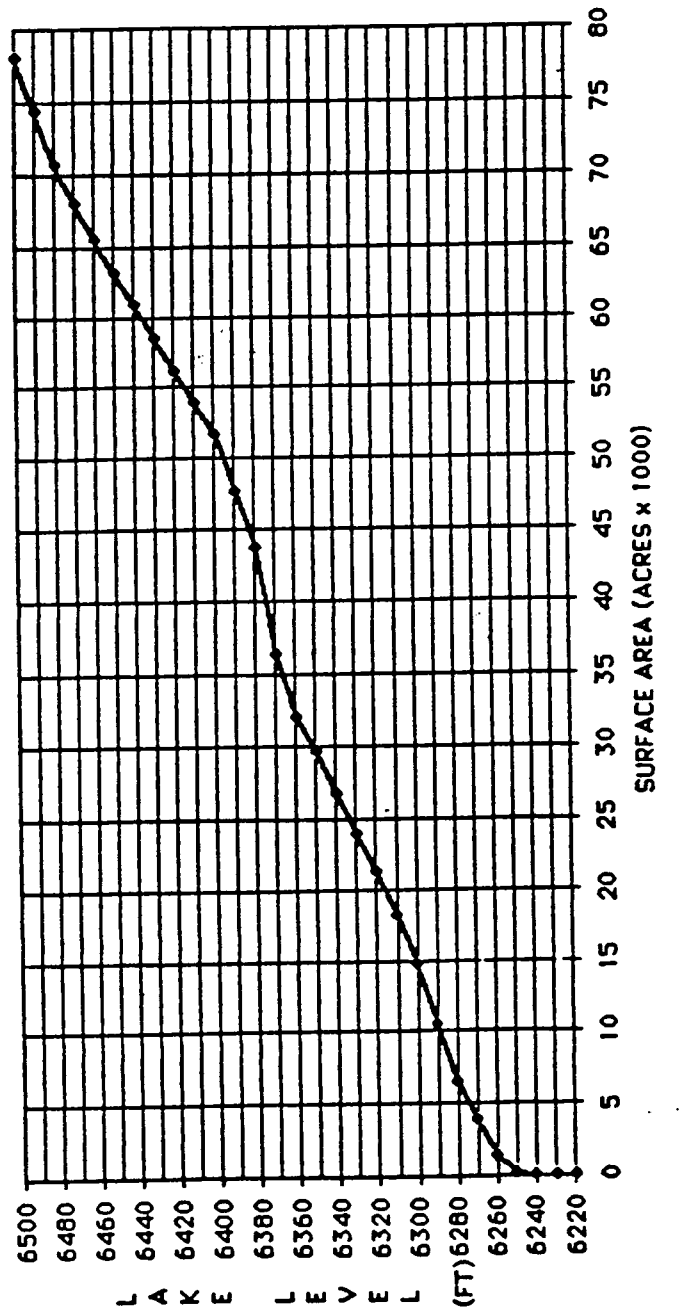
Appendix A

Stage/Area Relationships

The relationship between lake level (stage) and lake area is shown below on Figure A-1. These relationships were derived by planimetering the bathymetry of Scholl, et al (1967) for elevations below 6370 feet; USGS maps were used for lake levels above that elevation.

Figure A-1

MONO LAKE STAGE / AREA RELATIONSHIP



Appendix B

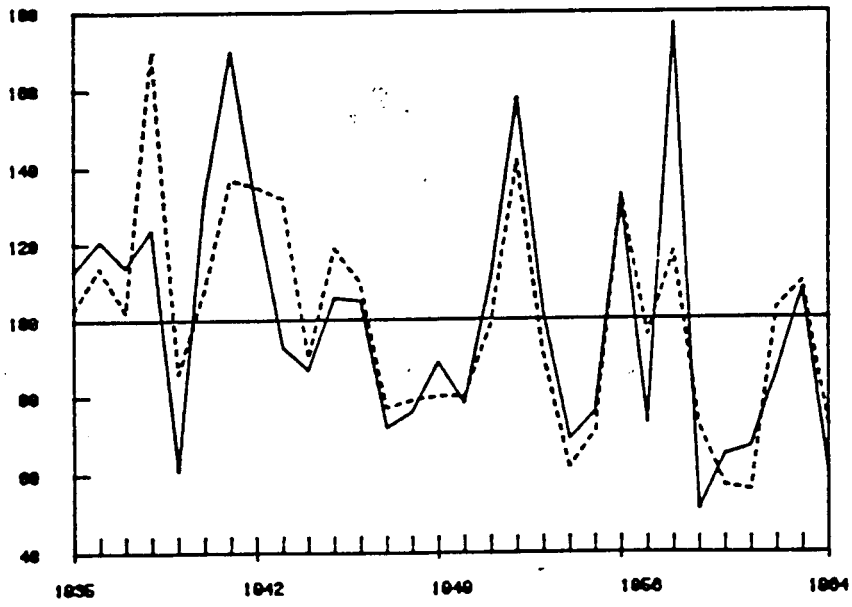
Correlation Between San Francisco Precipitation and Inflow to Mono Lake

Listed below are the data used to quantify the relationship between annual precipitation in San Francisco and annual flow of Mono Lake's major tributary streams. Streamflow figures include the sum of Lee Vining, Gibbs, Parker, Walker, and Rush Creek. The relationship is shown graphically on the following page.

Year	Measured Flow of Tributaries (av. = 121,400 acre feet)	San Francisco Precipitation (av. = 20.66 in.)
1934-35	125,000 acre feet	23.22 inches
35-36	139,000	24.96
36-37	124,000	23.39
37-38	206,000	25.48
38-39	104,000	12.53
39-40	131,000	27.17
40-41	166,000	35.05
41-42	164,000	26.87
42-43	160,000	19.10
43-44	109,000	17.86
44-45	144,000	21.85
45-46	133,000	21.64
46-47	94,000	14.89
47-48	96,000	15.59
48-49	97,000	18.28
49-50	97,000	16.05
50-51	120,000	22.96
51-52	172,000	32.56
52-53	110,000	21.10
53-54	75,000	14.27
54-55	86,000	15.74
55-56	162,000	27.17
56-57	117,000	15.04
57-58	143,000	36.48
58-59	67,000	10.46
59-60	69,000	13.47
60-61	68,000	13.90
61-62	125,000	17.71
62-63	133,000	22.17
63-64	87,000	12.34

COMPARISON OF SAN FRANCISCO PRECIPITATION (SOLID LINE) WITH MEASURED FLOW OF MONO LAKE'S TRIBUTARY STREAMS* (DASHED LINE) FOR THE PERIOD 1935-1964

(Data are presented as percent of normal for that period.)



_____ San Francisco precipitation.

- - - - - - - Measured flow of Mono Lake's tributary streams.

* Includes Lee Vining, Gibbs, Walker, Parker, and Rush Creeks. All Measurements taken above points of diversion.

APPENDIX C

Letter Concerning Correction of the Error

in the USGS Lake-Level Record

Following are copies of written correspondence between California State Deputy Attorney General Joseph Barbieri and Mr. Mike Butcher of the United States Geological Survey relating to an inconsistency in the Mono lake-level record. That record, published in the USGS series Water Supply Papers for California was recently corrected as per information provided in Butcher's letter.

JOHN K. VAN DE KAMP
Attorney General

State of California
DEPARTMENT OF JUSTICE

350 McALLISTER STREET, ROOM 6000
SAN FRANCISCO 94102
(415) 557-2544

(415) 557-8820

July 6, 1984

Mike Butcher
United States Geological Survey
29000 Avila Rd.
Laguna-Niguel, CA 92677

Dear Mr. Butcher:

On March 12, 1984, Scott Stine from the University of California at Berkeley spoke to you on the phone concerning a discrepancy in the United States Geological Survey lake level records for Mono Lake, California. I understand from talking to Scott that the Mono Lake levels published by the USGS are correct through September of 1976, but that the elevations published after that date are 0.37 foot too low. I further understand that the USGS will soon (1984? 85?) published a corrected list of lake elevations for the period 1975-present.

The State of California is currently involved in litigation related to the surface fluctuations of Mono Lake. All the parties to the litigation are interested in obtaining the most accurate data available regarding the fluctuations. Therefore, I would greatly appreciate receiving from you a letter stating

1) that the USGS lake level records for Mono Lake are incorrect for the period October 1976-present;

2) that the lake level records published by the USGS for the period October 1976-present are 0.37 foot too low; and

3) that the USGS will soon publish a corrected list of surface elevations for Mono Lake.

Very truly yours,

JOHN K. VAN DE KAMP
Attorney General

JOSEPH BARBIERI
Deputy Attorney General

JB:jut
cc: Scott Stine ✓

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Water Resources Division
24000 Avila Road, 5th Floor
Laguna Niguel, California 92677

July 27, 1984

Mr. John K. Van De Kamp
Attorney General
State of California
Department of Justice
350 McAlister Street
Room 6000
San Francisco, CA 94102

Attention: Joseph Barbieri

RE: Mono Lake Water Levels - letter dated July 6, 1984

Dear Sir:

The U.S. Geological Survey (USGS) publishes a series of data books each year entitled Water Resources Data. The majority of data presented are from the U.S. Geological Survey and other data are supplied by other agencies. The data on Mono Lake near Mono Lake, California is supplied to the U.S. Geological Survey, on a yearly basis, by the City of Los Angeles, Department of Water and Power.

The U.S. Geological Survey accepts this data at face value. No attempt is made by us to check the accuracy of the readings or to verify the correctness of the copy presented to the U.S. Geological Survey.

Following is a very brief history of the data collection effort at Mono Lake:

On June 15, 1912 a staff gage was mounted on a tree near Hammons Store in lot 6, SE, ¼ NE ¼ Sec. 31, t. 2N., R. 26, about 2 miles south from Mono Lake Post Office. This gage was maintained by the U.S. Forest Service.

On Sept 16, 1916 a new staff was installed at a boathouse 300 feet northwest of the former staff. Datum of the new staff was 10.0 ft higher than the former gage operated by the U.S. Forest Service.

The USGS Water Supply Paper 750 for the year 1933, page 75, revised the gage location to read "about a mile south of Mono Lake Post Office." The elevation (datum) of the zero of the gage was given as 6,423.90 ft above mean sea level.

In USGS Water Supply Paper 765 for the year 1934, all previous records were revised and additional unpublished gage heights collected by the City of Los Angeles, Department of Water and Power were included. All gage heights were reduced to a common datum of 6,390.29 ft above mean sea level according to the datum used in USGS bulletin 766 (1925) and also by the City of Los Angeles in its Mono Basin Survey; and 6,390.66 ft above mean sea level according to the U.S. Coast and Geodetic Survey levels of 1932 referred to as the 1929 general adjustment of the level net. Lake elevations have been furnished by the City of Los Angeles Department of Water and Power for subsequent years.

During the years since the adjustment the City of Los Angeles has continued use of the datum of 1925. For this reason all readings supplied to the U.S. Geological Survey are adjusted by + 0.37 feet to adjust to the general datum correction of 1929.

Due to changes in personnel the correction was omitted since October 1976 making the Mono Lake water levels incorrect relative to the datum of 1929. The error was not detected at that time and was continued through the 1982 water year publication of Water Resources Data.

The Mono Lake water levels as published are, therefore, 0.37 feet too low for the period of October 1, 1976 to September 30, 1982.

The U.S. Geological Survey intends to publish revised tables of the Mono Lake water levels for that period as part of Water Resources Data for California for the 1983 water year (Volume 1). This publication should be in print and available for general circulation before the end of the year.

Respectfully yours,

Michael T. Butcher

Michael T. Butcher
Supervisory Hydrologic Technician

Appendix D

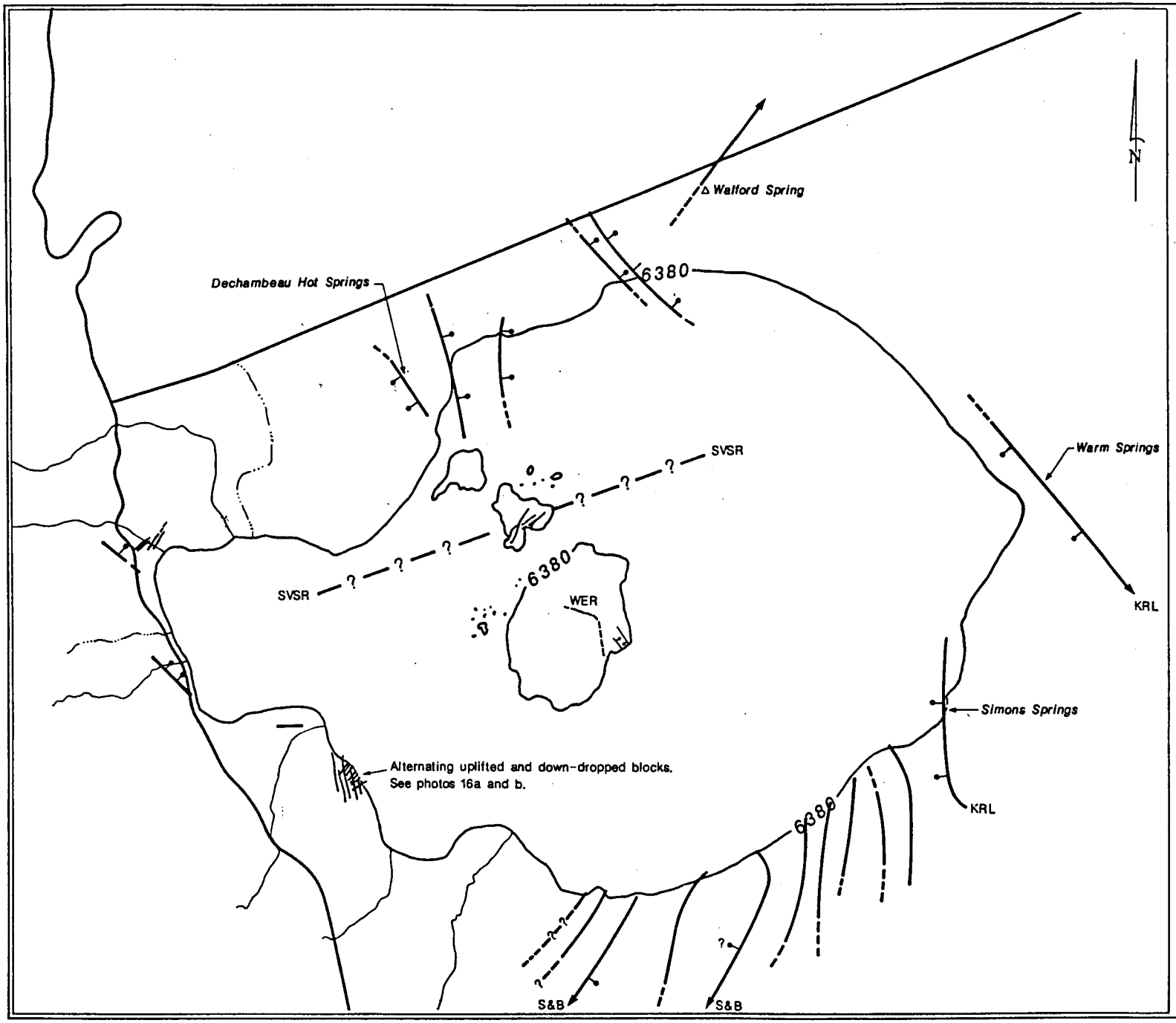
Faults of the Late Holocene Shorelands

A systematic investigation of recent faulting in the Mono Basin was not conducted as part of this study. In the course of field work, however, many previously unreported faults were discovered on and immediately adjacent to the late-Holocene shorelands of the lake. These features are mapped on Figure D-1. It must be stressed that Figure D-1 is not the result of an exhaustive search; it will undoubtedly have to be modified in the future.

The faults of the Mono shorelands can be divided into a number of geographical groups. Several of these groups (including the "Negit Island Group", and those groups along which the "delta groves" of tufa formed) were mentioned previously. Three other notable groups of faults are discussed briefly below.

The Dechambeau Embayment Group, east of Black Point, consists of at least three faults, all of which display obvious offset. This group includes the "Dechambeau Hot-Ponds Fault", so named because of the thermal waters that find their way to the surface along its trace. Evidence of hot spring activity can also be seen near the present-day lake margin at one of the other faults in this group.

The Bridgeport Creek Group, centered on Bridgeport Creek



LEGEND

Fault, offset uncertain.

Fault, ball and bar on dow

Suspected fault.

Initialized faults after:

KRL (Lajoie, 1968)
S&B (Siehand & Bursic
WER (Reed, 1972)
SVSR (Scholl, et al., 19

Figure D-1. Faults of the Late Holocen

along the lake's northern shore, includes three suspected faults, offset along which has been inferred from slight to conspicuous embayments in the lake shoreline.

The South Shore Group consists of nearly a dozen N-S trending faults that occur between South Tufa and Simon's Springs. Offset is obvious along several of the features; existence of the others is suspected on the basis of aligned tufa towers, and linear zones of relatively luxurient arbuscular growth.

This last fault group exerts a strong influence on the configuration of the southern shoreline of Mono Lake. Fault scarps, as well as linear bulwarks of tufa that have grown from the faults, deflect the counterclockwise longshore currents that prevail in this sector. At these points littoral drift is forced offshore into deep water, where it comes to rest. Longshore flow immediately downcurrent (east) of each of these obstructions is thus "sand-starved", a situation that fosters abrasion during times of rising lake levels. In the immediate lee of the faults, therefore, strandlines are typically the product of erosion, consisting of an abrasion platform and cliffline.

Longshore flow downcurrent of the faults, on the other hand, tends to be sand-laden and relatively non-erosive. Here strandlines are depositional, consisting of a shoreline embankment (either a berm or a bar). The west-to-east

transition from erosional to depositional littoral landforms characterizes nearly all of the fault-bounded segments of the southern shorelands.

In addition to these fault groups are several lone-standing faults worthy of mention because of the control they exert on the flow of groundwater. Aside from the Simon's Spring Fault (part of the South Shore Group) the best known of these is the "Warm Springs Fault" along the easternmost shore. In addition to being a zone of diffuse groundwater seepage this feature acts as a conduit for at least four free-flowing thermal springs. Spring activity is also evident along the trace of the "Walford Spring Fault" on the northeast shore. This fault is of particular interest because it offsets sand dunes, and because offset on the lakeward end of the trace terminates abruptly at the Dechambeau Ranch strandline, strongly suggesting that movement was restricted to pre-Dechambeau Ranch time (i.e. pre-3500 BP).

APPENDIX E

The Vorster Water Balance Forecast Model

Construction of the water balance forecast model of Vorster (1985) involved a process of formulation, calibration, and verification. The components used in formulation, and the manner in which the model was calibrated and verified, are given below.

I. Inflow components:

a. Sierra Nevada gauged Runoff (that is, the amount of water that enters the Mono Groundwater Basin by way of gauged Sierran watersheds). Calculated as the sum of annual discharge of the gauged streams of the Mono Sierra (Rush, Lee Vining, Mill, Walker, Parker, East Parker, South Parker, Bohler, Gibbs, and Dechambeau creeks), as measured by LADWP and Southern California Edison. Constitutes roughly 63% of the natural inflow to the Mono Groundwater Basin for the period 1937-83.

b. ungauged Sierra Runoff (that is, the amount of water that enters the Mono Groundwater Basin by way of ungauged Sierran watersheds). Calculated as the product of an average annual yield (derived for each ungauged Sierran watershed using the relationship between mean annual precipitation and mean annual runoff for the gauged watersheds) times an index of annual variation. Constitutes approximately 7% of natural inflow to the Mono Groundwater Basin for the period 1937-83.

c. Non-Sierra Runoff (that is, the amount of water that enters the Mono Groundwater Basin by way of non-Sierran watersheds). Calculated as the annual soil moisture surplus within non-Sierra

drainages (based on a modified Thornthwaite soil-moisture balance) times an arbitrary coefficient of 0.9 (to account for losses that occur due to phreatophyte ET at spring and stream sites located above the groundwater basin). Constitutes approximately 9% of natural inflow for the period 1937-83.

d. Net Land-Surface Precipitation (that is, the amount of water that enters the Mono Groundwater Basin as precipitation on the land surface, minus that expended as soil moisture recharge and evapotranspiration). Calculated as per non-Sierra runoff. Constitutes approximately 4% of natural inflow to the groundwater basin for the period 1937-83.

e. Mono Lake Precipitation (that is, the amount of precipitation that falls on the surface of Mono Lake). Calculated as the product of *a*) lake-surface area, *b*) average precipitation over that area (as determined from the Vorster isohyetal map), and *c*) an annual precipitation index (% normal). Thus, varies not only as a function of precipitation, but because of changes in the size of the lake as well. Constitutes from 11% to 17% of the natural inflow to the groundwater basin for the period 1937-83.

In addition to these "natural" (though in some cases human-modified) inflow components are several that are wholly artificial. These include the following:

f. Virginia Creek Diversion. Since the middle of the last century water from Virginia Creek (under natural conditions a stream of the Bridgeport Basin) has been diverted into the Mono Basin for irrigation purposes. In modern times this import has amounted to approximately 1100 acre-feet per year, or approximately 0.5% of the natural inflow to the Mono Groundwater Basin for the period 1937-83.

g. Net Municipal Inflow (that is, the net amount of water

added to the Mono Groundwater Basin due to municipal use). Amounts to approximately 0.2% of the natural inflow to the groundwater basin for the period 1937-83.

II. Outflow components:

h. Mono Lake Evaporation (that is, the amount of water evaporated from the surface of Mono Lake). Calculated as the product of *a*) the mean annual freshwater evaporation rate (=45 inches based on evaporation pan data), *b*) lake surface area, *c*) a coefficient that corrects for specific gravity (i.e. lake salinity), and *d*) an annual evaporation index (based on annual variation in evaporation as determined from the Long Valley Reservoir evap pan). Constitutes from approximately 45% to 92% of the outflow from the groundwater basin for the period 1937-83, depending on lake surface area.

i. Net Grant Lake Evaporation (that is, the amount of water evaporated from the surface of Grant Lake, minus the amount that falls as precipitation on that surface). Calculated as the product of lake surface area times an evaporation rate (derived annually from evap pans at Grant Lake); from this is subtracted the product of a precipitation amount (as determined annually from rain gauges at Grant Lake) and lake surface area. Constitutes <1% of the outflow from the groundwater basin.

j. Bare Ground Evaporation (that is, the amount of water evaporated from unvegetated surfaces in areas of high groundwater tables adjacent to Mono Lake). Calculated as the area of "bare ground" times evaporation rates that are assigned on the basis of the depth to the water table. Represents between roughly 1% and 8% of the total outflow from the Mono Groundwater Basin, depending on the surface elevation of the lake.

k. Riparian Evapotranspiration (that is, the amount of water lost to ET by riparian vegetation, including willows,

cottonwoods, jeffrey pines, aspens, and marsh vegetation growing along streams within the groundwater basin). Calculated as the product of an ET rate (a Blaney-Criddle ET value of 2.75 feet is used) and the acreage of riparian vegetation within the freebody boundary. Represents from 0.3% to 1% of the total calculated outflow from the groundwater basin, depending on the level of the lake and, during historic time, the amount of vegetation destroyed by water diversions.

l. Phreatophyte Evapotranspiration from lands above the Historic High Stand (that is, the amount of water lost to ET by phreatophytic vegetation--including Scirpus, Juncus, Typha, Distichlis, Salix, Sarcobatus, and Chrysothamnus--above 6428 feet). Calculated as the product of vegetated area times ET rates derived by the Blaney-Criddle method. Constitutes <1% of the total calculated outflow from the Mono Groundwater Basin.

m. Phreatophyte Evapotranspiration from lands below the Historic High Stand (that is, the amount of water lost to ET by phreatophytic vegetation (including species within the genera listed above) that has become established on lands exposed by the declining lake since 1919. Calculated as the product of vegetated acreage (a function of time and lake level), times ET rates derived by the Blaney-Criddle method. Constitutes <2% of the total calculated outflow from the Mono Groundwater Basin.

To these natural outflow components must be added several artificial outflows that have historically affected the water balance of the Mono Groundwater Basin.

n. LADWP Surface-Water Export. Since 1941 the DWP has diverted water from the Rush and Lee Vining Creek watersheds for municipal use in Los Angeles. Equals an average of approximately 115,000 acre-feet per year, or approximately 50% of natural

inflow to the Mono Groundwater Basin.

o. LADWP Groundwater Export. In addition to the water diverted from the tributary streams is a "groundwater export" of approximately 7200 acre-feet per year that occurs as a result of leakage of subsurface water into the aqueduct tunnel that passes under the Mono Craters. This amount of water is equivalent to approximately 3% of the total natural inflow to Mono Lake for the period 1937-83.

p. Evapotranspiration from Irrigated Land. Artificial loss of water also occurs due to ET from irrigated lands within the groundwater basin. Represents an artificial loss of approximately 2500 acre-feet, equivalent to <1% of the natural inflow calculated for the period 1937-83.

III Storage-change components:

q. Grant Lake Reservoir Storage Change (that is, the net change in reservoir storage in a given water year). Can be either a positive value (indicating a gain in storage) or a negative value (indicating a release from storage). Quantity ranges from -26,000 acre feet during the dry year 1959, to +34,000 feet for the year 1978 (a wet year that followed the 1976-77 drought).

r. Groundwater Storage Change (that is, the quantity of water gained (+) or lost (-) from permeable shoreland sediments due to fluctuations in lake level). Total for the base period 1937-83 equals -72,000 acre feet, with annual estimated changes ranging from -4300 acre feet in 1948, to +8000 acre feet in 1983, to near zero (134 acre feet) in 1937.

s. Mono Lake Storage Change (that is, the net change in lake volume in a given water year). Calculated as the sum of all inflow, outflow, and storage-change components of the water balance.

Calibration. Stepwise multiple linear regression analysis was used to calibrate the model (i.e. to evaluate and explain the model's overall error). Calculated annual values of the component "Mono Lake Storage Change" for the period 1957-1983 were compared to the annual storage change of Mono Lake determined from the stage/capacity curve; differences in the two were attributed to error in the calculation of the storage-change component. The annual errors in calculated storage change were then regressed against the annual indices of runoff and evaporation. The resultant equation estimates the model error for a given set of components and indices. The equation is:

$$\text{error} = -((8.487 \cdot \text{RI}) - (151.332 \cdot \text{EI}) + 143.440)$$

where

RI is the runoff index;

EI is the evaporation index.

The equation for deriving Mono Lake storage change (and thus a change in surface elevation) then, is:

$$\text{MLSC} = (a+b+c+d+e+f+g) - (h+i+j+k+l+m+n+o+p) - (q+r) - ((8.487 \cdot \text{RI}) - (151.332 \cdot \text{EI}) + 143.440)$$

where

a,b,c...r are the inflow, outflow, and storage-change components listed above.

Verification. To verify the model, annual lake levels for the period 1937-1956 (that portion of the base period not employed in calibration) were calculated using the equation above; lake levels so derived were compared to observed lake levels. Calculated and observed lake levels for the verification period are graphed on Figure E-1. The close correspondence of the two sets of values demonstrates that the model is a reasonable predictor of lake fluctuations.

To utilize the largest possible data set Vorster reasoned that because the average and the variance of the overall error in the 1937-56 calibration period is similar to those of the 1937-83 base period, the model equation should ultimately be derived using the entire base period. Calculated values of the component "Mono Lake Storage Change" for each year of the entire base period were thus compared to the annual storage change of Mono Lake as determined from the stage/capacity curve. The annual errors in calculated storage change were then regressed against the annual indices of runoff and evaporation; the equation so derived calculates Mono Lake storage change for a given set of components and indices. The equation is:

$$MLSC = (a+b+c+d+e+f+g) - (h+i+j+k+l+m+n+o+p) - (q+r) - ((13.950 * RI) - (128.845 * EI) + 117.096)$$

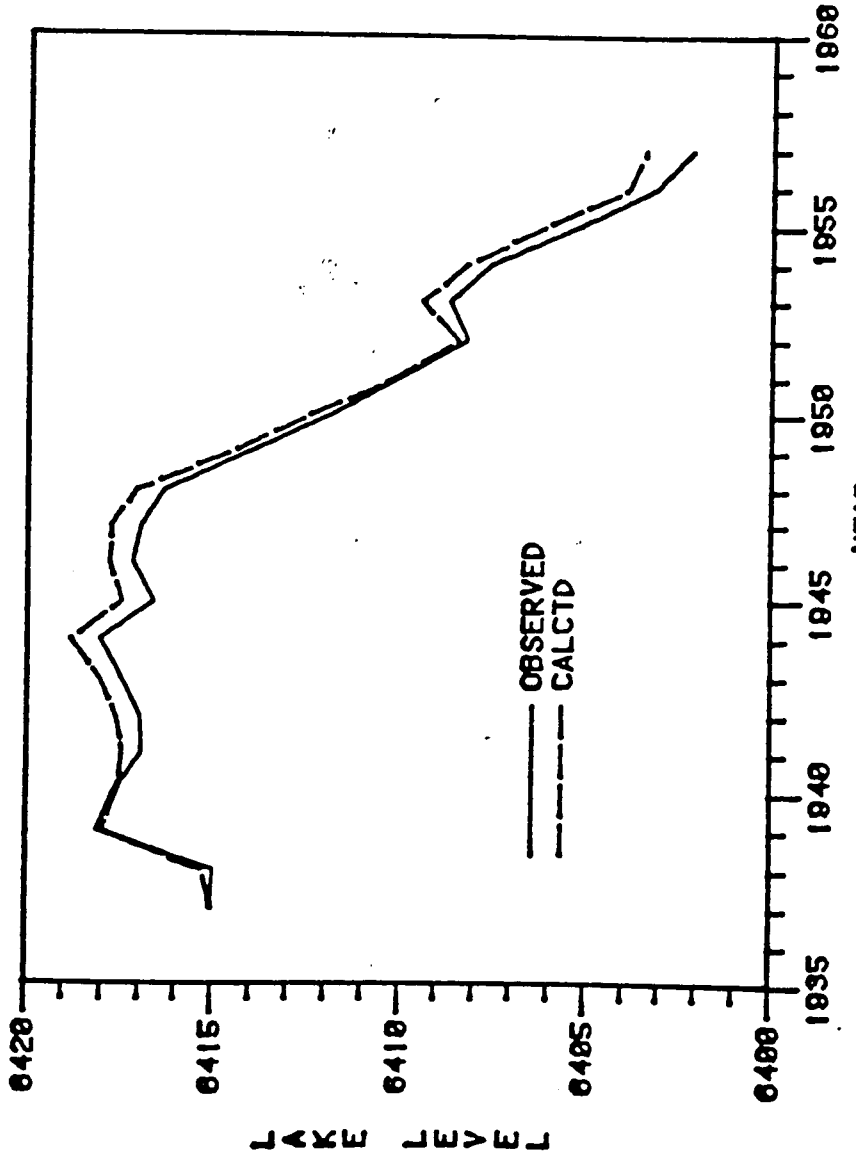


Figure E-1 COMPARISION OF OBSERVED AND SEQUENTIALLY CALCULATED LAKE LEVELS (MODEL VERIFICATION)

To facilitate comparison, the calculated and observed lake levels for the entire base period are graphed on Figure E-2.

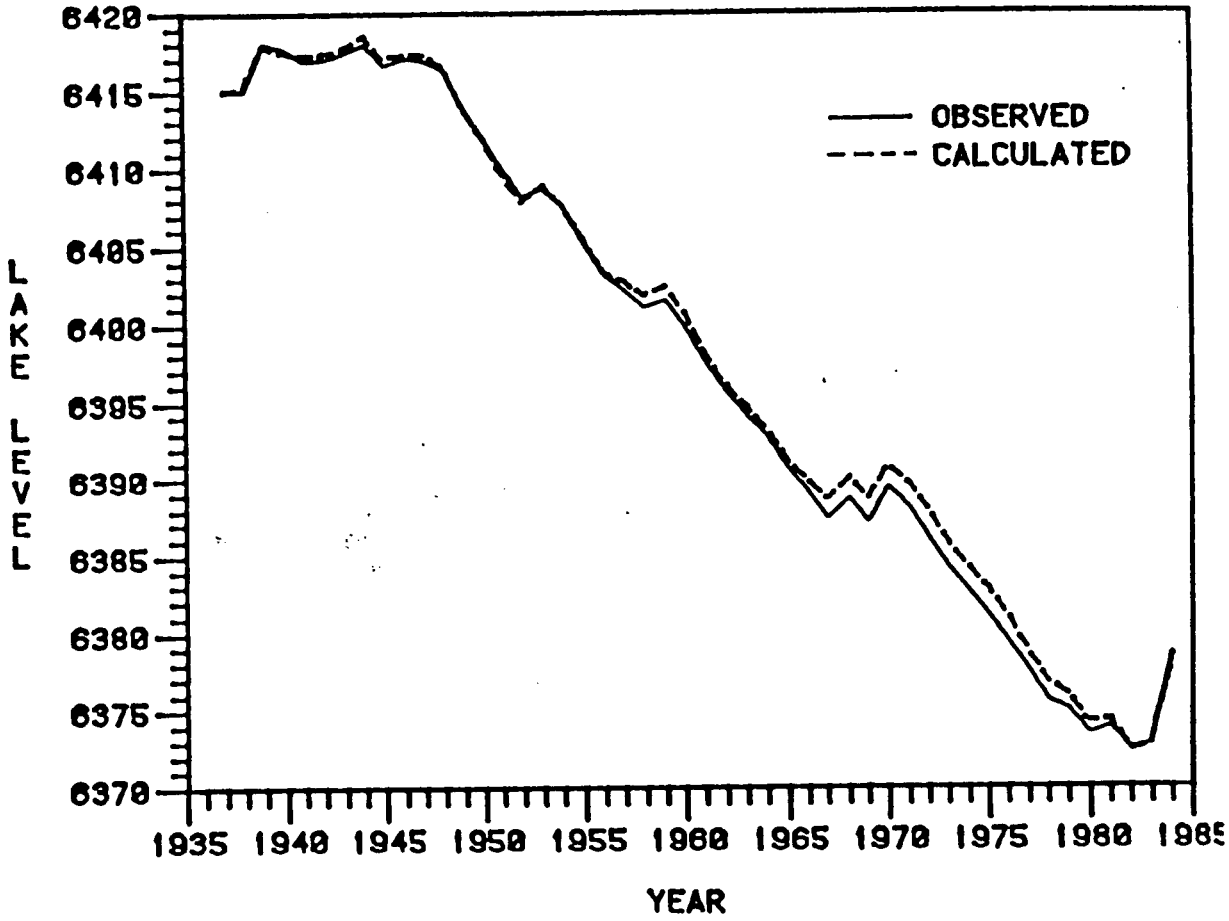


Figure E-2. Comparision of Observed Lake levels and Those Calculated by Model Calibrated with 1937-83 Data

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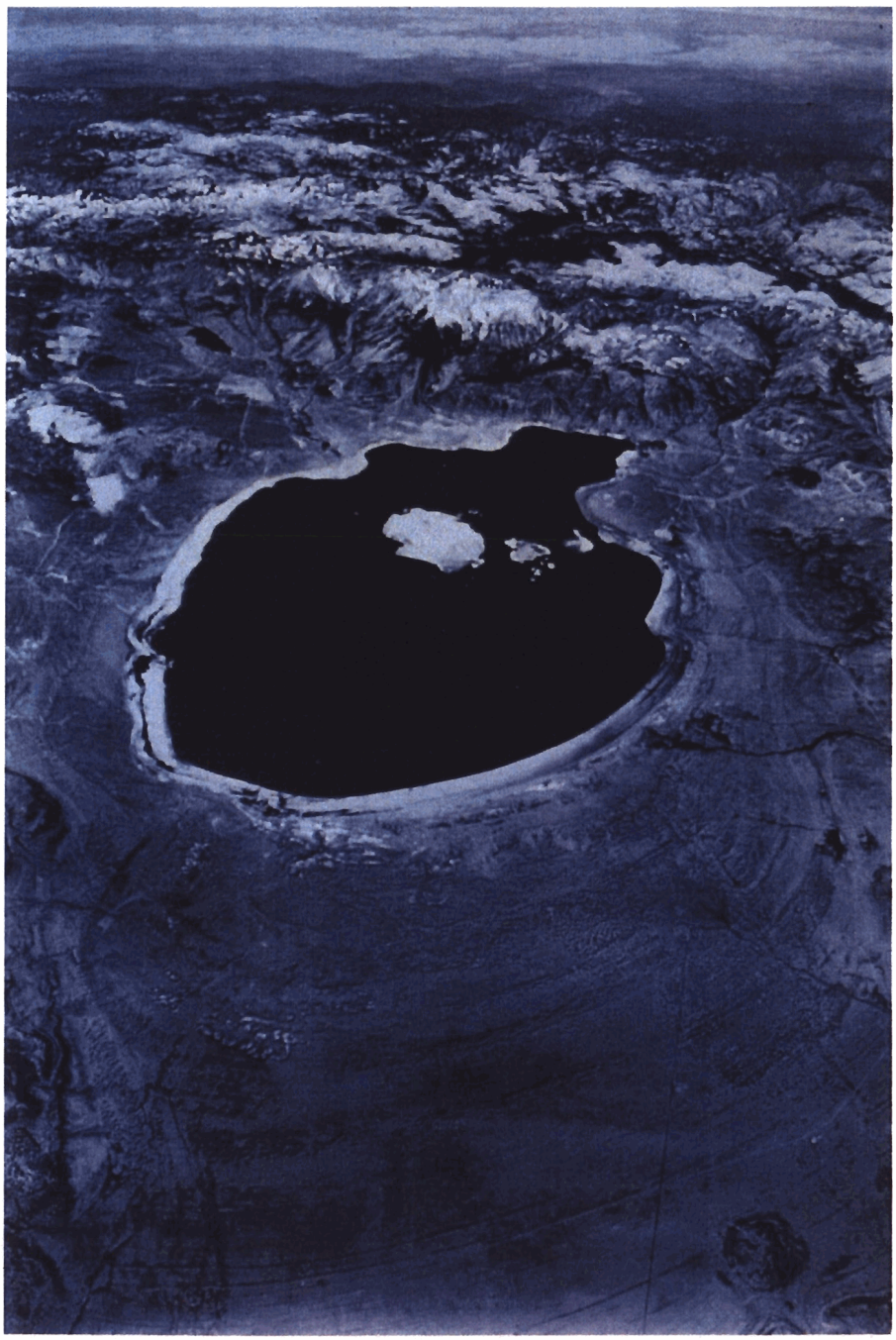
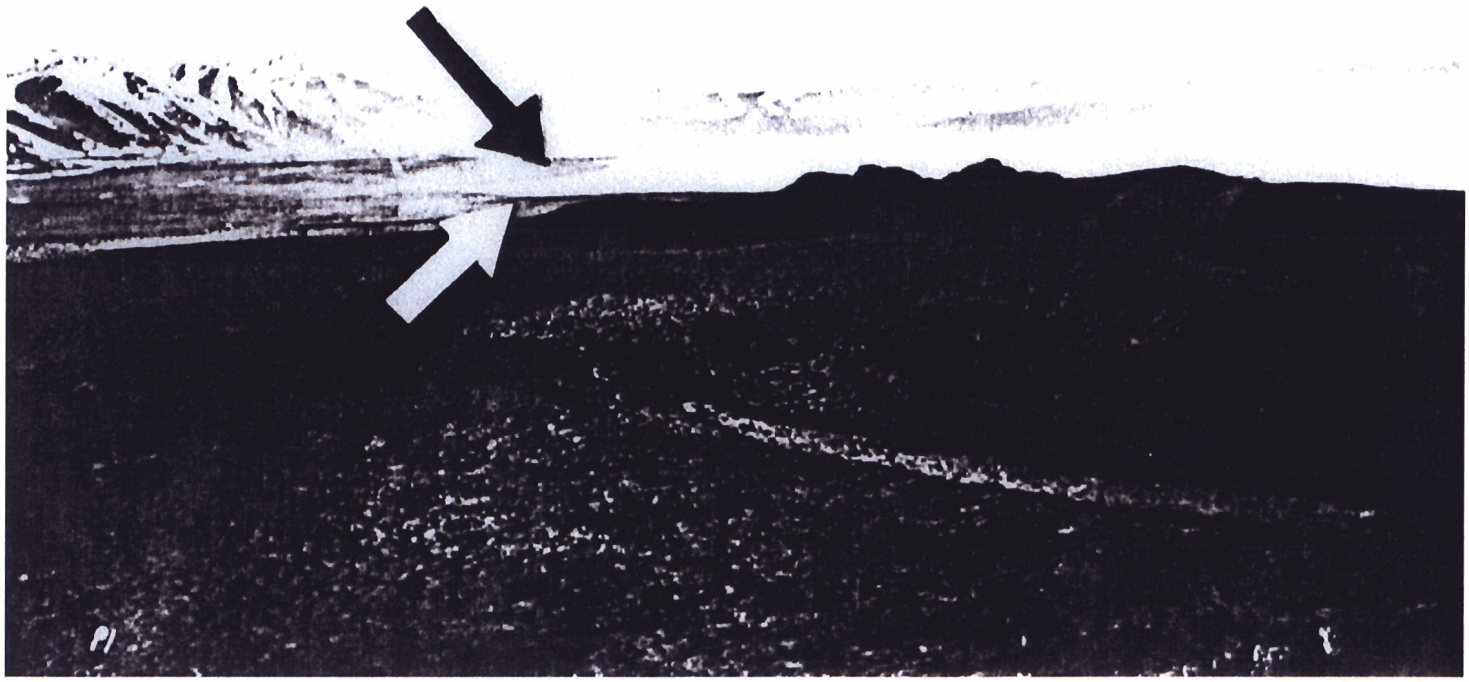
PHOTOGRAPHS

Photo 1. Mono Lake from 55,000 feet altitude, ca. June, 1968, looking west toward the Yosemite Sierra and the California Coast Range.Photo 1. Mono Lake from 55,000 feet altitude, ca. June, 1968, looking west toward the Yosemite Sierra and the California Coast Range.



2. Hypopycnal stratification at the mouth of Rush Creek, June, 1986. A lens of turbid stream water can be seen floating on the surface of Mono Lake. The line of whitecaps that fringes the freshwater lens results when waves of heavy lake water break against the mound of lighter water. Rush Creek flow at the time of the photo was approximately 19 cubic feet per second (cfs), a piddling amount compared to unimpared flows in large or even average years. (Rush Creek flow throughout the high runoff month of July, 1967 averaged 1500 cfs.)

3. Timothy O'Sullivan's photograph of Panum Crater and Mono Lake, ca. March, 1867. Note particularly the position of the shoreline in the Horse Creek Embayment (white arrow) and the Lee Vining Tufa Grove (just to the right of the black arrow). Comparison of this photograph with Photos 4, and Sa, b, and c, leads to the conclusion that in Ui67 Mono Lake stood close to its 1883 level (6410 feet) and far above 6378 feet--the level proposed by Lynch for the year 1867.

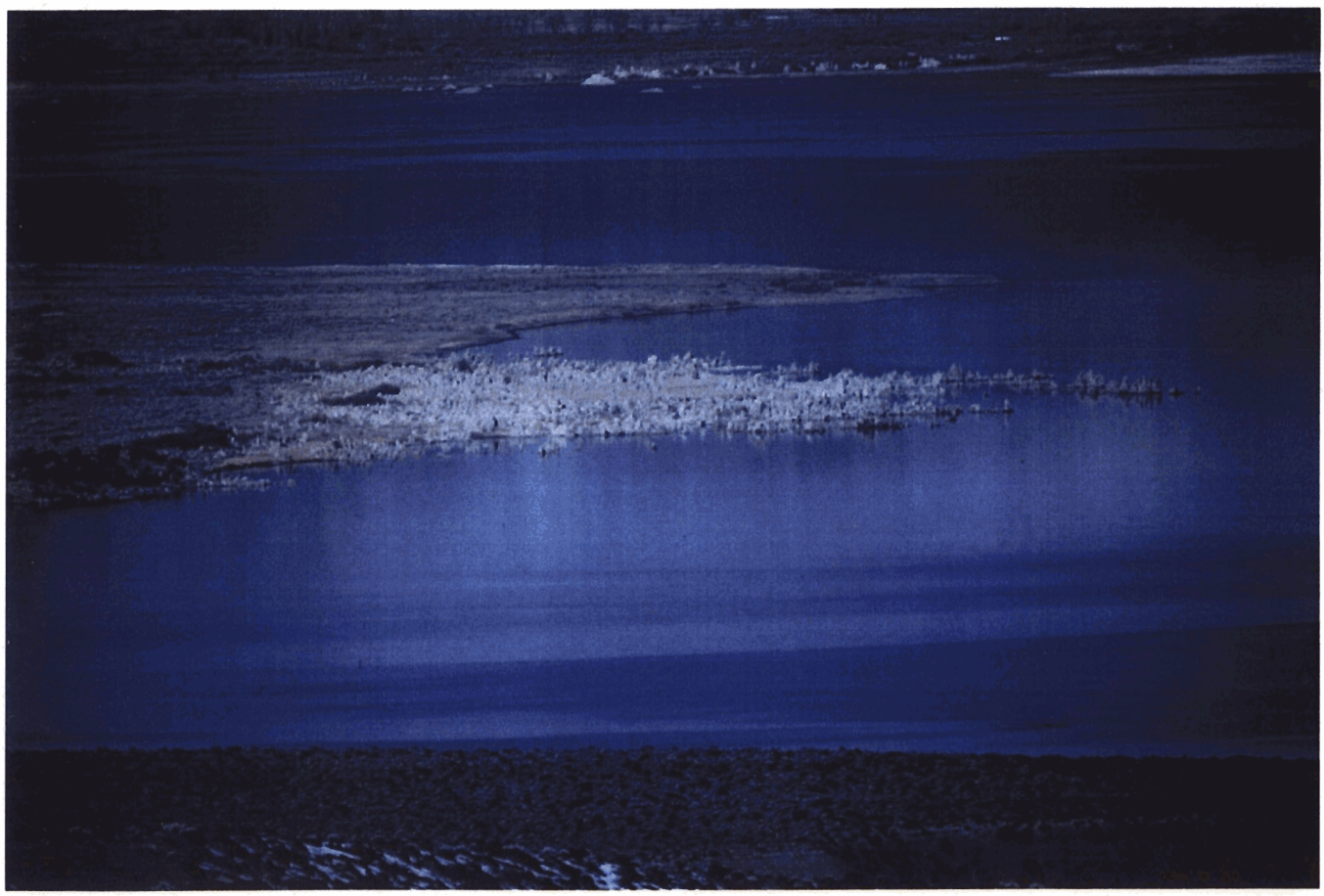


4. Israel Russell's photograph of Panum Crater and Mono Lake, ca. 1883. Compare the position of the shoreline in the Horse Creek Embayment and around Lee Vining Tufa with that on Photos 3, and 5a, b, and c.

5a. Panum Crater and Mono Lake, photographed from O'Sullivan's photo-spot in January, 1986. The level of the lake at the time of the photograph is 6378 feet--the elevation that Lynch proposed for the year 1867. Note thatthe shoreline in the vicinity of the Horse Creek Embayment (see also telephoto shot, Photo 5b), and around the Lee Vining Tufa Grove (see also telephoto shot, Photo 5c) stands far below the shoreline shown in O'Sullivan's photograph of 1867.

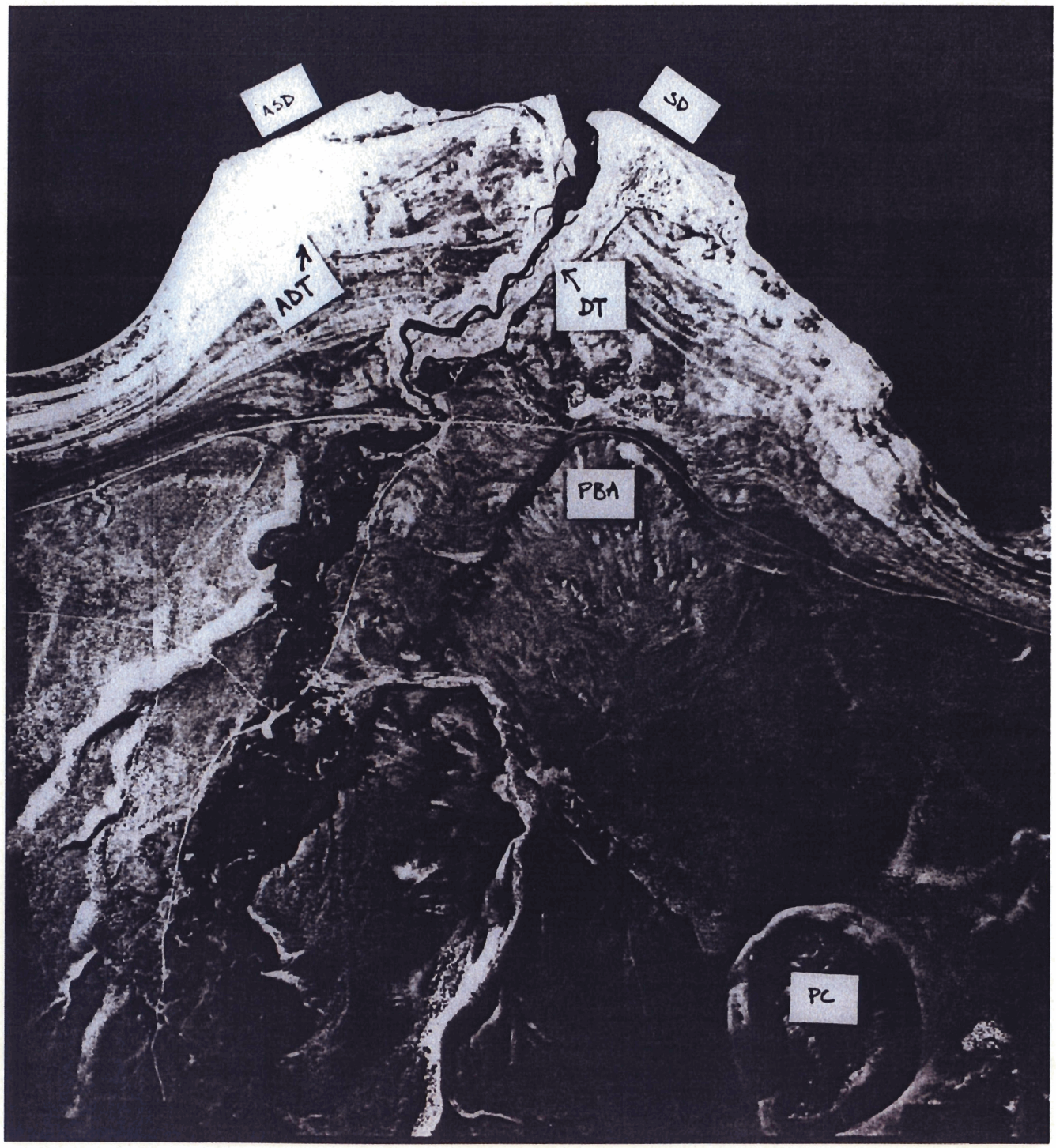
5b. Telephoto shot of the Horse Creek Embayment taken from the O'Sullivan photo spot, January, 1986. See caption, Figure 5a.

5c. Telephoto shot of Lee Vining Tufa taken from the O'Sullivan photo spot, January, 1986. See caption, Figure 5a.

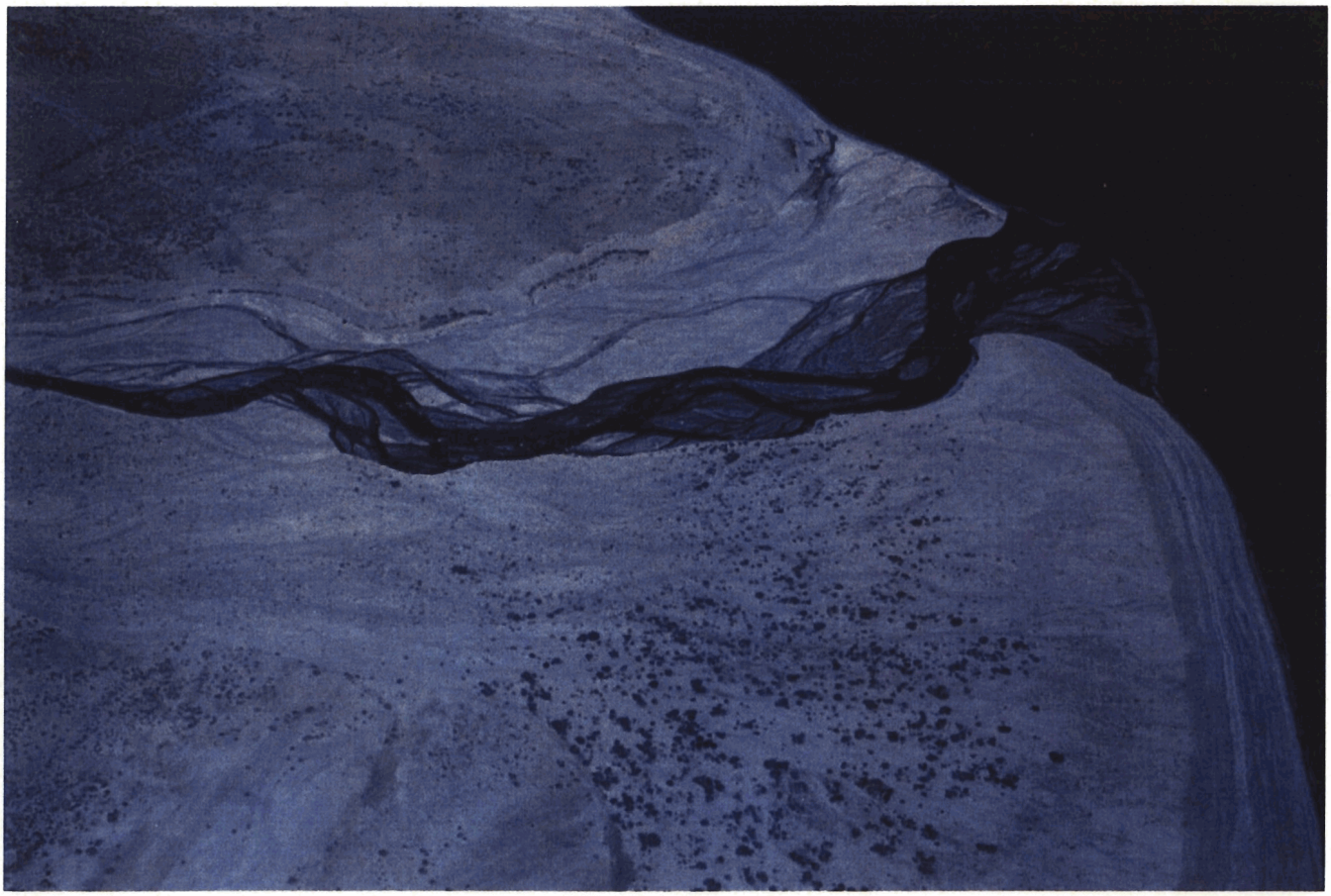


PHOTOGRAPHS

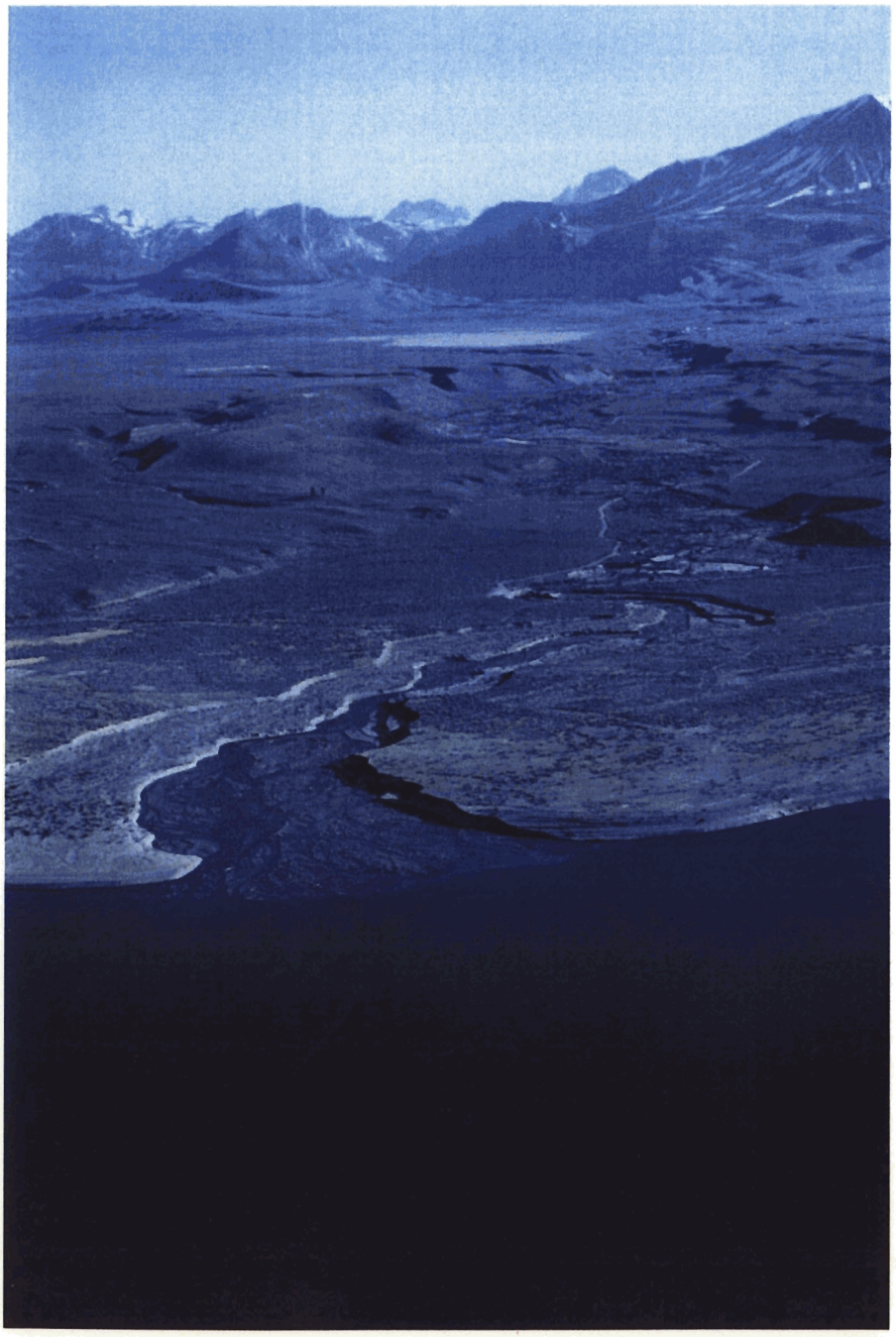
6a. Rush Creek Delta (north up), October 1, 1982 (lake level = 6372.7 feet). The modern subsidiary delta (SD) lying at the mouth of the modern delta trench (DT) was depostited in two stages, the first in 1967-69, and the second in 1980. An ancient delta trench (ADT) and an ancient subsidiary delta (ASD) lie to the west of their modern counterparts. A small confined-onset delta (dashed circle) lies within the confines of the trunk stream canyon. Note also Panum Crater (PC) and the Panum block avalanche (PBA).



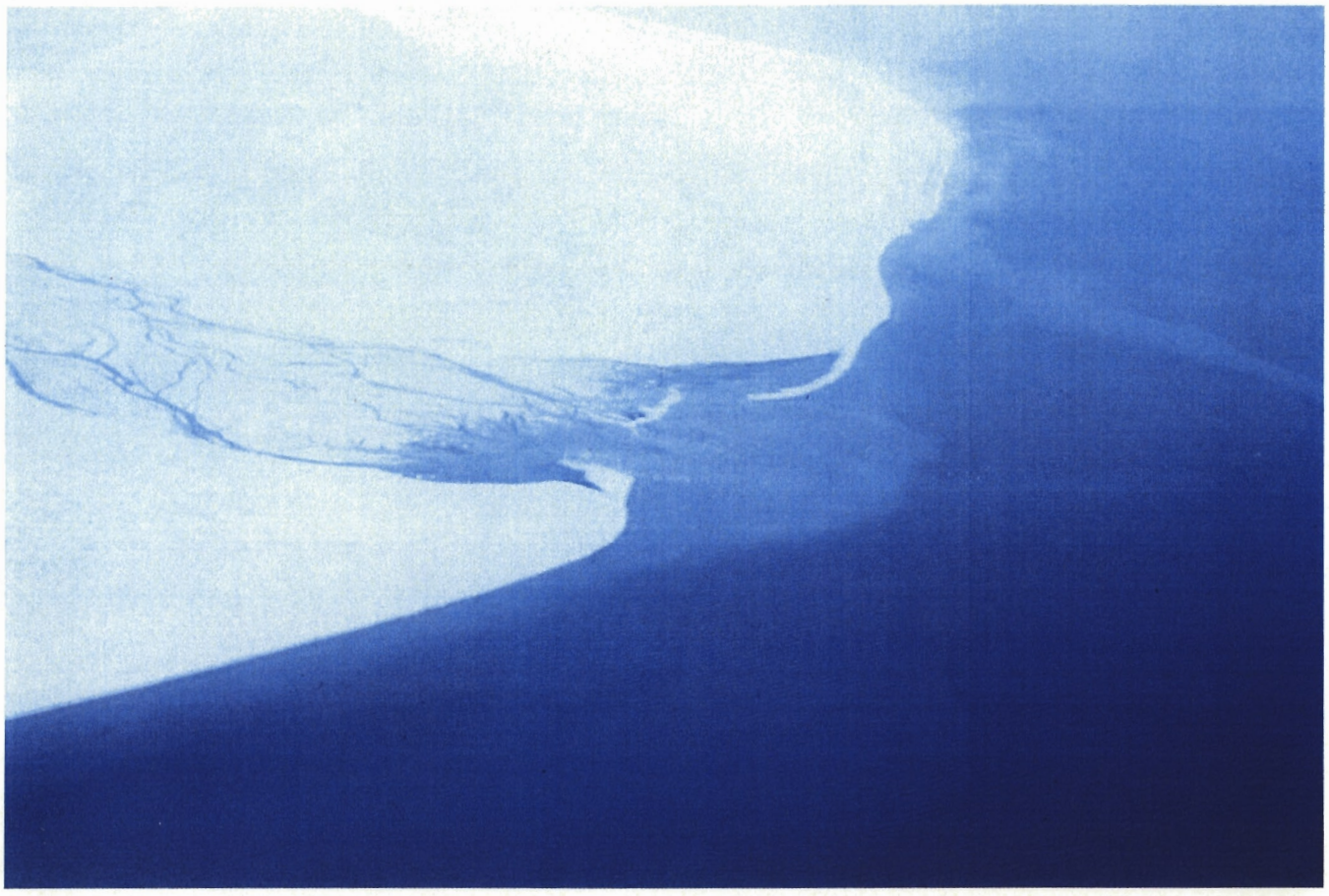
6b. The Rush Creek subsidiary delta, looking west (early summer, 1982). Note that the delta was deposited in two stages --the first in 1967-69 (right foreground), and the second in 1980 (presently occupied by the stream).



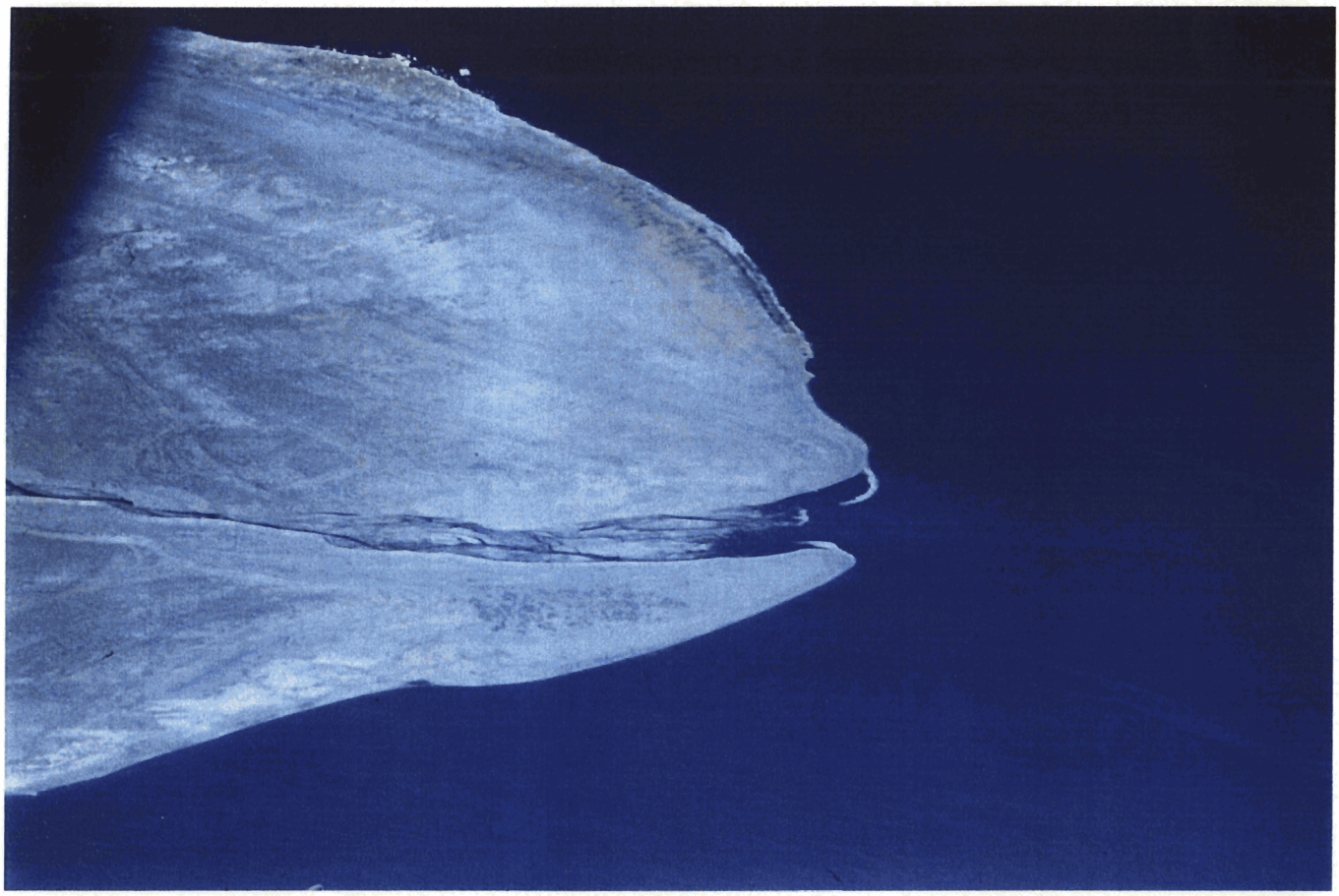
6c. The Rush Creek Delta looking south, August, 1983. Note the prominent trench terrace graded to the level of the 1967-69 stage of the subsidiary delta. The terrace was formed when the stream incised in 1980.



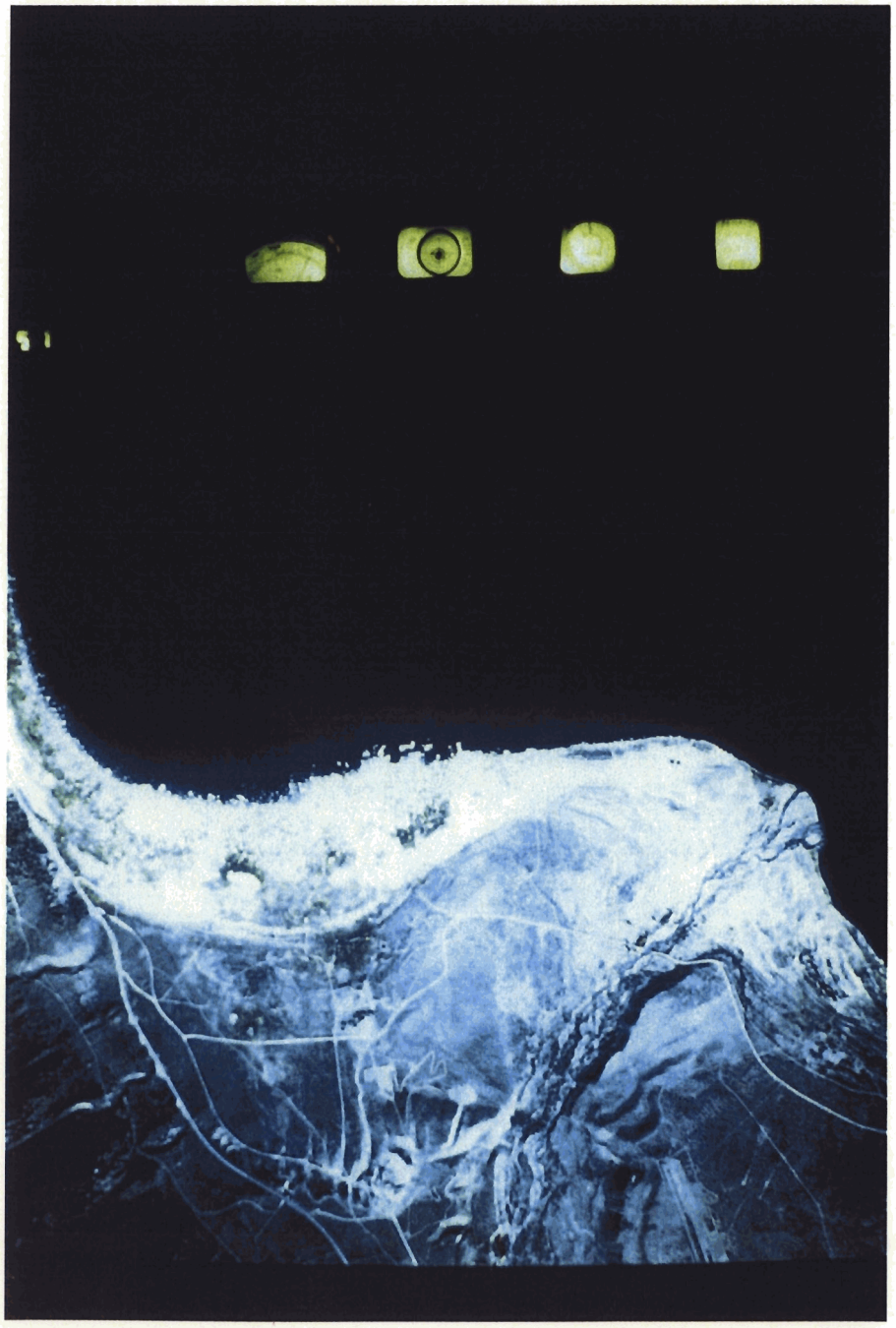
7a. View of the Rush Creek Delta, May, 1984. The recent rise in lake level has inundated the subsidiary delta and flooded the lower reaches of the delta trench. The subaqueous "ghost' of the subsidiary delta is clearly visible. An inset delta is forming within the delta trench. Note too the prominant bay-mouth bars that partially enclose the mouth of the trench.



7b. View of the Rush Creek Delta, May, 1984. See caption, Photo 7a.

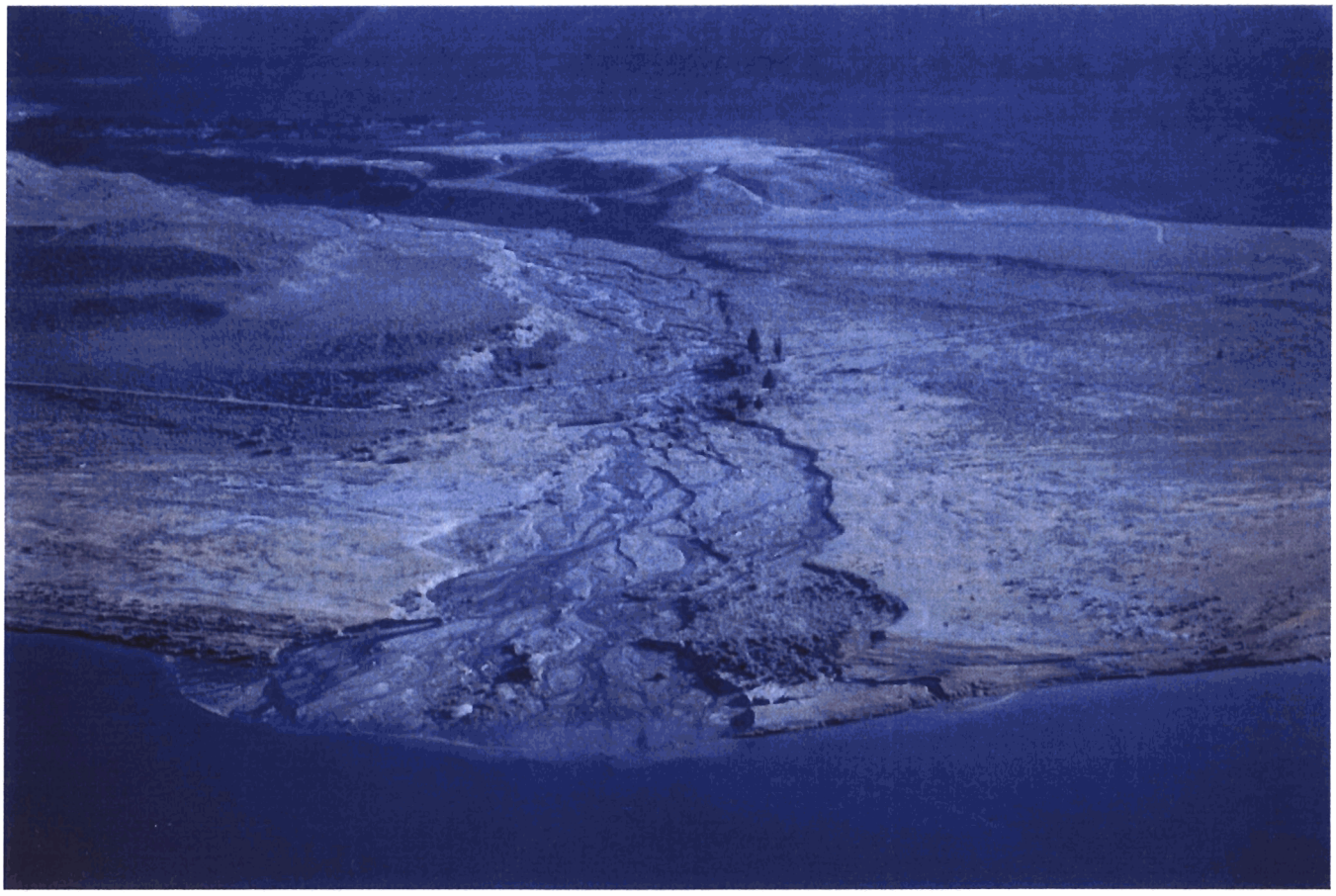


8a. Lee Vining Creek Delta, October 1, 1982 (north up). Note the modern delta trench and the subsidiary delta. Remnants of early-stage subsidiary deltas dating from the incision of the Pleistocene delta (ca. 10,000 BP) are visible in the middle ground to the left of the stream; the Historic High Stand is shown with the black arrow.

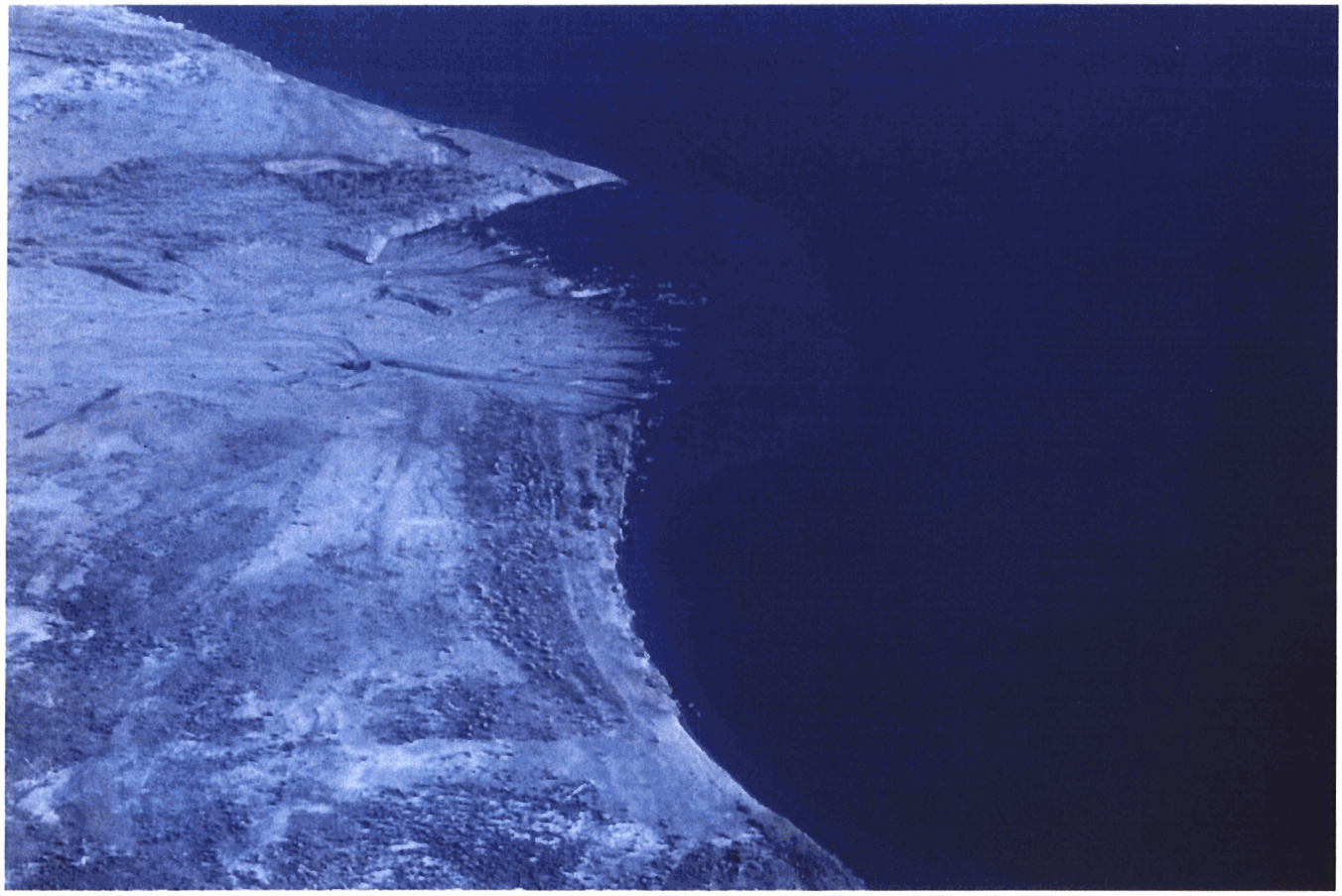


8b. Telephoto shot of the terraces that line the east wall of the trench that bisects the late Pleistocene delta on Lee Vining Creek. The lowermost of these is a fill-terrace graded to a confined-onset delta deposited approximately 3500 BP when the lake stood at an elevation of 6499 feet; the higher features are presumed to be cut-terraces eroded as the lake dropped in early Holocene time.

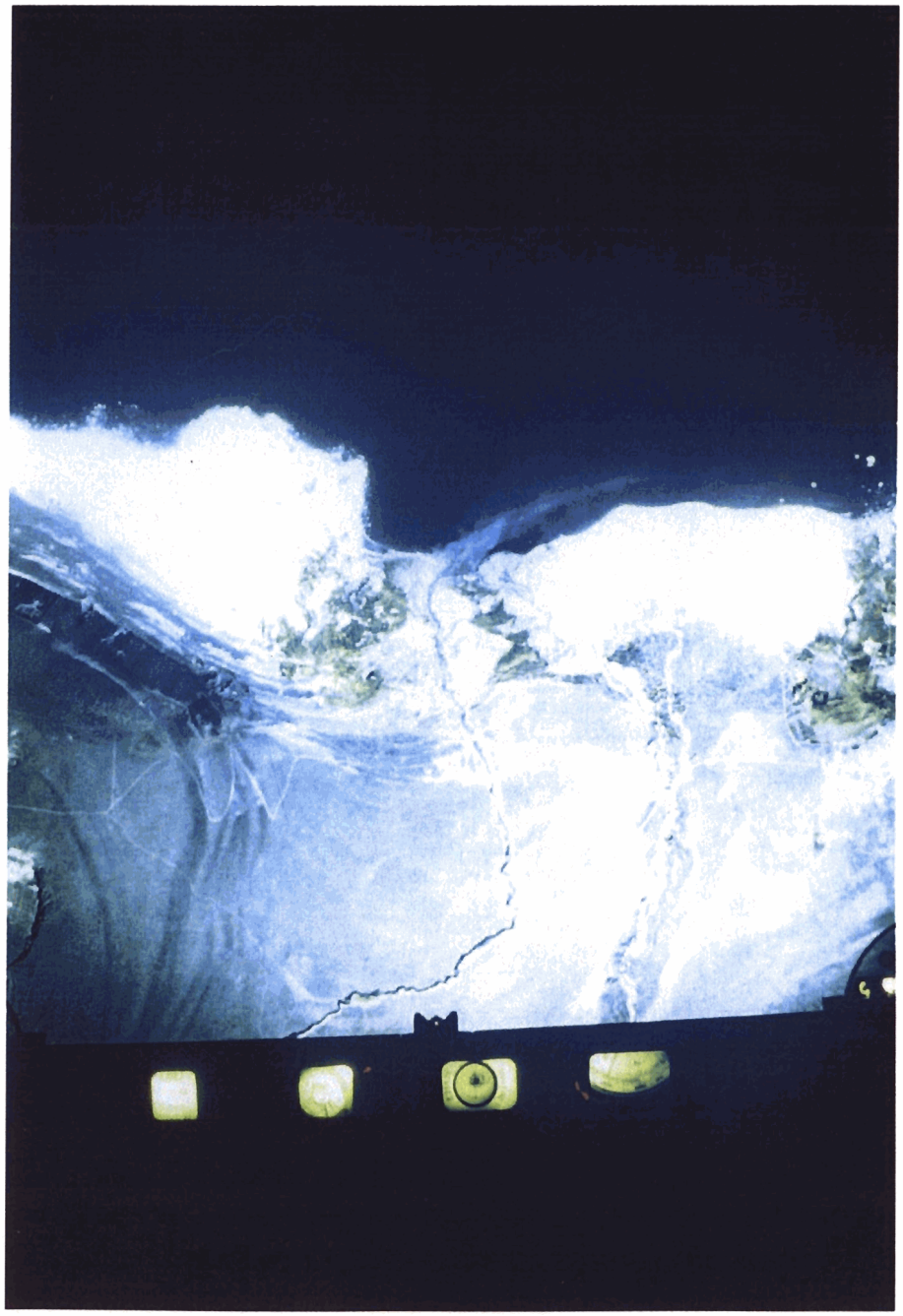
8c. Lee Vining Creek Delta, looking southwest (August, 1983). Remnants of the 1967-69 subsidary delta are preserved along the lateral fringes of the active stage of the subsidiary delta. Remnants of early stages of subsidiary deltas dating from the initial incision of the Pleistocene delta (ca. 10,000 BP) can be seen to the left of the stream; early Holocene cut-terraces are visible in the trunk-stream canyon.



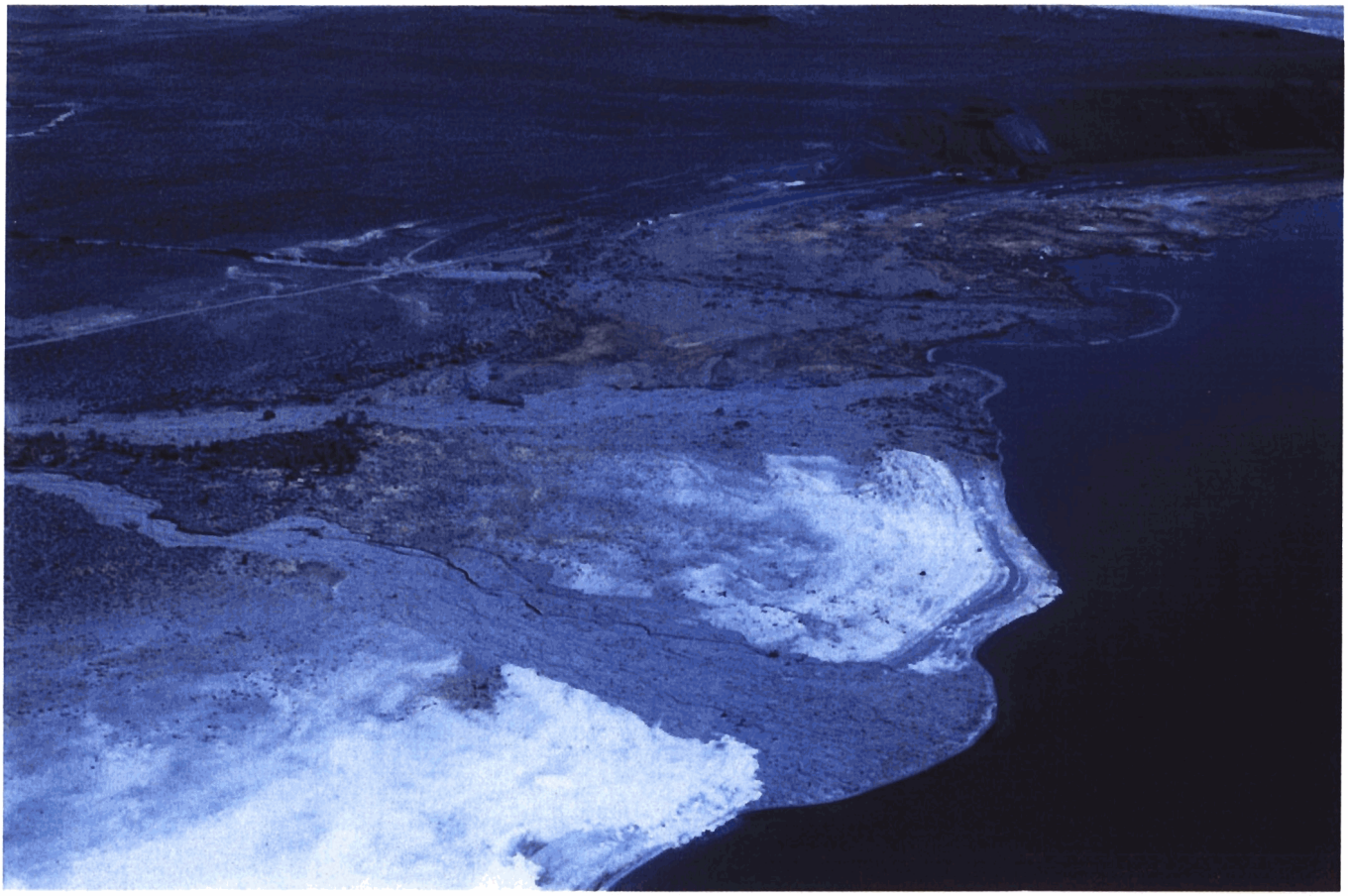
8d. View of the Lee Vining Creek Delta, May, 1984. The recent rise in lake level has inundated the subsidiary delta and flooded the lower reaches of the delta trench.



9a. The Mill (right) and Wilson Creek deltas, October 1, 1982 (north up). Note that the Mill Creek Delta displays two delta trenches and two subsidiary deltas; the easternmost of these is the main channel; the westernmost was cut in 1969 due to an articicially induced avulsion of the stream. The color of these channels constrasts with the white, tufaceous beach pavement that cements the delta at elevations below about 6400 feet. The Wilson Creek delta is likewise the product of artificial manipulation of the Mono streams; under natural conditions a tiny emphemeral watercourse, Wilson Creek has since 1940 carried much of the Mill Creek water that flows from the tailrace of the Southern California Edison hydro-generating plant north of Lundy Canyon. As a result, Wilson Creek has been artificially enlarged at the expense of Mill Creek.



9b. The Mill and Wilson Creek deltas, looking east toward Black Point, October 9, 1986. Avulsion of Mill Creek during the months before this picture was taken widened and deepened the delta trench associated with the avulsion channel (foreground), enlarging the subsidiary delta. Compare the small size of the subsidiary delta that lies at the mouth of the main channel of Mill Creek (mid-photo) with the artificially enlarged Wilson Creek Delta. Note too the prominant bar that has formed on the outer fringe of the Wilson Creek Delta.



10a. Turbid water from Wilson Creek being carried westward by a longshore current into the north end of the Western Embayment. Photo of October 1, 1982 (USFS). Regional wind in the Mono Basin on this day was the same as the prevailing wind (south and southwesterly). This photo, as well as the littoral embankments that project westward from Mill Creek and from the western flank of Black Point, indicate the presence of a backset eddy that is believed to arise due to the deflection of the prevailing winds by Black Point.

SEE PHOTO 9a

PLATE

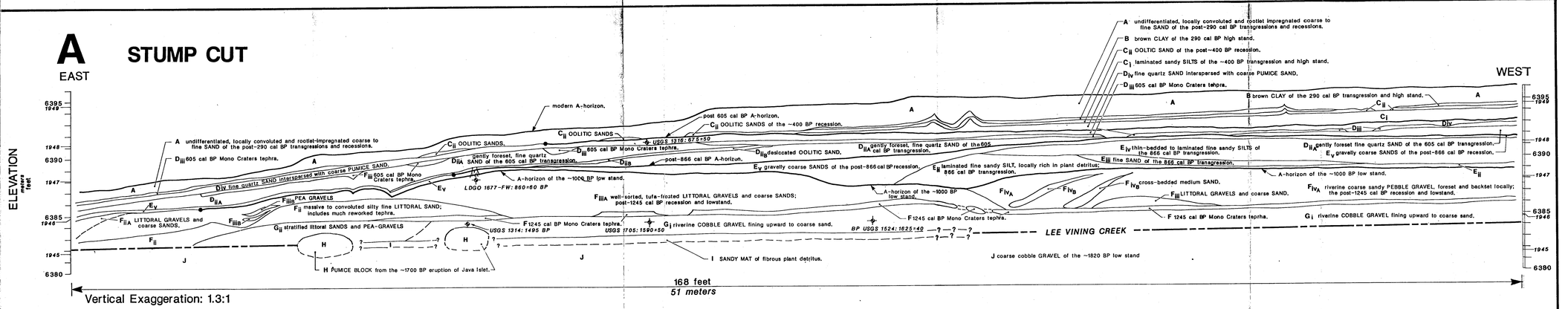
3 STRATIGRAPHY EXPOSED IN THE LEE VINING DELTA TRENCHES

LEGEND

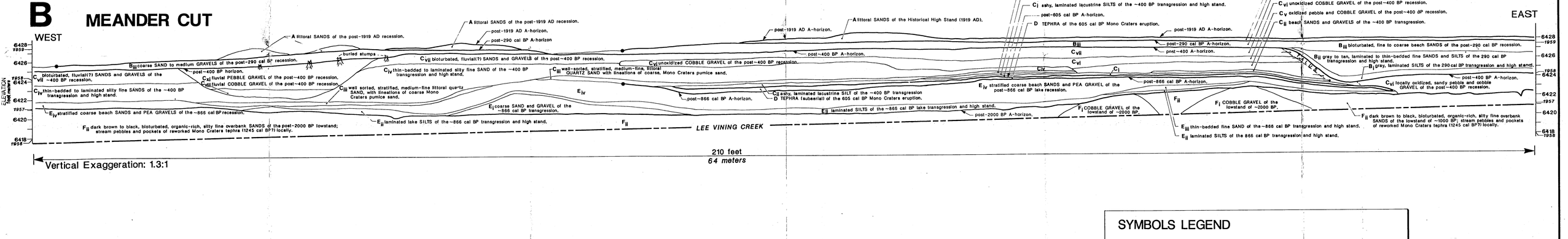
- soil, terminating at dot.
- contact at unconformity
- gradational contact

Note: Subunit designation does not necessarily reflect sequence of deposition.

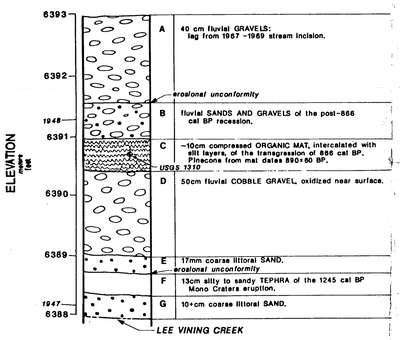
A STUMP CUT



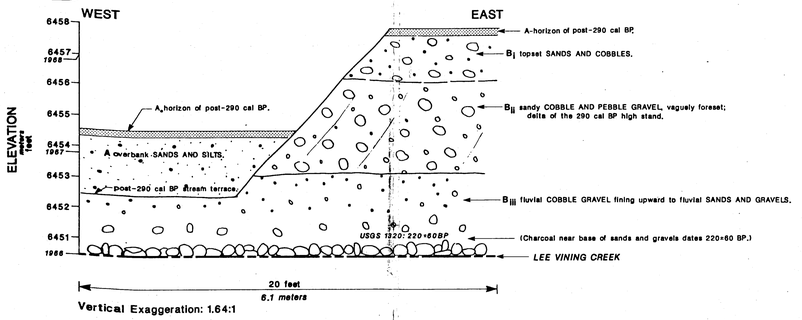
B MEANDER CUT



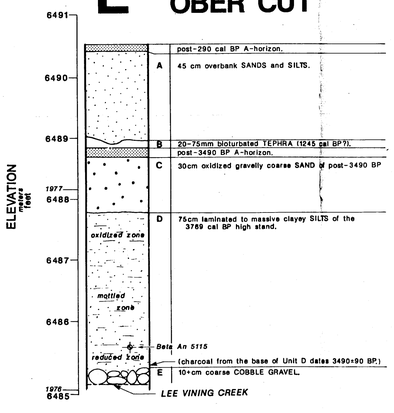
C TERRACE CUT



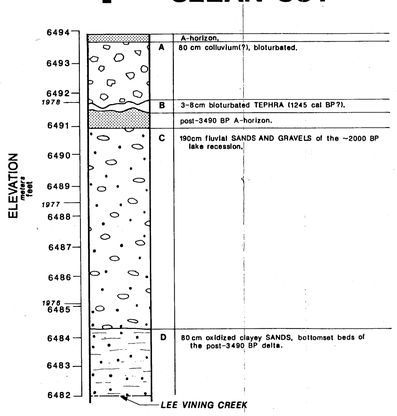
D FLICKER CUT



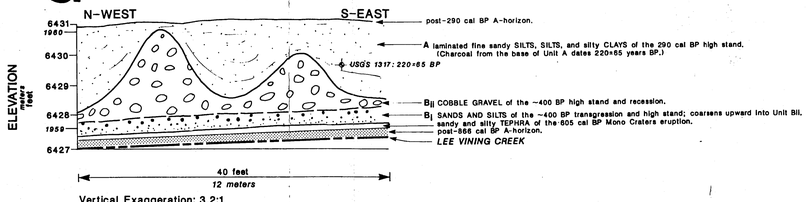
E OBER CUT



F CLEAN CUT



G DOUBLE BERM CUT

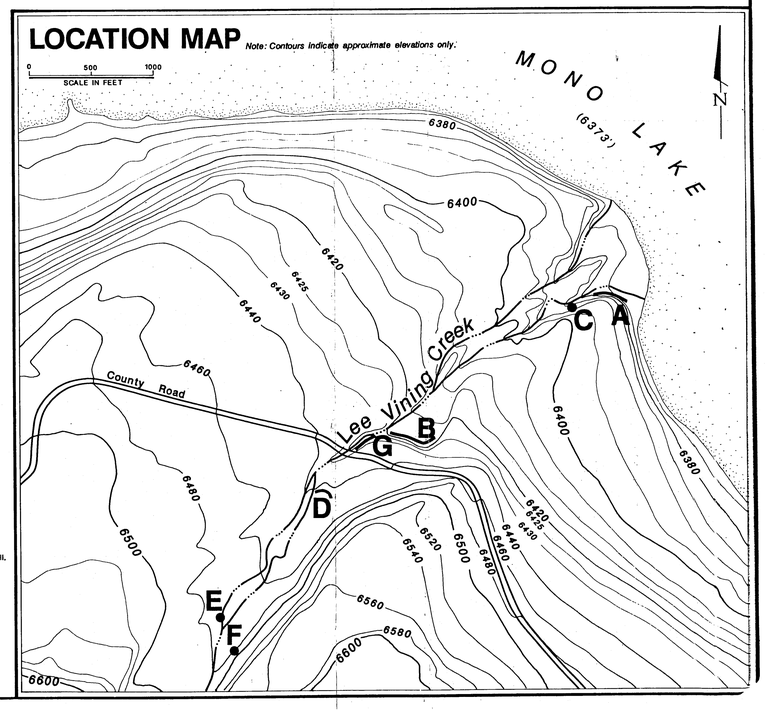


SYMBOLS LEGEND

- SILT
- SAND
- GRAVEL
- COLLUVIUM
- ORGANIC MAT
- CLAY (biogenic ooze)
- TEPHRA
- USGS 1314: 1495 BP — ^{14}C DATE IN YEARS BP

LOCATION MAP

Note: Contours indicate approximate elevations only.



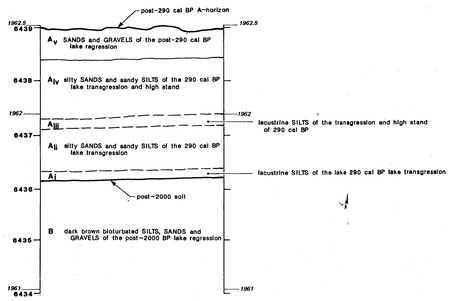
PLATE

4 STRATIGRAPHY EXPOSED IN THE MILL CREEK DELTA TRENCHES

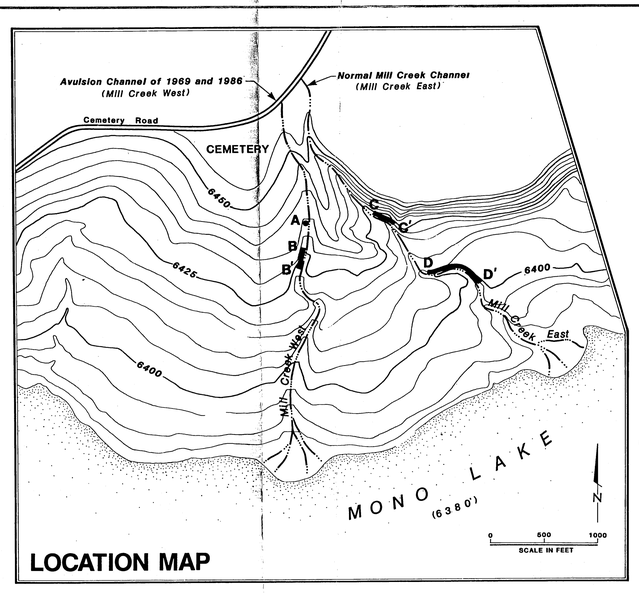
LEGEND

- soil, terminating at dot, queried where uncertain
- contact at unconformity; queried where uncertain
- gradational contact

A HAIR CUT

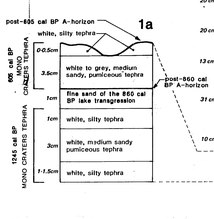


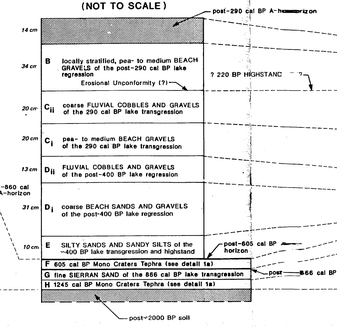
Vertical Exaggeration 12:1



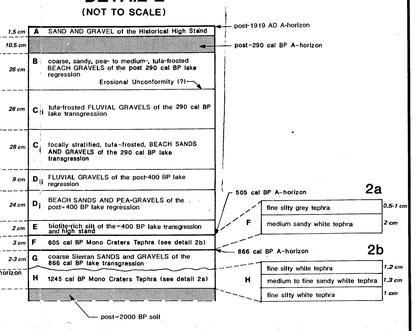
LOCATION MAP

DETAIL 1
(NOT TO SCALE)

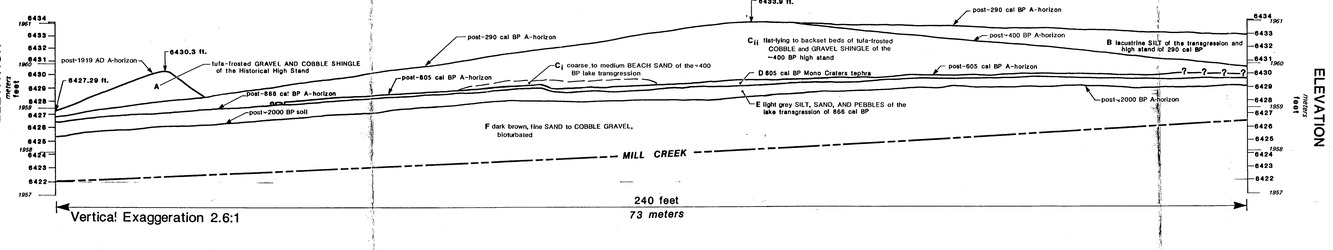




DETAIL 2
(NOT TO SCALE)

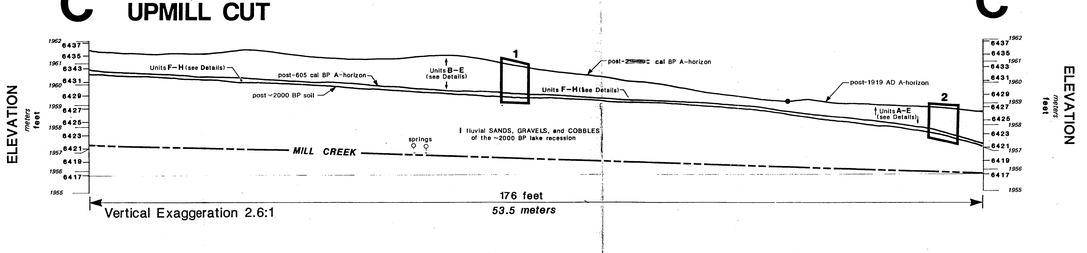


B BERM CUT



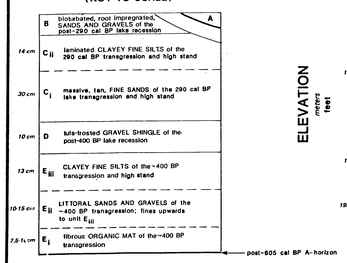
Vertical Exaggeration 2.6:1

C UPMILL CUT

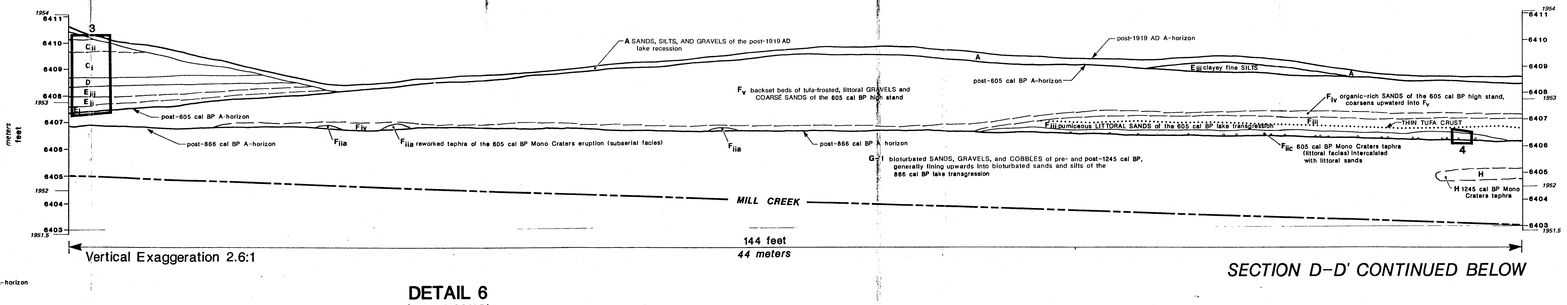


Vertical Exaggeration 2.6:1

DETAIL 3
(NOT TO SCALE)

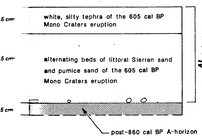


D MILLDOWN CUT (2 PARTS)



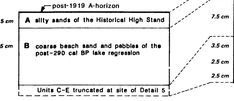
Vertical Exaggeration 2.6:1

DETAIL 4
(NOT TO SCALE)

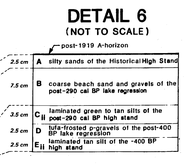


SECTION D–D' CONTINUED BELOW

DETAIL 5
(NOT TO SCALE)



DETAIL 6
(NOT TO SCALE)



MILLDOWN CUT (Cont.)

Vertical Exaggeration 2.6:1

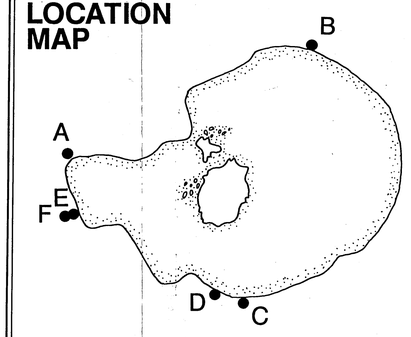
PLATE **5**

STRATIGRAPHY EXPOSED IN MISCELLANEOUS CUTS AND PITS ON THE MONO SHORELANDS

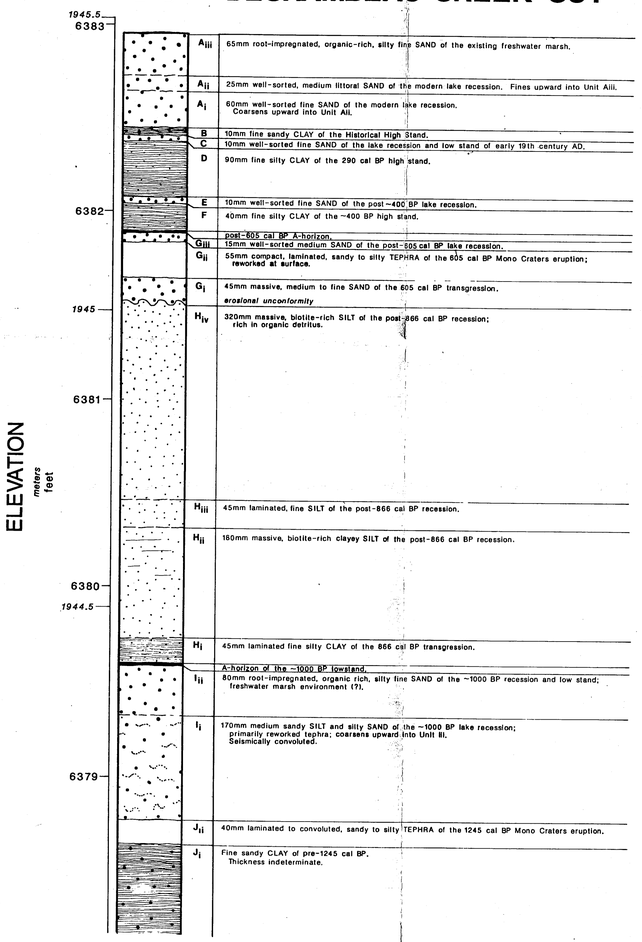
LEGEND

- SALT EFFLORESCENCE
- SAND
- OOLITIC SAND
- SILT
- CONVOLUTED SILTS AND SANDS
- CLAY (biogenic ooze), cracked where dessicated
- RHYOLITIC TEPHRA
- DACITIC TEPHRA

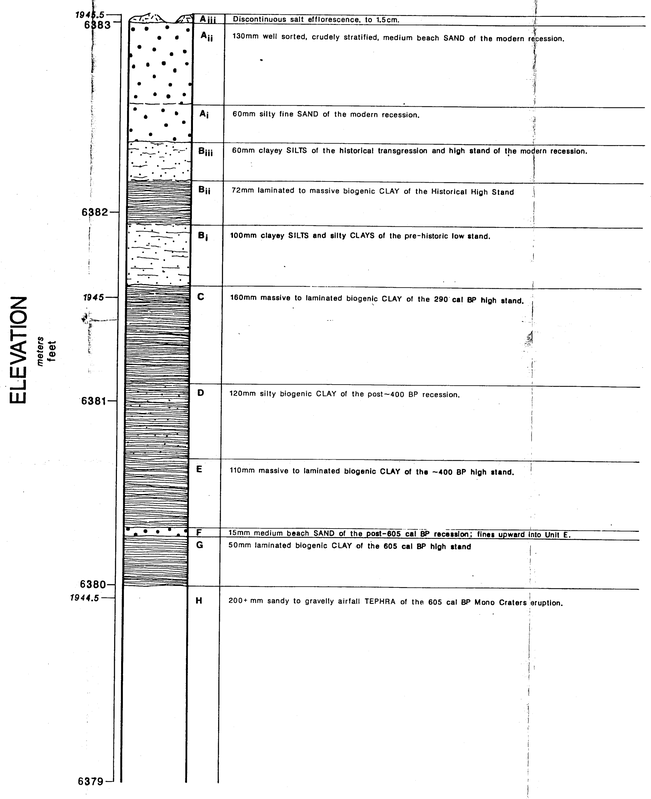
LOCATION MAP



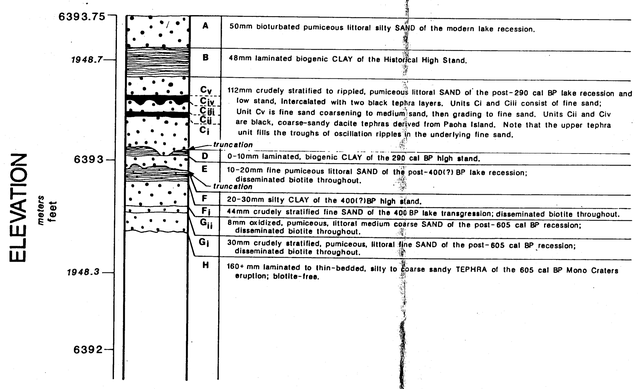
A DECHAMBEAU CREEK CUT



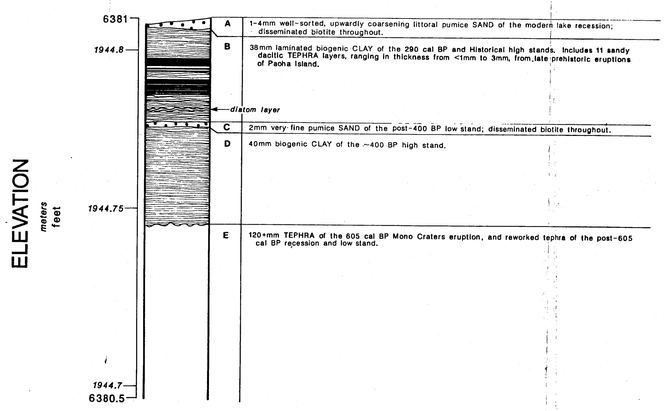
B TEN-MILE ROAD PIT



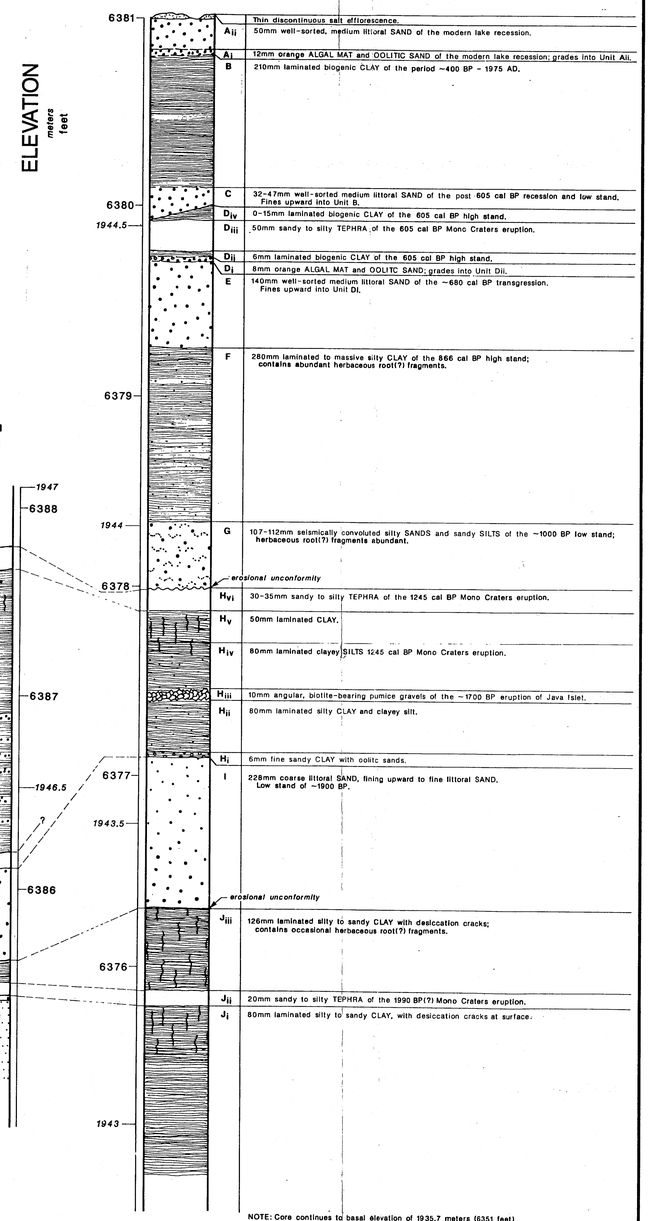
C SOUTH TUFA PIT



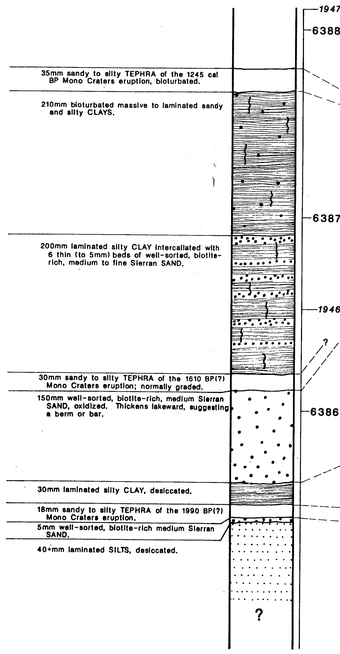
D NAVY BEACH PIT



E MARINA PIT 1



MARINA PIT 2 F



NOTE: Core continues to basal elevation of 1935.7 meters (6351 feet). Sediment consists of laminated CLAY and fine-sandy to silty CLAY, with occasional thin (to 1cm) layers of fine to coarse, well to poorly sorted angular sand and gravel. No tephra layers encountered; no oolitic sands, nor desiccated layers encountered.