# NEVADA BUREAU OF MINES AND GEOLOGY

## *BULLETIN 94*

# PLUVIAL LAKES AND ESTIMATED PLUVIAL CLIMATES OF NEVADA

M. D. MIFFLIN AND M. M. WHEAT

(Prepared in cooperation with Water Resources Center,
Desert Research Institute, University of Nevada System)

**MACKAY SCHOOL OF MINES**
**UNIVERSITY OF NEVADA • RENO**
**1979**

First edition, first printing, 1979: 1500 copies
Composed in IBM Press Roman type at the Nevada
Bureau of Mines and Geology
Printed by Messenger Graphics, Phoenix, Arizona
Composition: Janet Amesbury

---

For sale by Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada, 89557. Price $4.00

## CONTENTS

FOREWORD 5
ACKNOWLEDGEMENTS 5
ABSTRACT 5
INTRODUCTION 6
  Previous Investigations 6
  The Quantitative Problem 8
  The Quantitative Approach 8
  Pluvial Lake Mapping 10
    Mapping Procedure 10
    Age Relationships 11
    Lake Distributions 15
    Basin Overflow in Lahontan Time 27
    Basin Overflow in Pre-Lahontan Time 30
  Modern Climate and Estimation of Pluvial Climate 37
    Precipitation and Temperature 37
    Runoff 39
    Evaporation 40
    Comparison of Climates 40
    Estimated Full Pluvial Climate 43
    Evaluation of Lake Lahontan 43
    Modern Hydrologic Indices 44
    Other Estimates of Pluvial Climates 47
CONCLUSIONS 49
REFERENCES 50
APPENDIX 53
PLATE 1—LATE QUATERNARY PLUVIAL LAKES IN NEVADA in pocket

## FOREWORD

Hydrology of the closed basins in the Great Basin of the Western United States and similar regions of the world, offers one of the most sensitive measures of climatic change.

The prime objective of this study was to evaluate past pluvial paleoclimates of the Nevada portion of the Great Basin. The significance of this type of investigation is becoming more widely recognized with continued human activities generating situations where such knowledge becomes more than academic interest. In the future, major transfers of water on a regional scale may be realized in parts of the Western United States, including the Great Basin. Such transfers could again create large "lakes" in Nevada and provide water availability on a scale similar to pluvial conditions in some of the presently arid basins. Man-induced processes, both planned and unplanned, are producing measurable climate modification, and correlation of hydrologic impact with a given degree of climatic change can be beneficial. Recent evidence of natural climatic shifts, or cycles also makes accurate prediction of associated Great Basin paleoclimatic conditions more important than might have been evisioned a few years ago.

This research is also dependent on another problem not generally recognized until recently. Results of this study relate to the need for safe disposal of radioactive wastes on a time frame of the same scale as the Quaternary. Evidence continues to accumulate indicating that arid zone environments, and associated hydrology, may prove to be the only viable terrestrial environments for long-term disposal (storage) of radioactive wastes. Nevada may become important in radioactive waste disposal considerations; data and interpretations on this subject depend directly on the acceptability and design of such long-term disposal methods. Problems such as these indicate the need for additional research on paleoclimatology and associated paleohydrology of the Great Basin.

## ACKNOWLEDGMENTS

After a number of years of work covering large areas, it is impossible to properly acknowledge all the individuals who supported and cooperated in this research. The effort was supported in part by the U. S. Department of the Interior's Office of Water Research and Technology (Projects A-077-NEV and A-021-NEV), as authorized under the Water Resources Research Act of 1964 (PL-88-379), and in part by the Desert Research Institute, University of Nevada System. Throughout this investigation, perhaps the most significant continued support was from the late G. B. Maxey, then director of the Nevada Center for Water Resources Research. In recognition of his typical interest, encouragement, and support of such studies, his profound impact on the science of hydrogeology, and his love of Nevada and the associated hydrologic challenges, we have suggested that the pluvial lake in Baking Powder Flat (Spring Valley) be named Lake Maxey.

An essential part of this study was the cooperation of the Mackay School of Mines and the Nevada Bureau of Mines personnel (David Slemmons and John Schilling in particular) with respect to aerial photographs. D. F. Schulke of the Desert Research Institute provided invaluable aid in the statistical analyses included in this report. We are also in debt to many previous investigators of the Great Basin Quaternary for an inspiring and valuable discussion. Most significant were J. C. Frye, G. Hardman, C. V. Haynes, and R. B. Morrison. While at times our results may significantly disagree with their interpretations, there is no question as to the value of their efforts in the formulation of our results.

Very careful and constructive reviews of the text were made by Robert Curry, Luna Leopold, and Roger Morrison; their comments and perspectives are greatly appreciated. We also wish to thank Lucy Dunaway Miller for her accurate typing of the manuscript as well as the many individuals throughout Nevada whose hospitality and interest materially aided this study.

## ABSTRACT

The search for shoreline evidence in more than 81 basins of Nevada has yielded recognition of 53 pluvial lakes of Lahontan (Wisconsinan) age, probable shoreline evidence of three pre-Lahontan lakes in three basins, and absence of shoreline features in many basins previously thought to have contained pluvial lakes. Basin areas, basin floor altitudes, overflow relations, and other data have been developed to aid in quantitative analysis of full pluvial climates of Lahontan age in Nevada. Using modern aspects of Great Basin climates and associated hydrology, the authors feel the observed pluvial lake paleohydrology could have been maintained by: a) mean annual temperatures approximately 5°F lower than those of today; b) by corresponding pluvial mean annual precipitation averaging 68 percent over modern precipitation; c) by mean annual pluvial lake evaporation averaging 10 percent less than mean annual modern lake evaporation. The analyses indicate that modern climates of the coolest and moistest parts of Nevada (extreme northwestern Nevada and some parts of the northeast) are likely very similar to the full pluvial climates in parts of southcentral and northwestern Nevada.

Quantitative analysis and lack of shoreline evidence contradict the findings of a number of previously reported pluvial lakes of Lahontan age in southern Nevada, as well as several in other parts of Nevada. Most pluvial lakes refuted here appear to have been identified on the basis of fine-grain deposits related to ground-water discharge during the pluvial climate or mapping of playa deposits. The size and degree of development of mapped pluvial lakes consistently correlate with basin size, lake altitude, latitude of location, and basin closure. A consistent quantitative relation between modern climate and pluvial climate based on pluvial lake distribution and development generally supports the pluvial lake mapping of this study.

Shoreline features of Lahontan age vary in degree of preservation due to post-pluvial terrain stability caused by modern climate variation and associated vegetation density. The best shoreline preservation is generally found in relatively cool, moist parts of Nevada. Limited evidence suggests earlier pluvial lakes of Rye Patch age (Illinoian) were of similar size to the full pluvial extents of Lahontan age lakes. Most well-preserved bolson landforms developed within hydrographically closed basins of Nevada are believed to be no older than Paiute age (Sangamonian), and the majority of surficial deposits are of Lahontan age or younger.

# INTRODUCTION

Nearly every earth scientist who has spent some time in the Great Basin becomes interested in the "pluvial" landforms which abound in many of the topographically closed basins. Fundamental questions of where, when, and why run through the mind as basins are traversed and old shorelines are recognized in the presently arid bolsons. The authors are no exception, and initially began an attempt to better answer "why," believing that the "where" and "when" questions were well in hand. At an early stage of this research it became evident the "where" and "when" questions were not adequately answered in many cases, even after repeated attention by a number of investigators. As a result, the study expanded into mapping the extents of pluvial lakes and establishing age relationships for confident use in quantitative paleoclimate analysis. Much effort was devoted to developing plate 1, a map of late Quaternary pluvial lakes in Nevada, and the Appendix which summarizes both quantitative and qualitative data developed.

Plate 1 depicts accurate extents of pluvial lakes for which surface evidence in the form of shoreline features exist. Unless otherwise stated, the distribution, extent, and statistics of the pluvial lakes shown in plate 1 and the Appendix stem from this work. In many of the mapped pluvial lakes, details of shape or extent are different than on existing maps; further, a number of pluvial lakes shown on existing maps are disclaimed here and a few small pluvial lakes previously overlooked have been added.

The extent of the pluvial lakes reflects the hydrologic response to a past climate in basins with drainage closure. Modern hydrologic response in most of the basins once occupied by a pluvial lake is the occurrence of extremely limited and often ephemeral surface-water features. Usually, the lowlands contain playas, and less frequently, playa lakes. Availability of moisture in excess of evaporation and transpiration is so limited that few perennial surface-water features are present within the boundaries of these basins.

Pluvial lakes formed during paleoclimatic conditions when moisture input exceeded moisture output. In all probability, the development of pluvial lakes was a gradual process of a changing dynamic hydrologic equilibrium occurring over centuries of time. As the accumulation of water filled the lower parts of closed basins, more surface water and phreatophytic vegetation developed, which, in turn, generated greater discharge of moisture from the basins through evaporation and transpiration. Surface areas of the lakes expanded to maximum extents sufficient to evaporate all water in excess of that lost by evapotranspiration within the basins before runoff reached the lakes. Nearly all of the maximum lake extents displayed in plate 1 are believed to be essentially contemporaneous.

Most, if not all, basins containing large pluvial lakes were sinks for both surface water and ground water during pluvial conditions. Water entering either the surface-water or ground-water systems eventually left the basin either by evaporation from the lake surface or by evapotranspiration from surrounding areas of phreatophytes and moist soils. Modern climatic regimens generate more or less similar hydrologic conditions; however, some of the paleolake basins do not have ground-water discharge with modern climatic conditions. A statewide map of the distribution of ground-water flow systems and associated discharge areas shows that most pluvial lake basins in the northern two-thirds of the state are sites of ground-water discharge, but a number of pluvial lake basins in the most southerly extent of oqurrence are no longer ground-water discharge sites (Mifflin, 1968). Extreme aridity and minor ground-water recharge locally cause modern hydrologic conditions of interbasin flow that were less likely to have occurred during the pluvial climate.

In a general sense, parts of the areas once occupied by pluvial lakes now perform the same hydrologic function of moisture discharge but on a greatly reduced scale and in a modified manner. Moisture is lost from the bolsons through ground-water discharge by evapotranspiration from local areas of phreatophytes (usually within the area inundated by the pluvial lakes), by direct evaporation from ephemeral surface water on the playas (usually developed within the pluvial lake area), and through discharge of ground water from the playa areas by evaporation. A few closed basins still contain perennial bodies of standing water such as Pyramid Lake, Walker Lake, and Ruby Marsh due to sources of basin moisture concentrated by surface water systems or by ground-water discharge from limestone springs into a localized area (Ruby Marsh). At the other extreme are basins that discharge relatively small amounts of moisture in the old lake areas through evaporation of ephemeral surface water which occasionally reaches the playas.

Most moisture entering the Great Basin is eventually lost by evaporation or transpiration. Much of the precipitation occurs in amounts and intensities that only infrequently yield sustained runoff in drainage channels or limited ground-water recharge. In the high mountains, major canyons typically contain streams with perennial flow, but only a few western and northern basins have through-flowing streams. There are four important river systems of Nevada and adjacent California which rise in the Sierra Nevada: the Susan, Truckee, Carson, and Walker Rivers. Another important river, the Humboldt, heads in northeastern and northern mountains. All of them drain to northwestern Nevada basins which, during pluvial climatic conditions, were integrated into a large basin, Lahontan. At the present time, all of the streams and rivers of Nevada become losing streams in their lower reaches due to high rates of evapotranspiration and limited moisture input.

## Previous Investigations

Perhaps the earliest recognition of old lake features in Nevada was made by Henry Englemann, a geologist on the Simpson expedition of 1858-1859 (Simpson, 1876) who discussed evidence of a deep lake in the Lahontan Basin. Whitney (1865) also recognized lake deposits in the Great Basin at about the same time. The next recognition and study was G. K. Gilbert's (1875) disclosure of Pleistocene lakes in many closed basins of Nevada. About the same time, King (1878) published a map of Lake Lahontan, and applied the name in recognition of Baron LaHontan, an early adventurer and explorer. These early efforts were followed by I. C. Russell's extensive studies of Lake Lahontan (Russell, 1883, 1885), Mono Valley (Russell, 1889), pluvial lakes in southern Oregon (Russell, 1884), and Nevada in general (Russell, 1885, 1896). Russell's work which constitutes some of the best work done in these areas, was accomplished at a time when access was difficult, good base maps nonexistent, and background information rather sketchy. Russell (1885; 1896, p. 132) also may have been the first to estimate quantitatively, the necessary climate to produce Lake Lahontan. He estimates an increase in mean annual precipitation of about 20 inches if the temperature regimen were the same as today.

A subsequent phase of the study of pluvial lakes in Nevada might be considered the mapping era; it was essentially begun by Russell (1885, 1896) and Gilbert (1890) and was followed by the development of many maps. For a complete list of maps of pluvial lakes in the Great Basin up to 1948, Hubbs and Miller (1948, pp. 146-147, 156-166) give a fine review of the work and the sources of information. The following are investigations of importance in this period: Spurr (1903), Young (1914), Free (1914), Meinzer (1922), Miller (1946), and Hubbs and Miller (1948). Other maps that appeared prior to 1948 are generally compilations which rely heavily upon the Russell and Meinzer maps.

Hubbs and Miller's work is an invaluable reference; their use of names is followed whenever appropriate in this study. As biologists they rely heavily upon geologic interpretations of others; the net result is a compilation of nearly every pluvial lake in the Great Basin known up to that time, and thus includes lakes based on what we believe to be interpretive errors of earlier investigators. Hubbs and Miller (1948, pp. 145-146) also believe many of their mapped pluvial lakes were not perennial:

> Many of the smaller lakes, particularly in the southern part of the Great Basin, may have been ephemeral even at the height of the Pluvial period. Such qualifications are indicated in the table and in the text, whenever these indefinite lakes are mentioned. The policy has been to include on the map all but the very smallest of the playas that are shown on maps, on the theory (pp. 28-29) that nearly all such depressions probably contained at least shallow and semipermanent Pluvial Lakes.

Hubbs and Miller's objective of comparing hydrographic history with respect to the distribution of fish within the Great Basin led them to the above policy; however, the objective of this study, that of identifying pluvial lakes in equilibrium with the paleoclimate, requires omission of playa lakes. In a recently published study, Hubbs and others (1974) have greatly extended earlier work on relict fish in an area centering in east-central Nevada. Although They include considerable discussion with respect to physiographic evidence for overflow or basin closure of a number of basins, their mapping criteria (and interpretations in some cases) are inconsistent with this study.

Two more recently compiled maps are well known. Both maps have been influenced by earlier work, and thus, errors of interpretation were incorporated into the maps. A map by Feth (1961) is purported to be a compilation of probable extents of all reported Pleistocene lakes and is totally inadequate for the purposes of this research with respect to time relationships or criteria of mapping. The other and most widely used map, by Snyder and others (1964), was initially assumed accurate enough for quantitative hydrologic analysis in this study; it was compiled at a time when aerial photographs and AMS 1:250,000 base maps, as well as some topographic map coverage at a scale of 1:62,500 and 40 feet or smaller contour intervals, were available. Early in our reconnaissance work, however, we frequently differed with respect to interpretation of lake extent, existence, and overflow history. Such disagreements were so abundant and significant to quantitative estimates of the pluvial paleoclimate that a complete basin-by-basin photo-interpretation mapping effort was made to obtain pluvial lake areas, sites of actual lakes, and firm evidence of basin overflow. The map and appended data of Snyder and others (1964) were used to help establish the names and the basins to be studied, and in general, the hydrography of the Great Basin. Little quantitative data were taken from their work. The State of Nevada (1972) published the Nevada portion of their map, unmodified, as part of the Hydrologic Atlas of Nevada.

There are other recently published maps of pluvial lakes in Nevada. Morrison (1965a, p. 266) compiled a map of pluvial lakes and areas of alpine glaciation in the Great Basin. Much of his pluvial lake data came from previously mentioned sources and contains several errors. The map is also of inadequate scale for the objectives of this study; its main contribution here is the depiction of areas of known alpine glaciation, leaving little doubt as to the minor importance of alpine glaciation to the hydrologic regimes of most Great Basin pluvial lakes.

Studies which provide the basis for age of mapped pluvial features are important departure points for age correlations made in this study. Though many earlier workers correctly deduced that most of the pluvial landforms of the great Basin were correlative with alpine glaciation of the bordering ranges and the latest major alpine glaciation was correlative with the Wisconsinan continental glaciation of the Midwest, little confirming evidence was available until radiometric dating techniques became available. Additionally, localized detailed stratigraphic work and associated soil stratigraphy have permitted extension of geomorphic and stratigraphic relationships beyond better studied "control" areas. The most important work along these two lines began with the Broecker and Orr's (1958) radiocarbon studies of Lake Lahontan and Lake Bonneville, which confirmed that both pluvial lakes were, at least in part, Wisconsinan in age. Subsequent work (Broecker and Walton, 1959; Broecker and Kaufman, 1965; Born, 1974) substantiates and elaborates earlier conclusions.

In southern Nevada, another study provides both detailed stratigraphy, including soil stratigraphy, and radiometric control. Haynes' (1967) geological work of the Tule Springs archaeological investigation provides detailed data in the Las Vegas Wash area located about seven miles north of Las Vegas. His work is particularly interesting due to developed radiocarbon data from Wisconsinan equivalent or younger deposits. He also recognized up to 15 feet of lacustrine sediments of "Pluvial Lake Las Vegas" extending from Corn Creek Springs in the northwest to Craig Hills or beyond, to the southeast (Haynes, 1967, p. 78). Haynes dates these sediments, interpreted as lacustrine, as pre-22,600 years B.P. and correlates them with the Midwest Woodfordian deposits. In addition, other geologists, beginning with some early workers and extending to Maxey and Jameson (1948), Bowyer and others (1958), and Longwell (1961), considered these and similar deposits of the region to be lacustrine.

The origin of several such areas of "lacustrine" sediments in southern Nevada is a critical point not only in the validity and accuracy of the extent of pluvial lakes in plate but also in the reliability of adopted criteria used in this study for mapping Wisconsinan equivalent (or older) pluvial lakes in the Great Basin. We believe these southern Nevada sediments, which have been called lacustrine, were more likely formed in paludal and discharge playa environments.

Studies of paleosols, lacustrine stratigraphy, and correlation of sequences by Morrison (1964a, b), Morrison and others (1965, pp. 28-32, 38-48), Morrison (1965a) and Morrison and Frye (1965) have been invaluable to this study. These latter studies, as well as similar efforts in Utah in the Lake Bonneville deposits, such as Morrison (1965b), provided the background information for both photo and field interpretation of shoreline age and sediment character of lacustrine features in Nevada. Additionally, these studies have demonstrated the generally, well-sorted nature of lacustrine deposits associated with deep lakes, the existence and meaning of paleosols of varying degrees of development which aid in separating pre-Wisconsinan, early Wisconsinan, and late Wisconsinan equivalent sediments, as well as the degree of preservation of high energy lacustrine shore deposits of known age. A study of isostatic rebound in the Lahontan Basin (Mifflin and Wheat, 1971) also lends important perspective to age of shorelines in other Nevada basins. Both early and late Wisconsinan equivalent maximum shorelines have been noted and studied in various parts of the Lahontan Basin.

Pluvial paleoclimates also have received considerable attention. Jones (1925) made a paleoclimate estimate similar to Russell's. Antevs (1952) estimated a mean annual full pluvial temperature of 5°F lower than the modern temperature and apparently is the only modern investigator that favored a temperature difference between modern and pluvial climates similar to quantitative results of this study. Broecker and Orr (1958, p. 1029-1031) concluded a 5°C (9°F) temperature drop would be adequate to restore Lake Lahontan to its maximum level after establishing a continuity equation (similar to Equation 4 in this study), and then assuming evaporation would decrease and runoff would increase. Snyder and Langbein (1962) studied pluvial Spring Lake in eastcentral Nevada and concluded, (on the basis of modern climatic parameters and evaluation of a continuity equation similar to Equation 4), a probable decrease of 9°F mean annual temperature and an increase of 8 inches of precipitation. Morrison (1965a, p. 267) suggests an 8°F to 15°F decrease in mean annual temperature and more moisture, but does not elaborate on his method of derivation. Of the mentioned estimates, Snyder and Langbein (1962) are the most quantitatively explicit in justifying their estimates.

There are other recent studies that address the same objective as this study. Birkeland (1969), on the basis of clay mineralogy in paleosols in a part of the Lahontan Basin, suggests no major differences in climate since their formation. Galloway (1970) comes to an extremely different conclusion of a 10°C (18°F) lower temperature and less precipitation by studying "solifluction" deposits in New Mexico and pluvial lake size in the Great Basin. Curry (1969), on the basis of Sierra Nevada snowfall analysis, favors less extreme differences more compatible to the order of magnitude derived in this study. Weide (1974), using analytical techniques similar to Snyder and Langbein (1962), and Leopold (1951) applied to pluvial lakes in southcentral Oregon, favors a temperature decrease of 8°F, with 6 inches more precipitation.

## The Quantitative Problem

There have been numerous attempts to determine Pleistocene climates ever since evidence of differences between modern and past climates became recognized. Recently, Beaty (1970, 1971) questioned the generally accepted concepts of wetter "pluvial" climates after a study of age and rate of accumulation of alluvial fans of the White Mountains in California. He states:

> No one today seriously doubts the reality of past climatic changes, but those who interpret nonmeteorological evidence in terms of climate change have a responsibility to demonstrate, on meteorological grounds, the feasibility of their proposed climatic models.

Beaty believes the models must fit within the limits of what is known about atmospheric behavior and must reasonably fit the geologic, biologic, and hydrologic evidence. This study is mainly within the context of the constraints provided by geologic, climatic, and hydrologic evidence.

Most authorities favor the interpretation of cooler and perhaps moister conditions in temperature latitudes during full glacial climates. Unfortunately, most, if not all estimates of past climate require certain basic assumptions to quantify paleoclimate in terms of precipitation and temperature, because much of the evidence used to estimate climate is dependent upon both variables of climate. Thus, disagreements as to the degree of decrease in temperature or increase in precipitation stem mostly from differing assumptions adopted in quantitative estimation. There are few direct measures of paleotemperature and even fewer direct measures of precipitation.

## The Quantitative Approach

The fundamental concept of lake stage and associated lake size relating to inflow and outflow dates back to at least the mid-1800's. One terrestrial environment where quantitative estimates of paleoclimates (particularly pluvial paleoclimates) can be made based on this concept is hydrographically closed basins in arid areas. In such regions as the Great Basin closed basins were often the sites of pluvial lakes.

Generally, it is believed the maximum lake stages probably correlate with the extreme climatic changes. This assumption, however, could be in error to some degree in that the climatically induced changes in the hydrologic cycle and the associated high lake stands may not reflect the extreme conditions of climate with respect to temperature. Therefore, by definition, in this study pluvial refers to conditions of relative increases of moisture storage and "full pluvial climate" is used in the sense of maximum conditions of moisture storage within the basins.

Change in climate is measured by apparent differences among modern climatic measures (mean annual precipitation, temperature, and evaporation from deep bodies of water). This approach suggests the use of long-term records because of short-term variations of considerable magnitude common to the modern climates of the Great Basin. This in turn, greatly reduces the data base of modern climatic data and suggests the adoption of U. S. Weather Bureau Climatic Division data (1931-60). Areas with more or less similar climate have been delineated to form what has been called Climatic Divisions. The mean of long-term data from the individual stations within the Climatic Division forms the Climatic Division mean values, and these values have been adopted in this study to characterize the modern climates in the Great Basin. In figures and tables of the text, a number of Climatic Division mean values have been used, and these include the following climatic divisions:

| | |
|---|---|
| High Plateau of Oregon | (HPO) |
| Southcentral Oregon | (SCO) |
| Southeastern Oregon | (SEO) |
| Northern Interior Basins in California | (NIB) |
| Northwestern Nevada | (NWN) |
| Northeastern Nevada | (NEN) |
| Southcentral Nevada | (SCN) |
| Southern Nevada | (SN) |
| Western Utah | (WU) |
| Southcentral Utah | (SCU) |

In addition, the extreme northwestern part of Nevada, with a climatic division of southcentral Oregon, has also been called Extreme Northwestern Nevada (ENWN).

The size of a pluvial lake (surface area) is a quantitative measure of paleoclimate during prolonged periods of equilibrium of the pluvial lakes because it represents moisture leaving the lake:

Moisture into the lake = Moisture out

or

$$(ATR_T) + (ALPO = ALEL$$

or by rearranging and factoring,

$$ATRT = AL(EL — P_L) \qquad (1)$$

where,

$A_T$ = tributary area of the basin (total basin area minus lake area),

$R_T$ = combined runoff of surface and ground water per unit area per unit of time,

AL = maximum lake area as indicated by the highest shore,

$P_L$ = precipitation directly upon the lake per unit area per unit of time, and

$E_L$ = evaporation of the lake per unit area per unit of time.

A useful form of Equation 1 is obtained when the runoff ($R_T$) is stated in terms of climatic parameters; average basin precipitation per unit area per unit of time ($P_L$) minus average tributary basin evapotranspiration per unit area per unit of time ($ET_T$):

$$R_T = P_L — ET_T \qquad (2)$$

By substitution of Equation 2 into Equation 1, the continuity equation is put into terms of the product of measurable paleohydrologic areas and quasiclimatic parameters:

$$AT(PT — ETT) = AL(EL — P_L) \qquad (3)$$

It is important to differentiate between the general character of each parameter of Equation 3. The area terms ($A_T$, $A_L$) are directly measurable paleohydrologic parameters preserved as physiographic features at the land surface; in other words, these numbers are developed from the geomorphic evidence, summarized in plate 1 and the Appendix of this study. The terms embodying characteristics of climate ($P_T$ $P_L$ $ET_T$ $E_L$ $R_T$) are, in the paleohydrologic sense, measured only by indirect means and all may be influenced by paleotemperature; therefore, Equations 1 and 3 are written to make this distinction by establishing a pluvial hydrologic index (Z) of the closed basins:

$$Z = \frac{A_L}{A_T} = \frac{P_T \quad ET_T}{E_L - P_L} = \frac{R_T}{E_L - P_L} \qquad (4)$$

The relation of the lake area to the basin area quantified by the "Pluvial Hydrologic Index" (here informally named) has led most investigators of pluvial lakes to call upon cooler and wetter climates to explain the so-called pluvial features in the western states (Russell, 1885, 1896; Gilbert, 1890; Meinzer, 1922; Jones, 1925; Hubbs and Miller, 1948; Leopold, 1951; Broecker and Orr, 1958; Snyder and Langbein, 1962; Snyder and others, 1964; Reeves, 1968). Indeed, standing upon the highest wave cut terrace of Lake Lahontan or Lake Bonneville, and looking out over hundreds of square miles of desert (covered about twelve thousand years ago by several hundred feet of water), makes even the most conservative investigator a believer of past "wetter" conditions, if not "cooler" conditions. The question generally remains, however, how much "cooler" or "wetter" were the pluvial climates that gave rise to the pluvial lakes and related features? Occasionally, dissenting voices even challenge the idea of significantly "wetter" pluvial climates.

A pluvial hydrologic index (Z) is a quantitative measure of hydrologic response to pluvial climatic conditions, and is quantitatively related to commonly used modern climatic indicators such as mean annual temperature, evaporation, and precipitation. In order to identify the measurable physiographic and geographic parameters that influence the value of the pluvial hydrologic indices, 33 nonoverflowing pluvial lakes were tested by regression analysis using latitude, longitude, weighted basin elevations, and lake altitude as independent variables. It was found that lake altitude and latitude accounted for 75 percent of the variance of Z. Figure 1 is a double plot of the two significant parameters with respect to the mean of pluvial hydrologic indices in various regions of Nevada (grouping of these basins into regions is discussed in a later section). Two trends of the regionalized means (mean lake altitude/mean hydrologic index and mean latitude/mean hydrologic index) demonstrate the approximate rate of variance of the two independent parameters. The general influence of one degree of latitude change on the pluvial hydrologic index is about the same as a 500 feet change in altitude. An additional note of interest is the apparent linear aspects of the two trends when plotted on semilog coordinates of Figure 1. This suggests exponential functions of both parameters with respect to indices. Thus, the manner in which temperature, lake evaporation, precipitation, and runoff vary with respect to latitude and lake altitude combine into exponential variance of the pluvial hydrologic index. Relationships of the parameters of Equation 4, discussed in a section to follow, tend to demonstrate this.

Two additional aspects were developed (modern basin

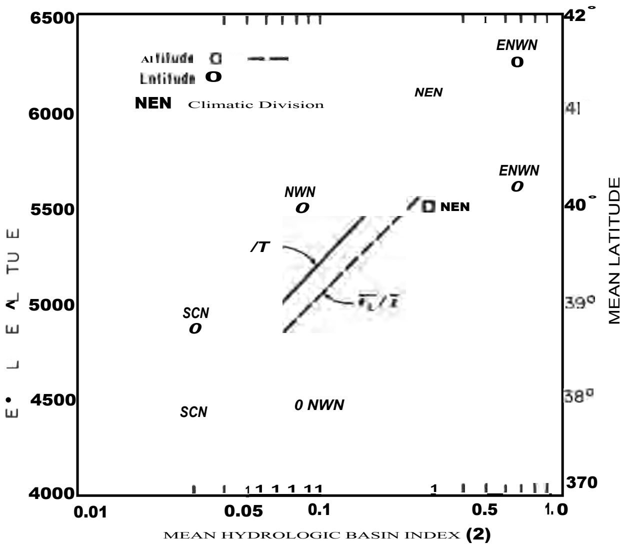

FIGURE 1. Relation of regionalized mean hydrologic basin indices, lake altitudes, and basin latitudes of Climatic Divisions which contained pluvial lakes.

precipitation and weighted basin altitude) but are not included in the Appendix. It was found that quantitative estimates of modern basin precipitation, as developed from the available precipitation map, yielded erratic correlation with the magnitude of measured pluvial indices. Uncertainty in accuracy of the data suggested abandonment of these data for analysis. The precipitation map of Nevada (Nevada Hydrologic Atlas, 1972) was developed by use of very sparse station data and judgment extrapolation (construction of isohyetal lines through use of altitude of terrain and vegetal patterns, as well as sparse runoff data). The weighted basin elevation data, as expected, had a correlation of 0.905 with lake altitude, i.e., a very high interdependence. While the elevation data did enter the prediction equation at step 3, it did not, however, add significantly to the variance and decreased the "F" ratio from 45.4 to 29.3.

The 75 percent of explained variance leaves a rather important amount of unexplained variance of the pluvial hydrologic indices. Error in lake area could be important; for example, if Lake Franklin (56 in plate 1) was 10 percent smaller (435 $\text{mi}^2$ instead of 483 $\text{mi}^2$) the pluvial hydrologic index would be reduced 16 percent (0.61 reduced to 0.51). Local variations in climates caused by rainshadow effects and differences in basin configuration which permit greatly increased or decreased evapotranspiration losses are likely in some cases but very difficult to quantitatively evaluate. Another important factor likely to have been operating was important amounts of interbasin flow of groundwater in the carbonate rock province of Nevada (Mifflin, 1968). It is possible that modern patterns of interbasin flows were changed, but magnitude of the flow was similar or perhaps even greater in a few areas. Jakes Valley (35 in plate 1) and Long Valley (44 in plate 1) provide interesting examples. Currently, Jakes Valley is estimated to leak between 13,000 to 17,000 acre-ft/yr groundwater to another basin, and the pluvial hydrologic index of 0.19 is considerably smaller than adjacent basins of similar character. Long Valley, immediately to the north, is estimated to currently leak about 8,000 acre-ft/yr but displays a pluvial hydrologic index of 0.41. If the 13,000 to 17,000 acre-ft/yr Jakes Valley loss is subtracted from Long Valley and added to Jakes Valley and new indices are determined by using pluvial climatic parameters developed in following sections of this study, four contiguous basins of similar character yield the following indices:

Butte (9 in plate 1) 0.28
Jakes (35 in plate 1) 0.27 or 0.29 (adjusted)
Long (44 in plate 1) 0.36 or 0.34 (adjusted)
Newark (49 in plate 1) 0.28

This analysis suggests that Long Valley may have been a regional sink for interbasin flow of groundwater during pluvial climates, and that the magnitudes of interbasin flows may have been similar to those estimated for modern climates, but not necessarily in the same directions or pattern. Several other eastern Nevada basins may have lost enough moisture through interbasin groundwater flow to reduce the pluvial hydrologic indices to recognizable low values:

Antelope (4 in plate 1) 0.16
Spring (Baking Powder, 61 in plate 1) 0.17
Stevens (63 in plate 1) 0.11

In the case of Spring there is firm evidence of some interbasin flow to the southeast at the present time.

## Pluvial Lake Mapping

The heart of this study is physiographic information on the distribution of pluvial lakes in Nevada. Plate 1 and the Appendix have been developed to accurately describe the paleohydrologic response of each hydrographically closed basin during the last full pluvial climate, that is, the time when the pluvial lakes were at fullest development. In order to compare lake size throughout Nevada to arrive at paleoclimate estimates, age relationships were a prime consideration. The use of Equation 4 also requires accuracy in lake and basin area. A further critical requirement in the pluvial hydrologic response data was recognition of lake overflow which, if it occurred, limited the measured pluvial hydrologic index to a value smaller than the potential index that would have occurred if closure had been perfect. Data of lesser importance in accuracy, but of value in the evaluation of Equation 4 were lake altitudes, basin floor altitude, latitude, and characteristics of shoreline features (preservation and development). The aforementioned physical aspects were prime objectives at some stage of this study.

### Mapping Procedure

The techniques used in the lake mapping and data gathering part of the study began with the location and collection of all available topographic base maps (AMS 1:250,000, USGS 1:62,500, USGS 1:24,000 advance sheets or final maps) and other topographic controls such as level lines and bench mark descriptions. The next step was the location of aerial photographs for all of Nevada (mostly available from the Nevada Bureau of Mines collection of AMS 1:60,000 and USGS 1:24,000 photographs). Supplemental photography was occasionally used, localized in coverage and of various scales from a number of sources such as the Nevada Air National Guard reconnaissance photography, the U. S. Bureau of Reclamation, U. S. Forest Service, and the U. S. Bureau of Indian Affairs. The starting point therefore, was to gather the best available control data in the form of aerial photos, topography, and elevation control. During the course of the study, many advance sheets from the U. S. Geological Survey became available.

The next step was stereographic photo interpretation of each topographically closed basin and each basin reported to have contained a pluvial lake. The visible shoreline features were mapped on overlays at the available photo scale, and corrections were made for photo distortion by visual comparison of overlay data, using the available base maps of the best scale and topographic control.

Lake areas were extended beyond the shore features by following the appropriate contour interval; they were measured by planimeter either from photo overlays or directly from adequately scaled topographic maps. Basin areas were generally developed from AMS 1:250,000 scale maps, but where possible they were cross-checked by measurement on better scaled maps. The final mapping step yielding plate 1 was to transfer the basins and lake areas (on 1:250,00, 1:62,500, or 1:24,000 scale work maps or overlays) to a 1:500,000 U. S. Geological Survey base map of Nevada. When newly issued topographic maps made it possible to check the accuracy of lake areas measured from aerial photo overlays, there was generally less than 5 percent error in lake areas. The largest noted lake-area errors (several 10 to 15 percent) developed from lack of adequate topographic control for lake margin extension in cases of limited shore preservation. The lake and basin area data of the Appendix are not directly measured from plate 1, where accuracy suffers from transfer problems and scale.

The final step was to develop accurate data of lake and basin floor altitude, test accuracy in photo interpretation, overflow relations, and possible error in age relationships. These aspects were established by available topographic maps or supplementary elevation control. Field reconnaissance was made to check mapped features and to note age relationships in many of the basins. There are varying degrees of accuracy with respect to data in the Appendix and the sources of the data are therefore indicated to give perspective to expectable accuracy. The majority of data gathering and fieldwork of this study extended to a period of more than six years. General revision of data presented in plate 1 and the Appendix was accomplished in the summer of 1972, and minor revisions were made as late as 1978.

## Age Relationships

Contemporaneity of shoreline features is based on the basin-by-basin study of aerial photographs with supplementary field reconnaissance. Such photo and field study yields the relative degree of shore features development, preservation, and weathering as the principal criteria for determining contemporaneity. A number of detailed studies mentioned previously establish "control" perspective with respect to age of mapped pluvial features. Principal control areas are in Lahontan Basin, Bonneville Basin, and Las Vegas Valley. Throughout the years, late Pleistocene deposits of each area have been studied in detail; this helps place into context the age relationships of lacustrine and other types of surficial deposits related to the shoreline features of this study.

A summarized correlation chart (table 1) gives interpretations of the age relationships. Generally, most pluvial lakes, as shown in plate 1, were interpreted to correlate with the Wisconsinan Stage of glaciation of the midwestern part of the United States, and most high shore features are believed to correlate with a late Wisconsinan Stade. Lake Lahontan and Lake Bonneville have been correlated with the Wisconsinan Stage by most investigators.

In Bonneville and Lahontan basins the maximum shorelines are believed by most investigators to be early Lahontan in age (figs. 2, 3, and 4). Detailed isostatic rebound studies (Mifflin and Wheat, 1971) demonstrate this is not the case in all of the Lahontan Basin. In northeasterly valleys of the basin, the highest beach deposits overlie older beach deposits upon which the Churchill Soil developed.

Evidence resulting from the isostatic rebound work indicates there was important regional warping or tilting to the north between the time of early Lake Lahontan high lake stand and associated deposits (Eetza Formation) and the younger Lake Lahontan highest stand and associated deposits (Sehoo Formation). This caused the highest lake stand of Sehoo time to inundate the older Eetza shoreline in the northeastern part of the basin; however, there is often such close similarity in the general appearance of the high shores of both ages in the Lahontan Basin that it originally required a good soil exposure at exactly the highest shoreline bar to demonstrate the differences in high shore age in the Lahontan Basin.

As a result, the detailed age of the highest shore features in most of the other basins, after spot checks of shore features, cannot be definitely determined. Based on occasional exposed weathering profiles that were found, and comparing the relative degree of preservation between high and lower shore features, it is believed Early and Late Lahontan maximum lakes were usually about the same levels, and the majority of high shoreline features mapped were formed in Late Lahontan time. If this is not the case, the slight difference in size between Early and Late Lahontan lakes is so small with respect to lake area it would not significantly alter the value of measured pluvial hydrologic indices.

There are some exceptions in shoreline age noted in this study. Lake Wellington in Smith Valley (39 E in plate 1) is probably Early Lahontan in age (fig. 5). There are well-developed soils on very limited shore features in the basin. The history of this basin is complicated by probable stream capture of a headwater portion of the East Walker River near Sonora Junction in the Sierra Nevada by the West Walker River due to ice damming. Map relations of pre-Tahoe Till erratics in this area presented in Wahrhafting and Sharp (1965) suggest the probable stream capture could have been as young as Mono Basin, or as old as Sherwin or McGee glaciations. The Smith Valley lacustrine deposits and paleosols, along with the overflow history of Lake Wellington, and the suggested East Walker River capture have only been studied on a reconnaissance basis. If overflow occurred because of stream capture during one of the early Sierra Nevada glaciations, the preserved gravel bar in the north end of Smith Valley seems too well preserved to correlate with the event. Based on the degree of soil developments and general preservation, it is more likely Early Lahontan age. Initial overflow from Smith Valley appears to have occurred at about 5,000 feet MSL, but the preserved high bar in the northern part of the basin is approximately at 4,800 feet MSL; thus, the favored interpretation of the hydrographic history is that initial overflow and some downcutting resulted in Smith Valley when the headwater capture of East Walker River occurred, perhaps as

TABLE 1. Correlation of observed basin features.

| Midwest Frye and Willman, 1960 Time Stratigraphy | | Sierra Nevada (various authors) Rock Stratigraphy | Lahontan Basin Morrison and Frye, 1965 Rock Stratigraphy | Time Stratigraphy | | Suggested Correlations of Basin Features |
|---|---|---|---|---|---|---|
| Recent | | Neoglaciation | Fallon Formation (part lacustrine) | | K ce | Surficial playa deposits, active alluvial fans with distributary drainage and little soil development, eolian features. |
| Wisconsinan | Valderan<br>Two Creekan<br>Woodfordian | Tioga Till<br>Tenaya Till | Sehoo Formation (lacustrine) | Lahontan | Late | Age of most shoreline maxima, minor fan development in northern Nevada relatively more active in central and southern Nevada, active groundwater discharge/deposit formation in southern Nevada. |
| | Farmdalian | post Tahoe Soil | Churchill Soil<br>Wyemaha Formation | | r y | Minor fan development, eolian deposits, limited channel deposits of through flowing streams locally noted. |
| | Altonian | Tahoe Till | Eetza Formation (lacustrine) | | | **Extensive** well-preserved high shore features in Lahontan Basin, terrain stability in northeast Nevada, less in southern Nevada. Active groundwater discharge/deposit formation in southern Nevada. |
| Sangamonian | | pre-Tahoe Soil | Cacoon Soil<br>Paiute Formation | pre-Lahontan | | Prolonged development of alluvial fans, where now exposed; often have tributary drainage patterns and multiple strong soil profiles. Most inactive fans believed to be of this age. |
| Illinoian | | Donner Lake Till (Mono Lakes Till) | Rye Patch Formation (lacustrine) | | | "Old" shore features believed of this age (Diamond Valley, Long Valley, Newark Valley). Evidence indicates lakes of this pluvial were equal or smaller than Lahontan age lakes. Capture by W. Walker, initial overflow of Smith Valley seems of this age. |
| Yarmouthian | | strong soil | Humboldt Valley Soil<br>Lovelock Formation | | | Prolonged development of active fans, associated multiple strong soil profiles. Landforms of this age rarely well preserved at land surface. Confident correlations unaccomplished. |
| Kansan | | Hobart Till | Lacustrine unit reported | | | Basin landforms of this age range are usually buried or greatly modified in local exposure. Most ancient fans still retaining basic constructional form are of Paiute age, and perhaps a few might be of Lovelock age. Basin-ward lacustrine sequences generally buried by several hundred feet or more of younger sediments. In southern Nevada some basin landforms may be of this age range in favorable locations of preservation. Major hydrographic differences may have existed as late as Rye Patch time due to tectonism causing basin faulting and regional warping. |
| Aftonian | | | | | | |
| Nebraskan | | McGee Till | | | | |
| | | | | | | |

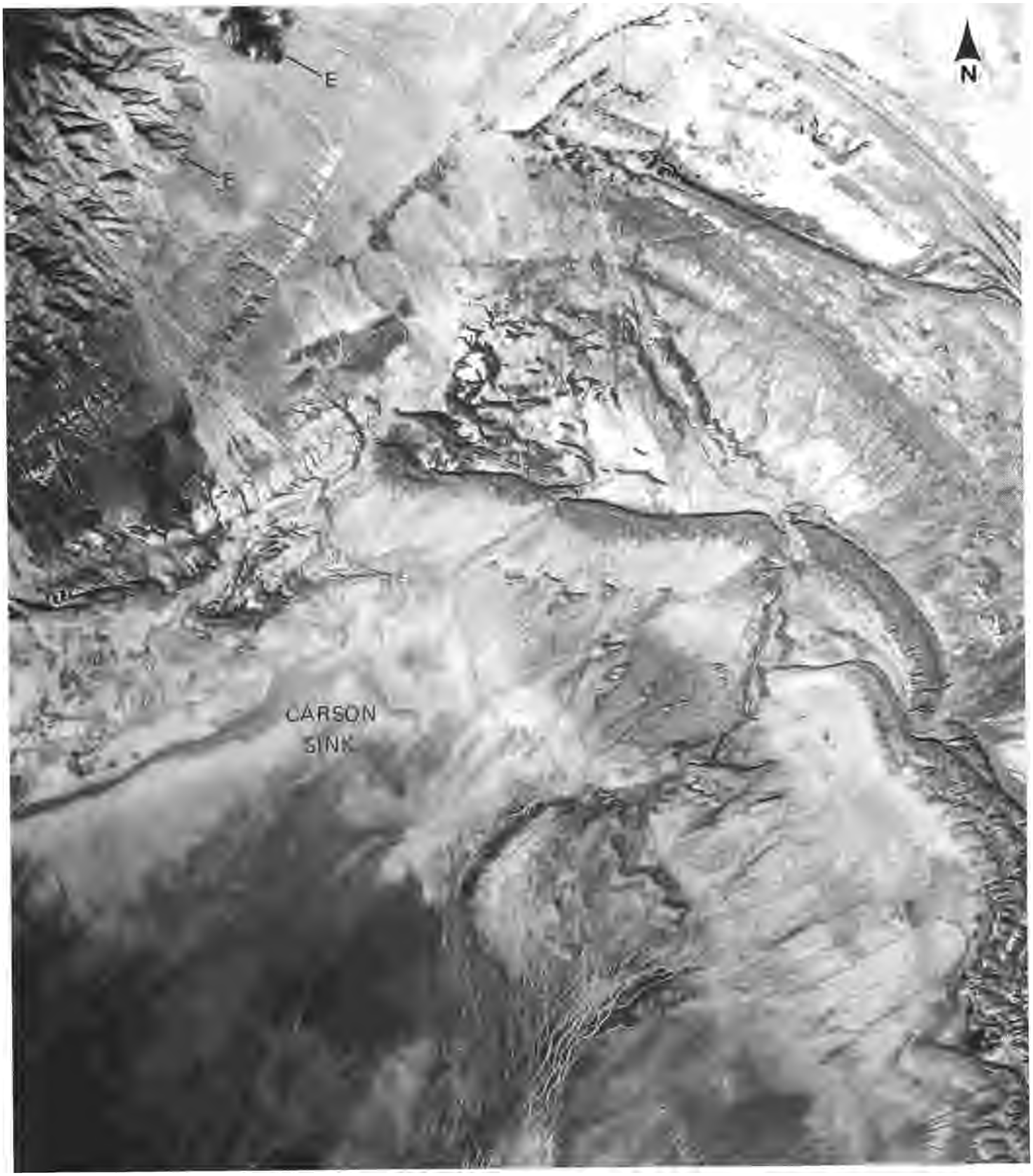

FIGURE 2. View of shoreline features of Lake Lahontan in the northeast corner of the Carson Sink which demonstrate the degree of development and post-lacustral destruction by erosional processes. With the exception of the Early Lahontan shoreline at (E), all features are Late Lahontan in age.

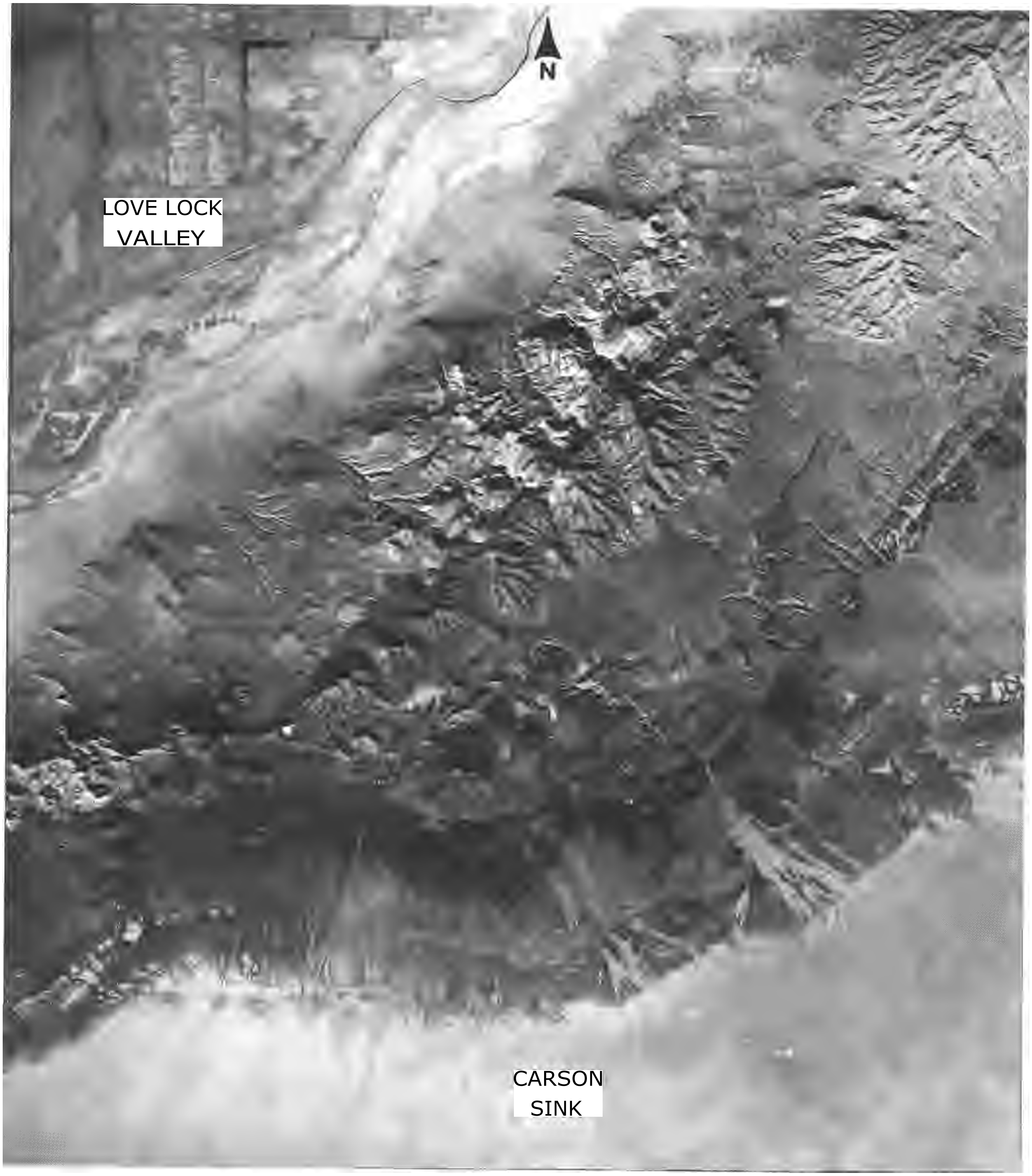

FIGURE 3. View of Lake Lahontan shoreline features near Lovelock, Nev. The area illustrates the variation in shoreline feature development and preservation due to exposure and post-pluvial terrain stability.

late as Mono Lake time. Additionally, during Early Lahontan time the basin refilled to 4,800 feet MSL and overflowed through the partly incised Wilson Canyon outlet, and then continued to maintain exterior flow in Late Lahontan time by entrenching a floodplain through deltaic and lacustrine deposits in the valley. While this interpretation is currently favored, other scenarios have been postulated which, if proved by subsequent investigation, may place some shorelines in Smith Valley as old as pre-Lahontan.

Other shorelines of apparent great age have been noted in scattered locations. In Diamond Valley recognizable shore features between 6,000 and 6,080 feet MSL (fig. 6) are at least in part pre-Lahontan in age and the oldest could be pre-Rye Patch (pre-Illinoian). The Lahontan age shore is believed to be close to 6,000 MSL, with overflow to the Lake Lahontan drainage (fig. 7). In two other valleys limited extents of "old" shoreline features are still visible slightly higher than those of Lahontan age. These occur in the south end of Long Valley (44 in plate 1, fig. 8) and in the southeast of Newark Valley (49 in plate 1). The local preservation above Lahontan age shore features may be due to tectonic warping in this region between Lahontan and Rye Patch pluvials.

In general, all of the recognized evidence indicates pluvial lakes of Lahontan age were generally as large, or perhaps slightly larger, than Rye Patchian pluvial lakes. In the few areas of Nevada where the "old" shore features have been found, basin overflow and associated downcutting, regional tilting, or local warping have caused the "old" features to be locally spared from subsequent obliteration by the Lahontan age shore features. In Lahontan Basin, where extensive field work has been accomplished in shoreline studies, there has been surprising evidence of regional warping or tilting of measurable magnitude from Early Lahontan time to the present and also some suggestive evidence of even longer term regional warping that may have given rise to important differences between paleohydrography of the Lahontan pluvial and that of Rye Patch and older pluvials. Significant differences could be true of much of the Nevada portion of the Great Basin.

## Lake Distributions

The smallest confidently measured pluvial hydrologic index proved to be 0.03 in magnitude. There are a few basins where perennial pluvial lakes of even smaller size may have existed, but photographic and field evidence was judged too weak to reliably map. These questionable basins occur in northwestern and southcentral Nevada, and the uncertainty is usually noted briefly in the Appendix. Data given in the Appendix demonstrate all recognized pluvial lakes had maximum depths of more than 20 feet. The field evidence indicates gradations to smaller surface-water features of shallower depths; however, at a critical depth (approximatley 25 feet), wave action, longevity, and lake level stability were such that weakly developed shore features could not be recognized with the techniques of mapping used in this study.

A further mapping complication observed was that basins which yielded little runoff during pluvial climates are now extremely arid with sparse vegetation. Post pluvial erosion processes have been vigorous in these basins and yield rapidly accumulating bolson deposits which cover or destroy pluvial lake landforms. Perhaps 80 percent of the Lahontan equivalent shoreline features are preserved in some of the northeastern basins. The interpluvial climate has been moist enough to provide vegetal densities that have stabilized terrain (figs. 9 and 10). In drier parts of northwestern Nevada and much of southcentral Nevada, as little as 10 to 20 percent of the pluvial shore features may be preserved. In some areas, even such recent features as century-old railroad grades have been extensively obliterated by active fan accreation and erosion. In the drier regions such as in the Sand Spring Valley, shoreline features were initially less well developed because of generally smaller and shallower bodies of water, and subsequent erosional processes have been less conducive to extensive preservation of such features (fig. 11). Upon initial study in these areas, the accuracy of pluvial lake mapping was uncertain due to the above mentioned problems; however, after fieldwork and sufficient mapping to demonstrate the decreases in pluvial hydrologic indices into these areas, it is believed that most, if not all, of the Lahontan age lakes of more than 30 or so feet in maximum depth have been recognized, and the southernmost basins of Nevada have not been the sites of Lahontan age pluvial lakes. This does not rule out shallow playa lakes which rarely develop well defined shore features due to lack of wave action and lake level stability.

For a number of basins our mapping disagrees with previously published interpretations of the existence of Late Pleistocene pluvial lakes. In nearly every case it seems the interpretations have gone astray by confusing playa deposits or confusing paludal deposits caused by concentrated ground-water discharge for lacustrine deposits. In several important cases there is no basin closure at the present time, and during the Lahontan pluvial of greater moisture availability there should have been an even better opportunity for exterior drainage. Possibly a few of these areas were sites of pre-Lahontan lakes, but it is somewhat doubtful due to absence of "old" shore features or overflow channels comparable to those where overflow has been documented.

The most important disagreements generated by total absence of shoreline features are as follows: in Steptoe Valley (28 in plate 1) south of Currie, Nev., a large pluvial lake was interpreted by Clark and Riddell (1920), and other map makers have continued to include this lake. This valley, however, has extensive areas of lacustrine-like deposits that are probably related to ground-water discharge or shallow water paludal environments (figs. 12 and 13). It is possible, if the northward regional warping extends to this region of Nevada, that a much older (pre-Rye Patch?) lake existed in this basin and that by Rye Patch time, Goshute and Steptoe Valleys were integrated by a channel cut near Currie. Hot Creek Valley (53 A in plate 1), with no closure and containing lacustrine-like sediments related to pluvial ground-water discharge, was reported as a pluvial lake by Hardman in Snyder and others (1964). Pahrump Valley (50 in plate 1) has extensive lacustrine-like deposits in some areas and no significant closure. These deposits are interpreted to be partly playa and partly paludal deposits caused by localized and concentrated ground-water discharge. Hubbs and Miller (1948) and Maxey and Jameson (1948) believed these deposits to be evidence of a pluvial lake. Ivanpah Valley (34 in plate 1) was cited by Hewett (1956) as containing a pluvial lake

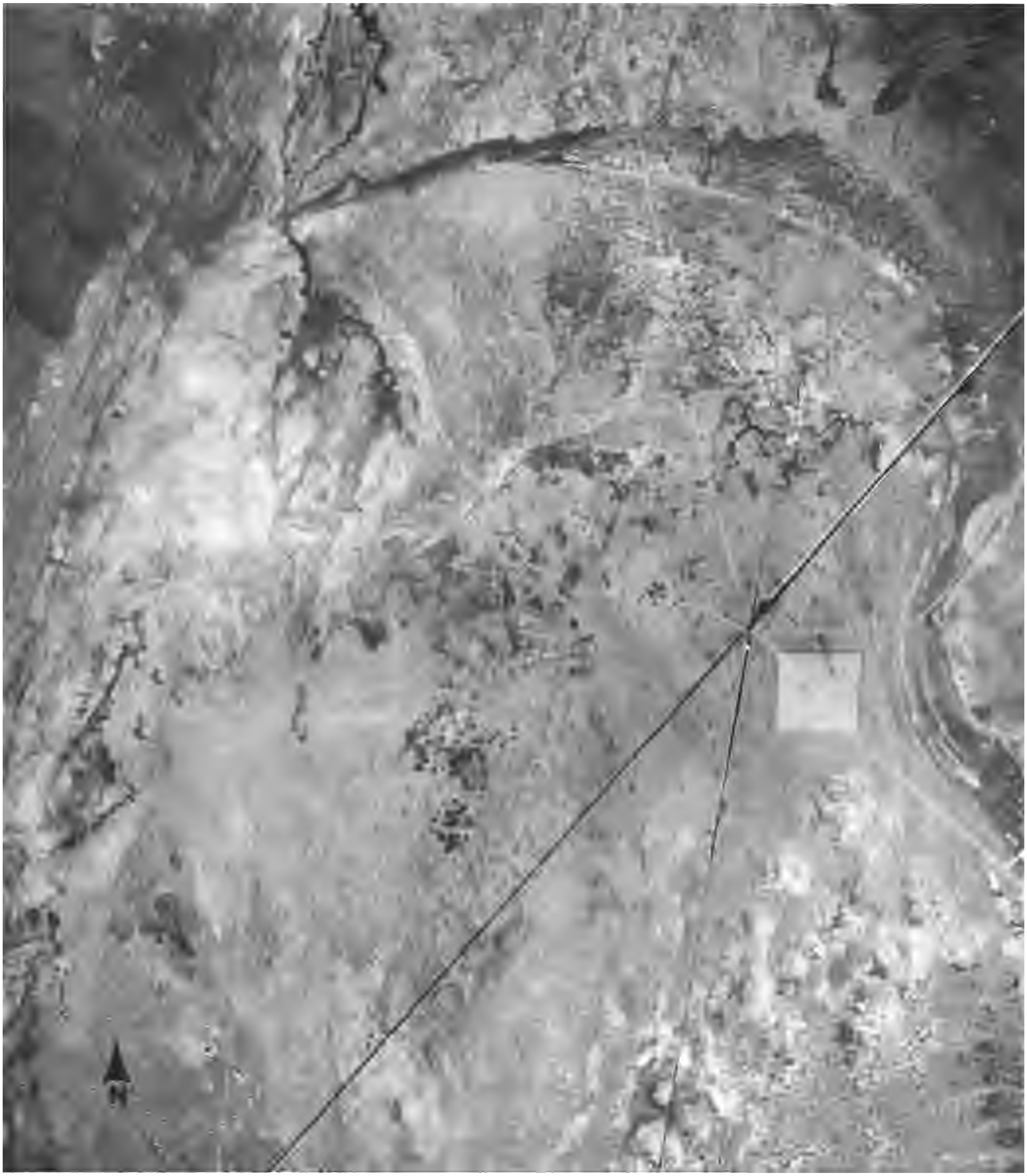

FIGURE 4A. Comparative views, with similar exposures about 15 miles apart of shoreline features in Goshute Valley (4A), and Bonneville Basin (4B). The degrees of shoreline development and preservation are very similar, suggesting similar age. There have been numerous interpretations of age of the maximum Lake Bonneville shoreline; in this area it occurs at 5,200 feet MSL and seems to be of the same age as shore features assigned to Late Lahontan age in this study. The degree of shoreline feature preservation with respect to alluvial fan development in both valleys indicates that the majority of fan development predates the last major lake cycle, and that post pluvial terrain stability has persisted in this region of Nevada.

FIGURE 4B. Bonneville Basin.

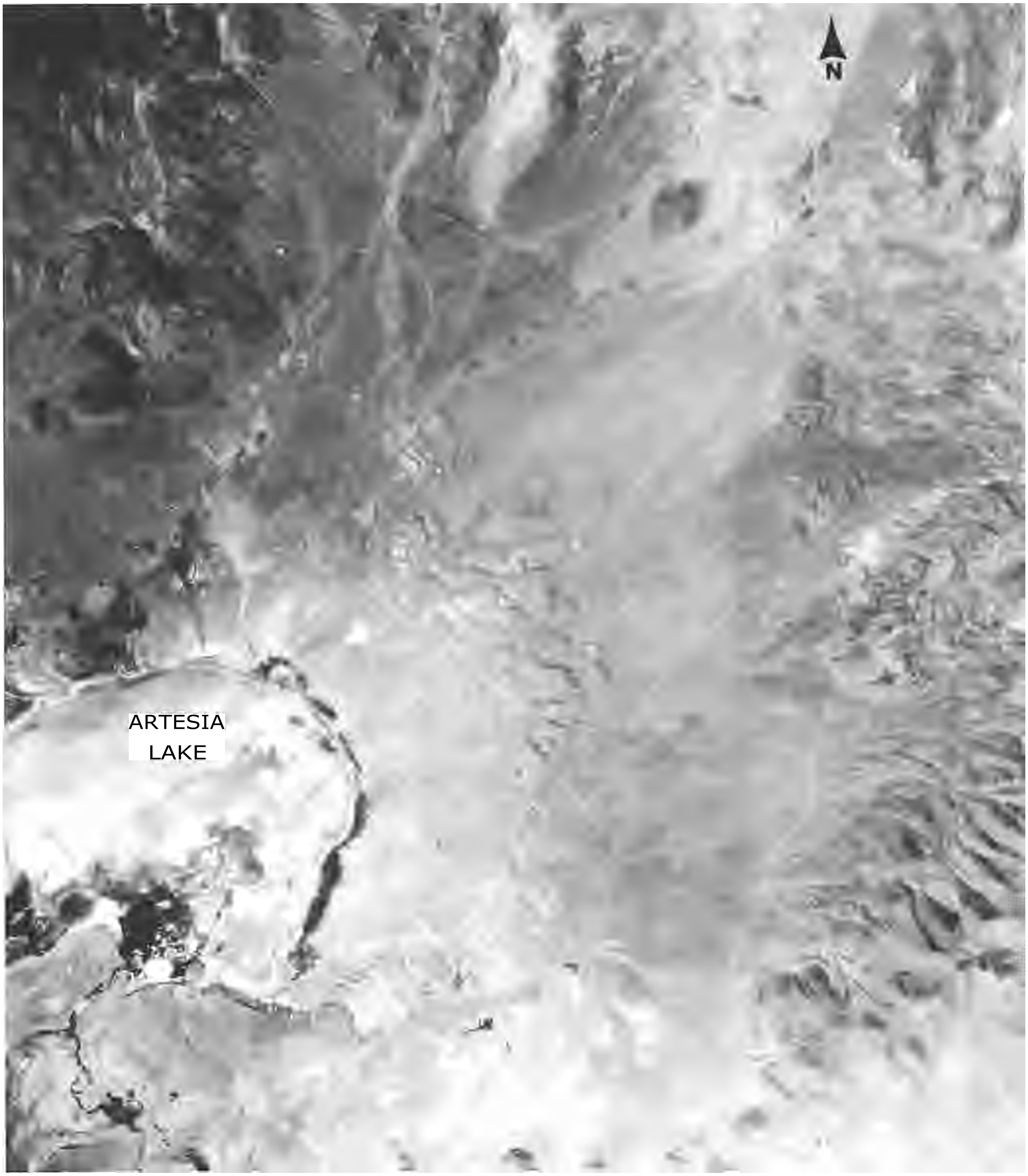

FIGURE 5. Feature A is the well-preserved segment of the high shore bar of Lake Wellington in the northern part of Smith Valley. The arrows point to the best preserved shoreline feature in the valley, and clearly these features are older than shorelines of Late Lahontan age. However, observed relationships indicate a complicated history of capture of a part of the East Walker River drainage by the West Walker River, with initial Smith Valley overflow at a higher elevation than the preserved shoreline feature, then with development of deltaic-lacustrine sediments in the basin and the shoreline features, and then subsequent down cutting and maintenance of exterior drainage.

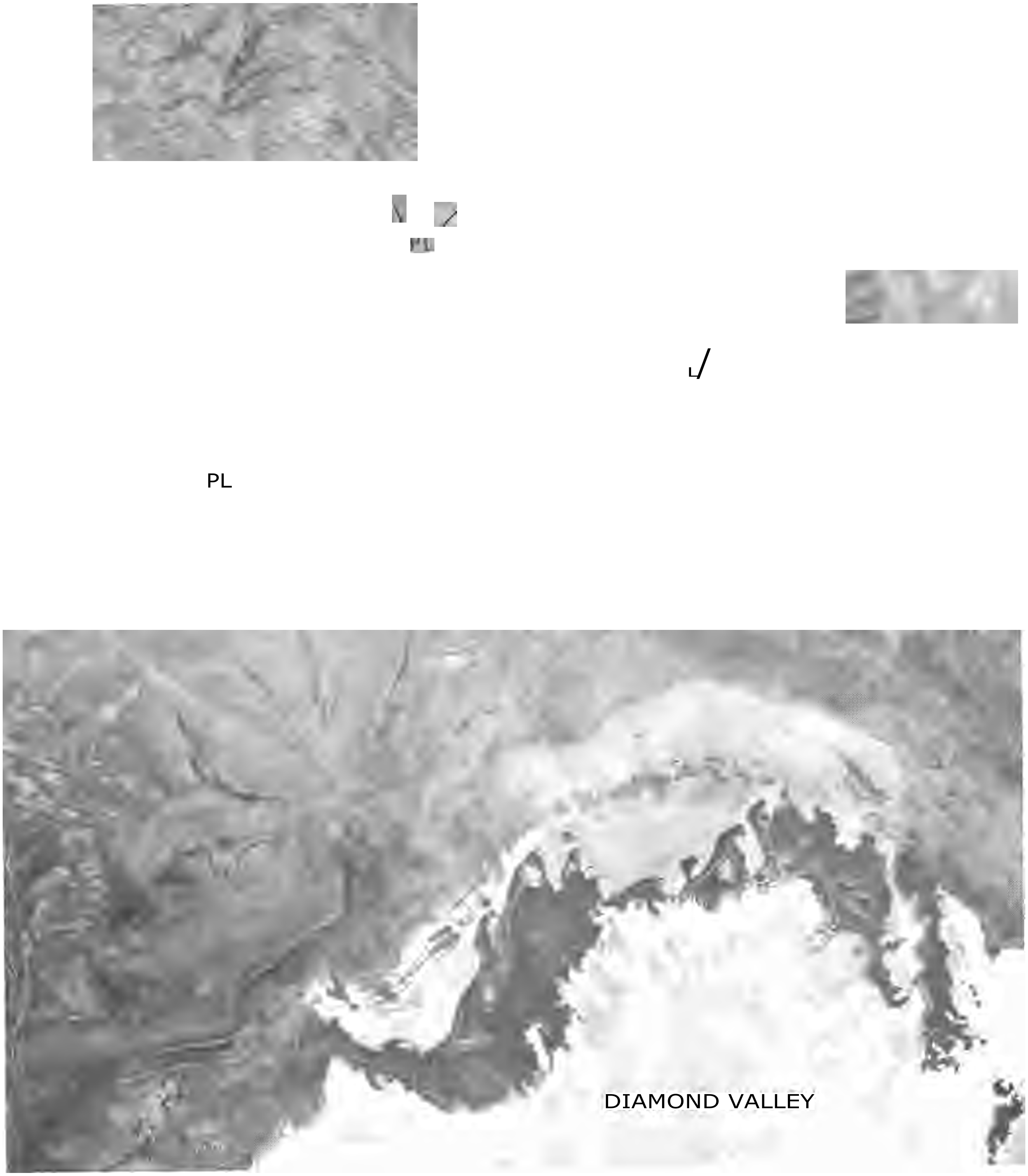

FIGURE 6. View of the north end of Diamond Valley where pre-Lahontan shoreline features (PL) occur up to 6,080 feet MSL, and the Lahontan shoreline features (L) occur at 6,000 feet MSL, approximately 160 feet above the lowest level of overflow from the valley.

FIGURE 7. View of the northeast overflow pass (P) from Diamond Valley to Lake Lahontan drainage. Only Lahontan aged shoreline features (L) can be distinguished with confidence in this area of overflow, but evidence of older, higher shore features indicates initial overflow occurred in pre-Lahontan time at about 6,080 feet MSL or more, about 240 feet higher than the youngest Late Lahontan channel level. Post pluvial infilling places Railroad Pass at 5,895 feet MSL.

FIGURE 8. View of the Pre-Lahontan bar (A) in the south end of Long Valley, and an alluvial deposit of approximately the same age (B). This is the best well preserved example of a shoreline feature above Lahontan age shorelines (L) in a non-overflowing basin, and it may be related to local warping and/or faulting, or regional tilt. In Newark Valley. adjacent to the west, similar old shore features are preserved along the southeast embayment of Lake Newark.

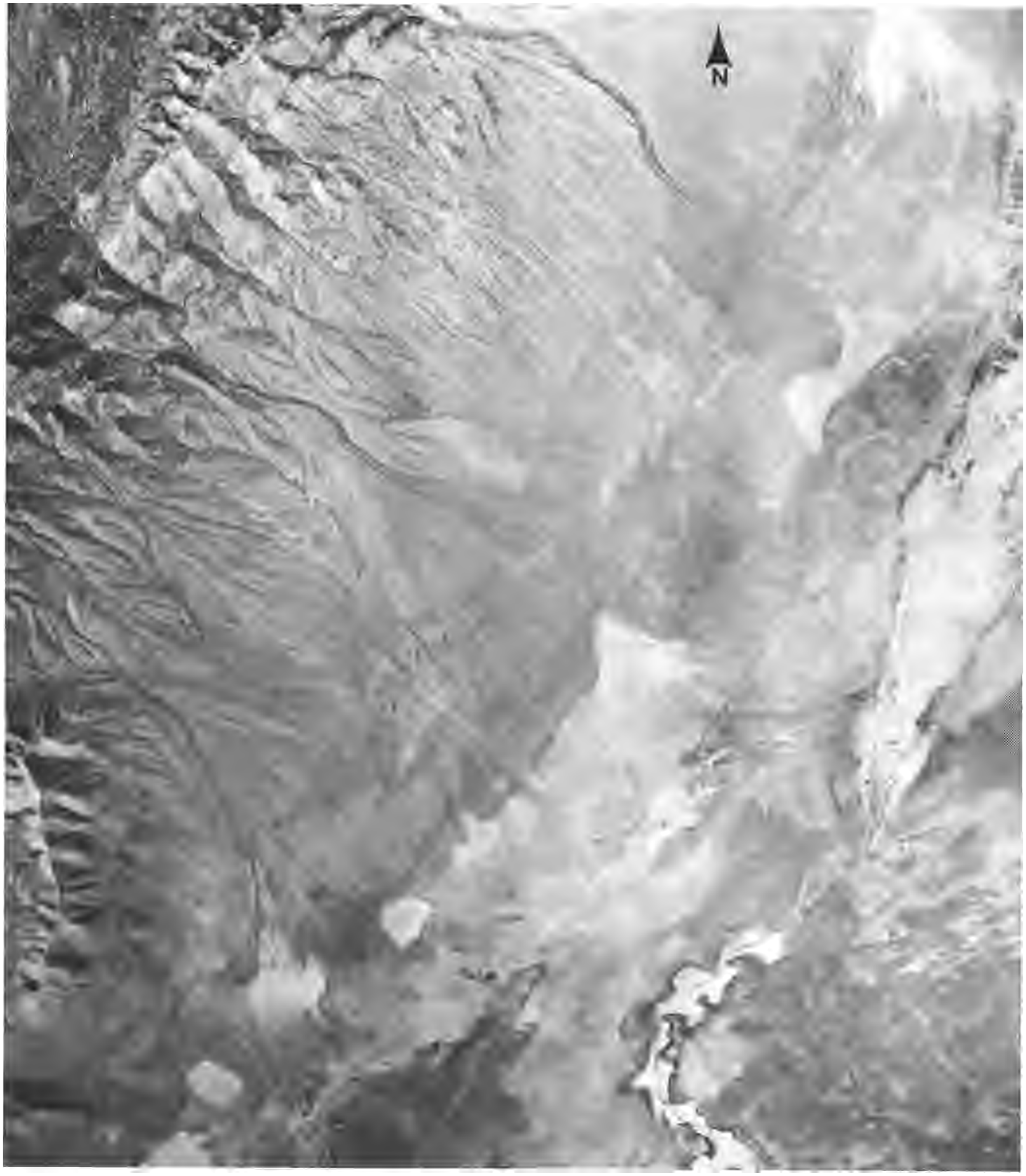

FIGURE 9. View of the western flank of Goshute Valley where well-developed and preserved shoreline features of Lahontan age demonstrate post pluvial climates have generated relatively stable terrain.

FIGURE 10. Example of Lake Lahontan shorelines (arrows) in Silver State Valley, a northeastern sub-basin of the Lahontan Basin. Relatively shallow water and limited fetch permitted only moderate development of shoreline features that are relatively well preserved.

FIGURE 11. View of Penoyer Valley (Sand Spring Valley) where firm evidence of Lahontan age lake is absent. Features which are suggestive of shoreline features (S) vary greatly in elevation where present, and are absent in other quadrants. It is likely that shallow playa lakes were present during pluvial climates, and that apparent shoreline-like features are related to the past position of groundwater discharge during the pluvial climate.

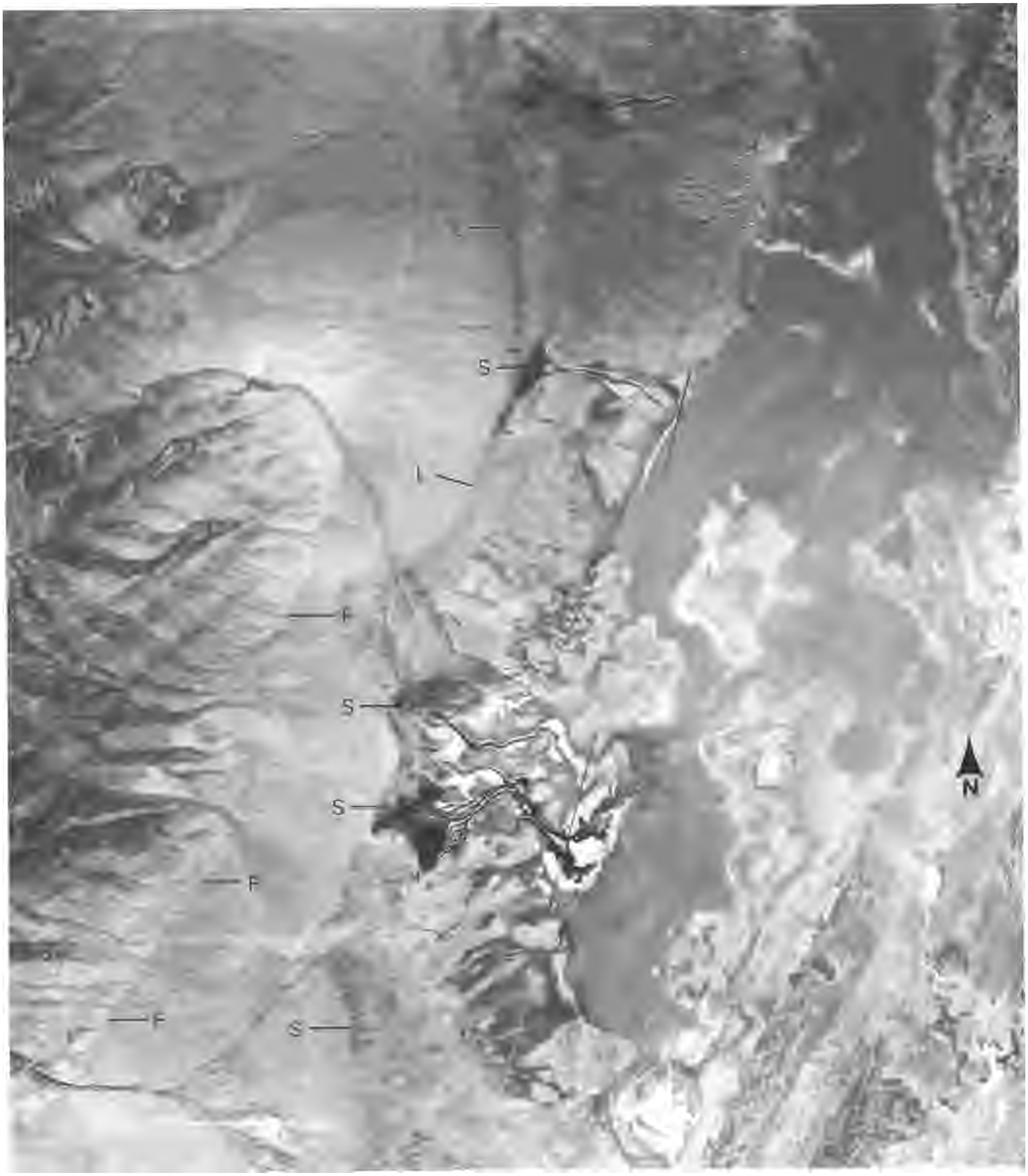

FIGURE 12. View of the west side of northern Steptoe Valley where groundwater discharge and associated phreatophytes create lineations (L) easily mistaken for shoreline features. Large springs and seepage areas (S) occur at or near the break in slope formed by the toe of alluvial fans and lower energy deposits of the axial plain of the bolson. The mountainous terrain is composed of carbonate rock, and the large springs are believed closely associated with localized zones of solution permeability. A range-front fault trace is well developed (F).

FIGURE 13. View of the north end of Steptoe Valley south of Currie where a series of faults (F) localize groundwater discharge and create lineations. This area is the lowest part of Steptoe Valley and absence of Lahontan age shoreline features on the northwest flank of the valley helps confirm the origin of lineations in the valley which might be confused with shoreline features.

based on fine-grained deposits; they are more likely pluvial playa and recent playa deposits. Mesquite Valley (46 in plate 1) has lacustrine-like deposits, again believed to be ground-water discharge related and again cited by Hardman in Snyder and others (1964) as a pluvial lake area. Fish Creek Valley or Fish Lake Valley (the south part of basin 15 in plate 1) has been cited by Hardman in Snyder and others (1964) as having a pluvial lake; here again are the fine-grained deposits related to ground-water discharge with no basin closure. There are several other, less important basins with similar types of disagreement in interpretation, as can be seen by comparison of data presented in plate 1 and the Appendix as well as most published maps.

An important interpretive disagreement revolved around pluvial "Lake Las Vegas" in Las Vegas Valley. General mapping has been done in this region by Maxey and Jameson (1948), Bowyer and others (1958), and Longwell (1961). Haynes (1967) studied some of the deposits in detail. Again, the lacustrine-like sediments attributed to pluvial "Lake Las Vegas," seem to be paludal and/or playa deposits related to relatively more extensive and vigorous ground-water discharge in Las Vegas Valley during the Lahontan pluvial period (fig. 14). Careful study of similar deposits near Ash Meadows, Nev., has led Denny and Drews (1965) to conclude a nonlacustrine origin. Additional rationale can be examined in Mifflin (1967, pp. 15-17; 1968, pp. 15-20). Some of these deposits yield molluscan shells that have convinced some investigators of a lacustrine origin; yet a clear separation between localized paludal depositional environments and more extensive lacustrine depositional environments seems difficult on the basis of the biological evidence discussed by Yen (1951) and Taylor (1967).

Price (1966, pp. 22-24) reports to have found molluscan shells from three widely separate exposures of the Las Vegas Formation in Las Vegas Valley and gives a table with identification and interpreted environment made by Ernest J. Roscue of the Field Museum of Natural History:

| S/2 S36,T19S,R60E | Environment |
|---|---|
| *Pelecypods* | |
| *Pisidium* sp. or spp. | Freshwater |
| *Gastropods* | |
| *Euconulus* sp. | Terrestrial |
| *Lymnaea* sp. | Freshwater, may inhabit very moist terrestrial environments, e.g., mud banks |
| *Physa* sp. | Freshwater |
| *Pupilla(?)* sp. | Terrestrial |
| NE/4 S13,T21S,R60E | |
| *Pelecypods* | |
| *Pisidium* sp or spp. | Freshwater |
| *Gastropods* | |
| *Euconulus* sp. | Terrestrial |
| *Gyraulus* sp. | Freshwater |
| *Lymnaea(?)* sp. | Freshwater, may inhabit very moist terrestrial environments |
| *Pupilla(?)* sp. | Terrestrial |
| *Zonitid(?)* | Terrestrial |

Currently, in Nevada, there are a number of localized paludal environments with mollusks, and some exist where there is no significant topographic closure. As can be seen in plate 1, Las Vegas Valley has been omitted as a closed basin due to no closure (there is no physiographic evidence of shoreline features or possible hydrographic closure of Lahontan age to explain a large lake which could yield the distribution of "lacustrine" Lake Las Vegas sediments). The total evidence supporting the interpretation of a nonexistent large Lake Las Vegas outweighs the somewhat ambiguous fossil evidence; for example: a) absence of plausible basin closure of the correct age; b) pluvial hydrologic indices trending to essentially zero values well to the north of the latitude of Las Vegas Valley and at higher basin elevations; c) total absence of shoreline features throughout Las Vegas Valley, and d) modern, usually spring-fed marshy environments in playa margin areas in several parts of the Great Basin.

The comparison of plate 1 with the most recently compiled maps of others (Snyder and others, 1964; Morrison, 1965a) demonstrates rather profound differences, particularly in southern Nevada. Even though the map by Snyder and others is said to be based on the criterion of shore features, results of this study show this is not entirely the case. It seems clear that assumptions of others, undoubtedly motivated by the lacustrine-like, fine-grained deposits related to other modes of origin, caused them to map pluvial lakes in southern Nevada and in adjacent areas in California. Those basins in California nourished by the high Sierra Nevada or other high ranges seem plausible sites of Lahontan age pluvial lakes, however, several California basins do not have such nourishment areas. The most reliable criterion for recognition of pluvial lakes of Lahontan age is presence or absence of shoreline features since other lines of evidence may be quite misleading.

### Basin Overflow in Lahontan Time

A number of basins overflowed during the Lahontan pluvial through low passes into adjacent basins. Those pluvial lakes that clearly overflowed during Lahontan time are in Buffalo Valley (39 B in plate 1 and fig. 15), Diamond Valley (39 C in plate 1 and fig. 7), Bawling Calf Basin (39 A in plate 1), Hawksy Walksy Valley (2 A in plate 1), Summit Valley (2 B in plate 1), New Years Valley (65 A in plate 1), and Washoe Valley (30 G in plate 1); the latter two are still very shallow playa lakes which continue to overflow periodically. All of the above have well-developed features of overflow. The Tahoe Basin (39 F in plate 1) continues to overflow but was periodically blocked by ice dams in Lahontan time (Birkeland, 1964).

Summit Lake Basin (2 B in plate 1) has an overflow history that is complex as well as interesting. The general history of drainage to both the Alvord Basin to the north in Oregon and to Lahontan Basin constitutes a potential hydrologic mechanism for transfer of indigenous fish between these two major basins in the mid to late Pleistocene, a hydrographic history unrecognized in studies by Hubbs and Miller (1948). The latest Late Lahontan overflow., approximately 5,856 feet MSL to Virgin Creek (Alvord Basin), is demonstrated by early man's artifacts discovered during this study along the highshore of Lake Parman. Layton (1970) studied and described these artifacts and more recently, turned up identical tools at Last Supper

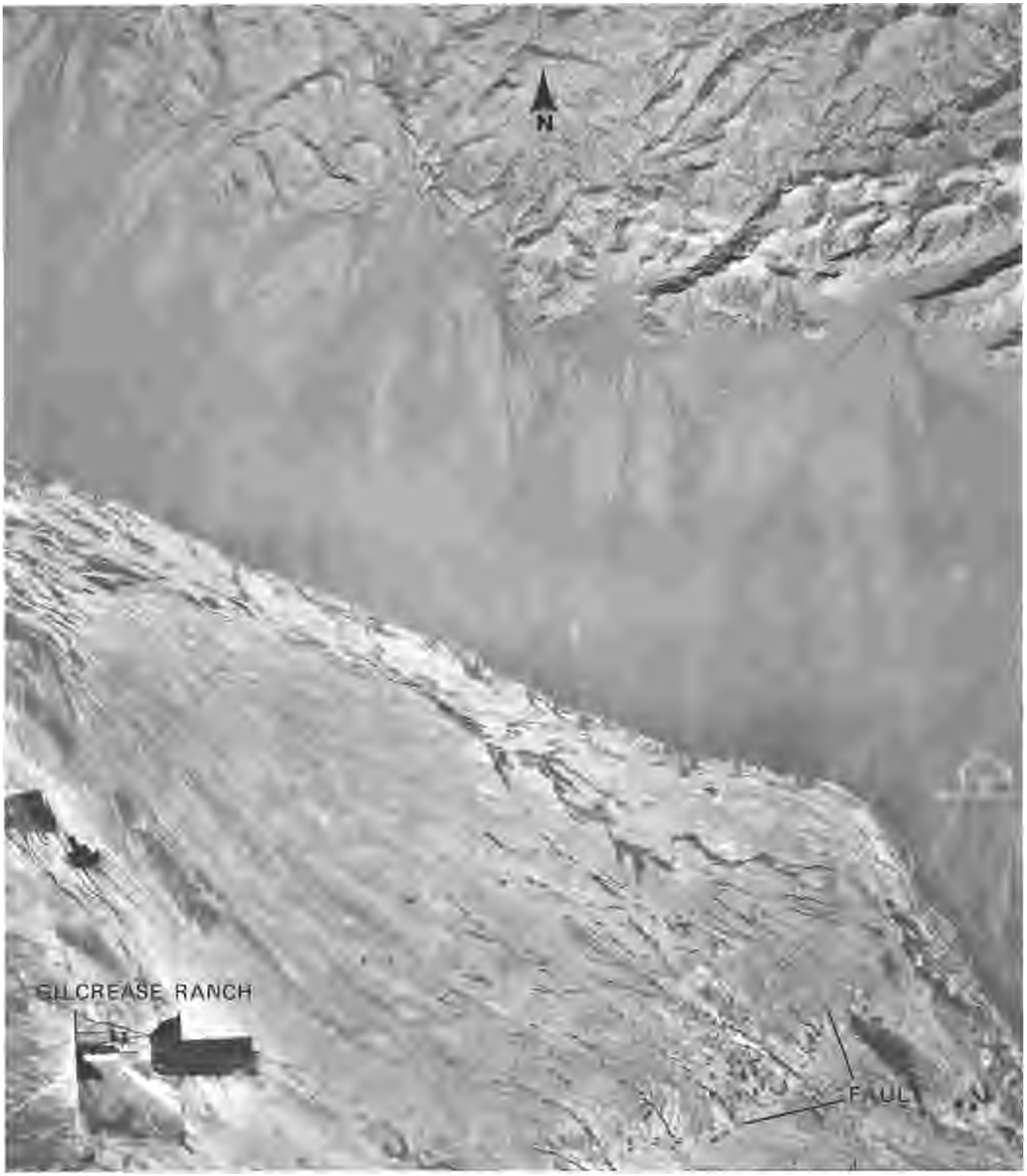

FIGURE 14. View of fine-grained deposits in northern Las Vegas Valley near Tule Springs. These and similar deposits in southern Nevada have often been interpreted as lacustrine in origin, but the majority of evidence suggests paludal and phreatic playa environments of deposition. More vigorous localized groundwater discharge forming extensive areas of marsh and phreatic playas during the pluvial periods seems the best interpretation.

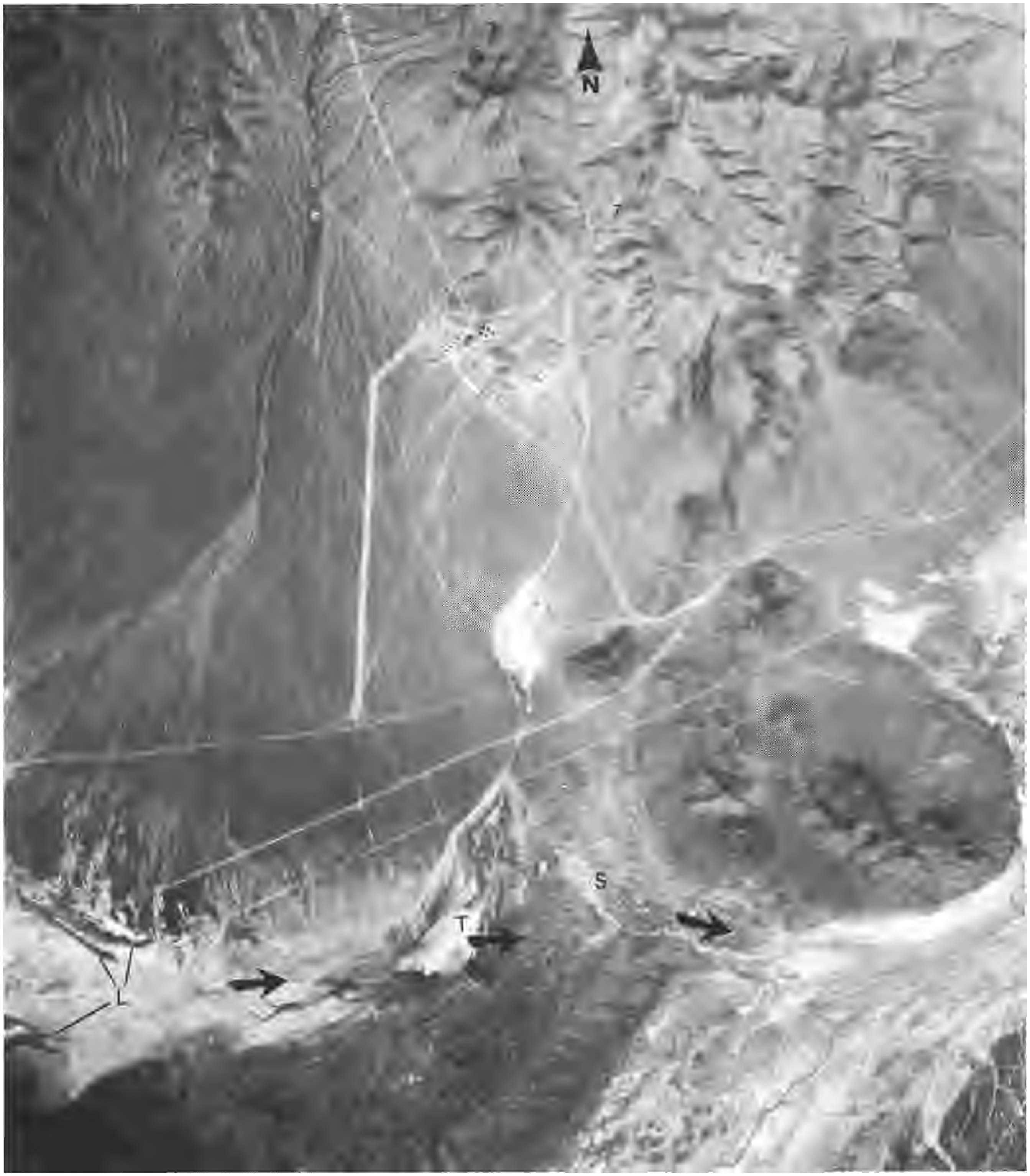

**FIGURE 15.** View of the northeast area of Buffalo Valley where Lahontan age overflow occurred. The position of highest shoreline bars (L) of Lahontan age of Lake Buffalo suggest present closure of the basin overflow channel is likely post-Lahontan in age, and consists of sand dunes (S) and mine tailings (T). Large arrows indicate apparent overflow path to Lake Lahontan drainage.

Cave, located about 12 miles to the north, which have been dated by $C^{14}$ methods at about 9,000 years B.P. (Layton, personal communication, 1977).

Drainage of Summit Lake Basin to Lahontan Basin via Soldier Creek was blocked by the massive Snow Creek landslide; the present altitude of basin closure on this feature is about 5,910 feet MSL, with no evidence of overflow. This altitude of landslide closure is interesting to compare with the apparent level necessary for initiation of overflow to Virgin Creek, approximately 5,920 feet MSL based on present landform altitudes near the overflow channel. There is no reliable date on the Snow Creek landslide; however, moderately rugged topography with undrained depressions and moderate weathering suggest an Early Lahontan or younger age of landslide formation. The well-developed incised overflow channel to Virgin Creek (60 plus feet) also argues for prolonged overflow to Alvord Basin (fig. 16). Earlier drainage history is less apparent. It was noted that headward erosion along Soldier Creek drainage captured at least part of Summit Lake drainage before the Snow Creek landslide occurred, but the drainage canyon of Soldier Creek below the slide is not overfit when compared to other tributary channels of the same drainage. This, plus the well-developed overflow channel to Virgin Creek, argues for earlier initial overflow to Virgin Creek prior to the landslide blockage and perhaps only a short Lahontan pluvial period of drainage to the Lahontan Basin. The latter hydrographic history is the favored interpretation based on available evidence.

Diamond Valley, with repeated overflow and downcutting, is the only recognized basin within Nevada with such an extended overflow history recorded by pre-Lahontan shore features (fig. 6). Two other lakes may have overflowed during Lahontan time to a minor extent. Lake Maxey (61 in plate 1), in Spring Valley probably leaked a limited amount of ground-water underflow northward to Lake Spring (62 in plate 1 and figs. 17 and 18). Lake Gale in Butte Valley (9 in plate 1) has a possible overflow channel to the north, but if overflow occurred, the history is not clear from field relationships. The maximum bar closes the lake basin within the valley. A short distance to the north there is an incised overflow channel through old alluvial fan deposits (fig. 19). There has been no preservation of higher shore features in the valley. Perhaps periodic overflow occurred during the Lahontan pluvial to Ruby Valley (56 in plate 1), but is seems more likely that there were no overflows of this age. The pluvial hydrologic index of 0.28 suggests the possibility of overflow at this time when compared with somewhat larger indices of adjacent valleys; however, bounding ranges of Butte Valley are not as well nourished by moisture as some adjacent valleys. Lake Valley (19 in plate 1) leaked ground-water underflow but not to the extent of greatly decreasing the hydrologic index. It is believed that basin closure of Sand Spring Valley (53 B in plate 1) was formed in post Lahontan time by volcanism. Scott and Trask (1971) have discussed apparent age relations of the volcanics in the area of necessary closure. Reveille and Railroad (53A and 53 in plate 1) Basins have a joint tributary system which indicates flow periodically fed either one or the other, and have been combined in quantitative analysis. No evidence for overflow of Lahontan age for Lake Franklin in Ruby Valley (56 in plate 1) or Lake Gilbert in Grass Valley (31 in plate 1 and fig. 20 ) has been found; however, Snyder and others (1964) reported overflow of both.

### Basin Overflow in Pre-Lahontan Time

Some additional areas may have seen overflow during pre-Lahontan pluvials. As previously mentioned, Steptoe Valley may have contained a lake in pre-Lahontan time that eventually became integrated with Goshute Valley through overflow at Currie, Nevada. If the latter is the case, it occurred no later than Rye Patch (Illinoian) time. Goshute, in an early pluvial, may have overflowed to Bonneville Basin through a northeasterly pass. Lake Valley (40 in plate 1) with only an alluvial fan closure on the south in Lahontan time, could have been open to Delmar Valley in earlier pluvials.

Lahontan Basin, with its great extent and numerous integrated subbasins, may have spilled during a pre-Lahontan pluvial to the south as far as Clayton Valley (11 in plate 1). This possibility is suggested on the following lines of recognized evidence:

1) In the Walker Lake subbasin, north of Thorne, Nev., there is a large point bar that was active during Lahontan time. Above the highest Lahontan beach of 4,360 feet MSL there are typical well sorted and rounded "lacustrine" gravels to at least 4,480 feet MSL, suggesting the root zone for the point bar is older and formed by a lake with a much higher maximum level (fig. 21).
2) To the south of the Walker Lake subbasin of Lake Lahontan are a series of valleys, separated by alluvial fan closures below 5,000 feet, offering possible paths for ancient basin integration.
3) Rhodes Salt Marsh, Columbus Salt Marsh, and Clayton Valley, are anomalous concentrations of saline deposits, when compared to their drainage areas. One explanation for the abnormal salt concentrations would be a series of overflow basins acting periodically as evaporation basins for drainage spill during pre-Lahontan pluvials.
4) There are relatively thin Rye Patch (Illinoian) lacustrine sediments, in part deltaic, in the central part of Lahontan Basin, north of Lovelock, Nev., but at a lower elevation than Lahontan age sediments. The impression the Rye Patch formation exposure gives is a depositional environment near the upper lake level close to the confluence of the ancestral Humboldt River. These sediments are about 200 feet lower than the maximum stages of Lake Lahontan in this area.
5) Evidence that ties the previous observations together into the suggestion of pre-Lahontan southward overflow from the Lahontan Basin is evidence of regional downwarping to the north and northeast during and since the Lahontan pluvial (Mifflin and Wheat, 1971). The rate and amount of warping, should it also have been active in pre-Lahontan time, would have been sufficient to raise the suggested Walker Lake subbasin overflow area as much as 300-400 feet higher than the Rye Patch sequence at Rye Patch Dam during the time between the Rye Patch (Illinoian) pluvial and the present time. The 4,480 feet MSL "lacustrine" gravels near Thorne fit the warping evidence.

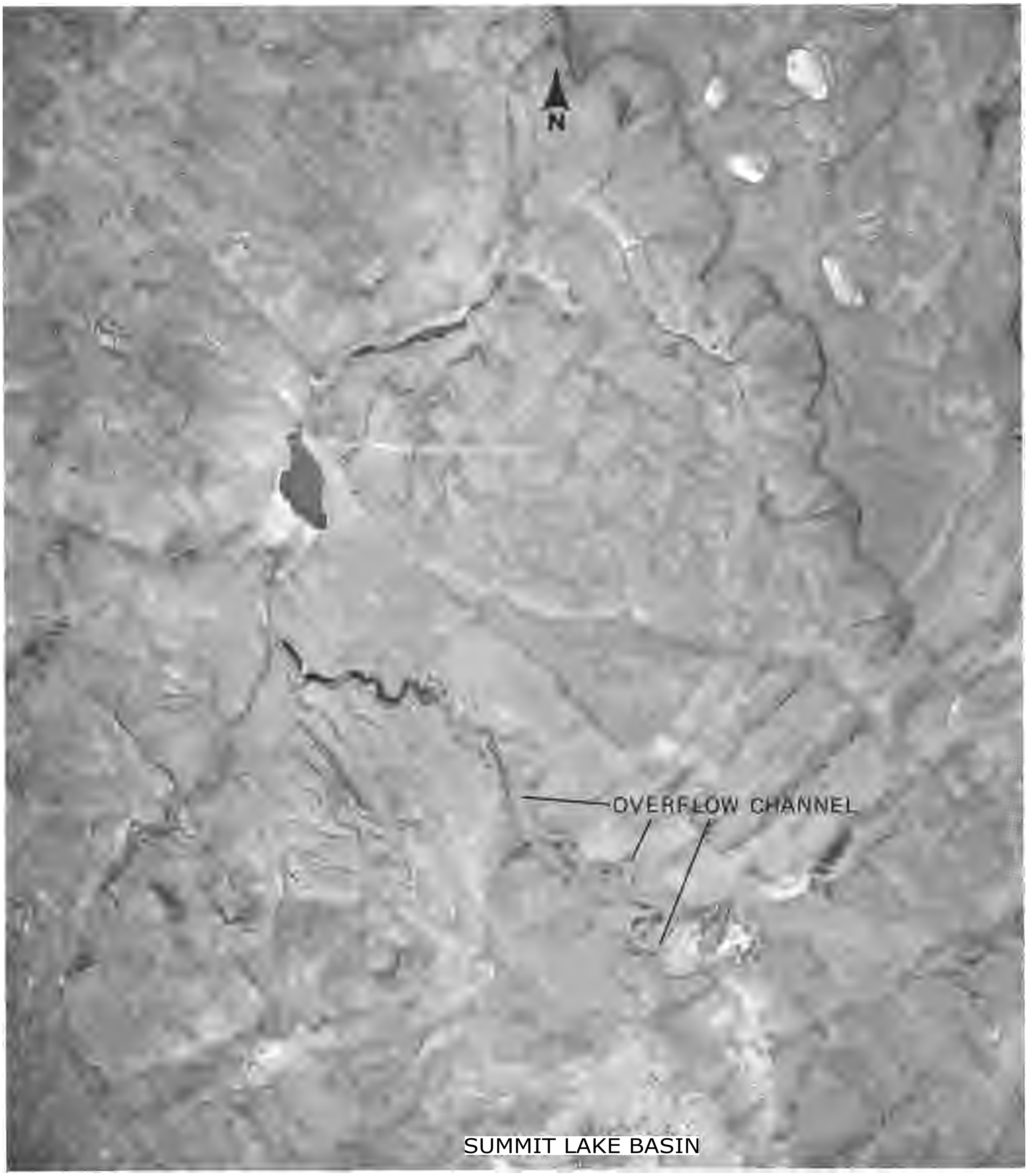

FIGURE 16. View of the overflow channel from Summit Lake Basin to Virgin Creek and Alvord Basin. Latest overflow appears to have occurred in Late Lahontan time; however, overflow to Lahontan Basin has also occurred, perhaps in Early Lahontan time.

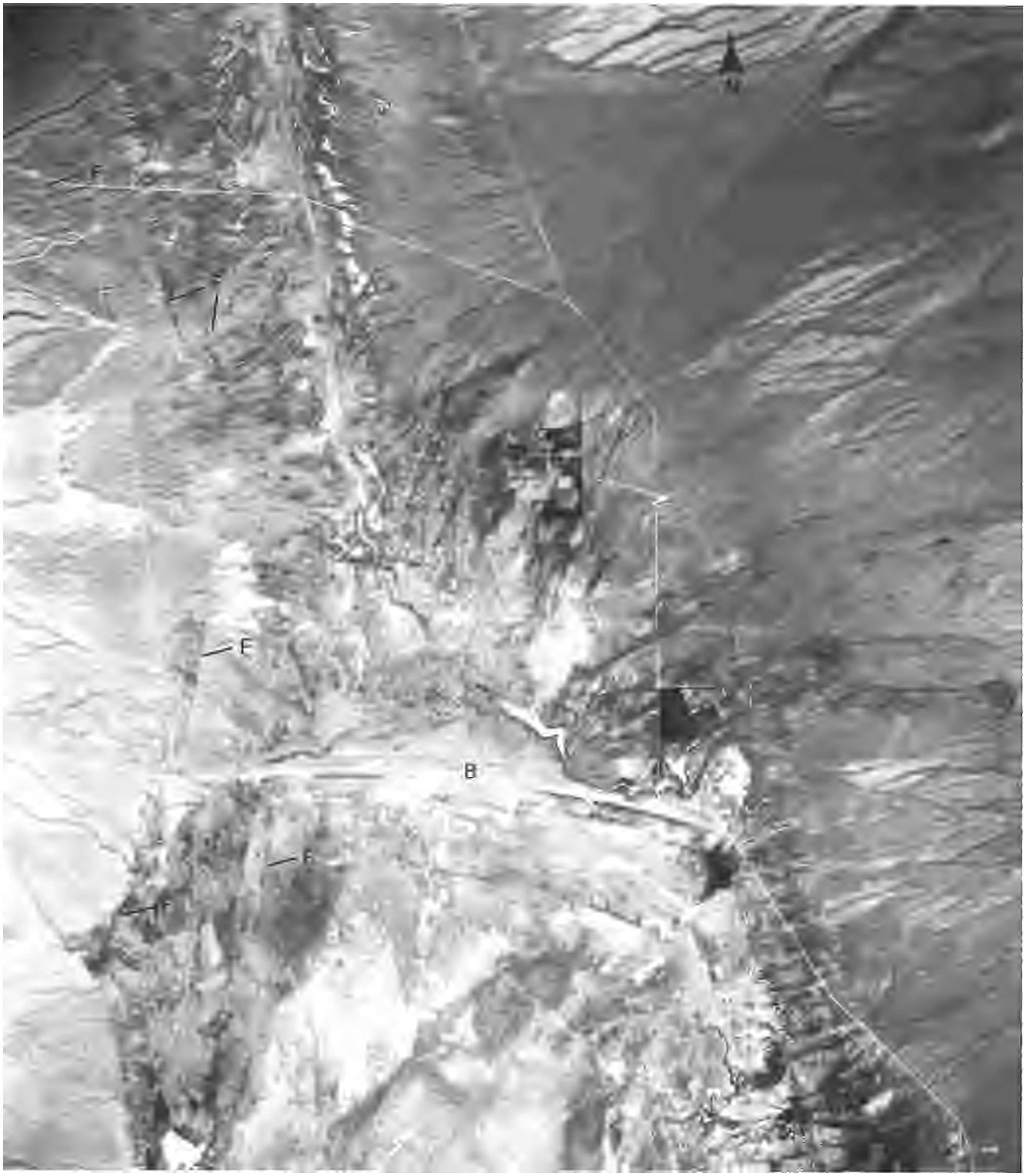

FIGURE 17. View of the north shore of pluvial Lake Maxey in Baking Powder Flat. The terminal bar (B) closes the basin, and numerous fault traces (F) can be seen. Groundwater discharge occurs at and near the highest shore.

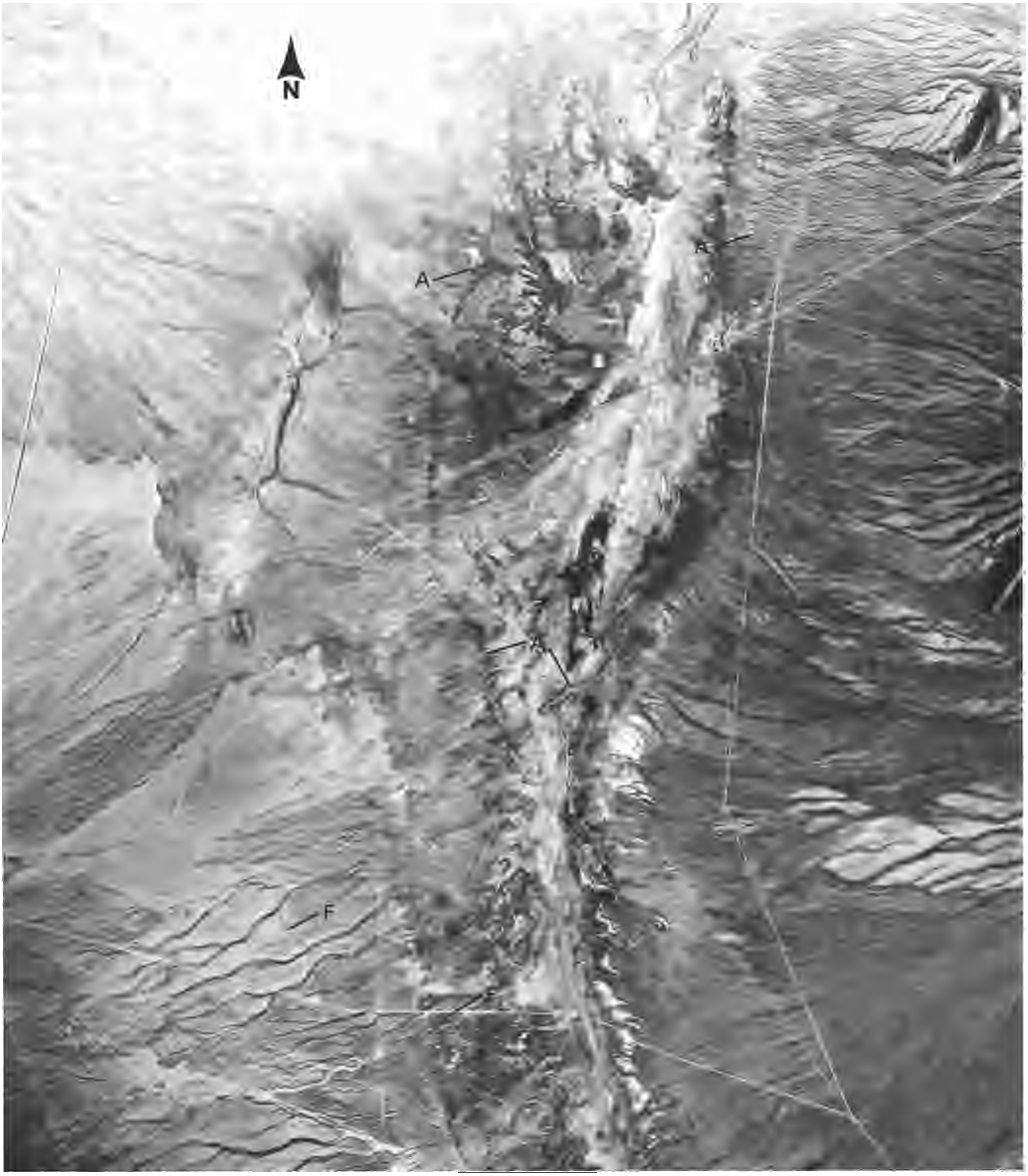

FIGURE 18. This photo illustrates the maximum stage shoreline of Lake Spring in its southernmost extent (A). Numerous faults (F), groundwater discharge deposits, and weakly developed shore features due to very shallow water make identification difficult. To the south of this photo is the well-developed northernmost high bar of Lake Maxey.

FIGURE 19. View of what has been considered the overflow channel in the north end of Butte Valley. The maximum shoreline bar **(B)** of Lahontan age occurs below the topographic closure (T). Active groundwater discharge in the area has created well-developed lineations (G). Overflow may have occurred in pre-Lahontan times, or the well-developed northward drainage channel (D) may be the result of the combination of ephemeral runoff and perhaps more vigorous groundwater discharge during pluvial climates. The channel is deeply incised into alluvial fan deposits of pre-Lahontan age.

FIGURE 20. Mosaic view of the north end of Grass Valley where Lake Gilbert overflow has been indicated by various investigators. The topographic closure (T) is approximately 127 feet above the level of the maximum Lahontan age shore feature (L). Overflow appears highly unlikely in pre-Lahontan time also. Three well-developed shoreline bars indicate prolonged stability at three lake stages, which in turn suggest three periods of differing pluvial conditions.

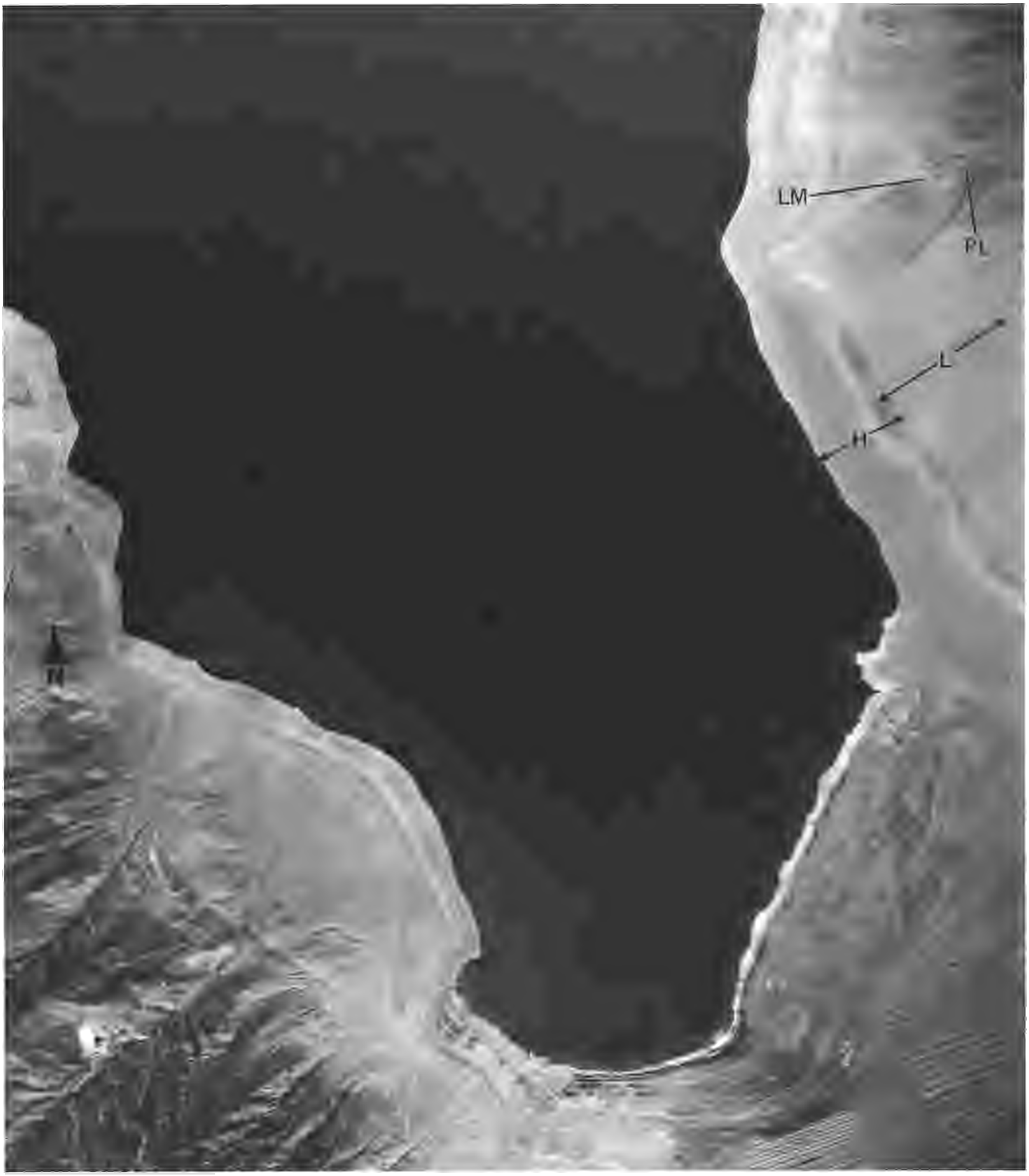

FIGURE 21. View of the south end of Walker Lake and the Thorne Point bar. Above the clearly maximum Lahontan age shoreline at about 4,370 feet MSL (LM) occur well-rounded gravels and landform expression of possible pre-Lahontan bar material up to 4,480 feet MSL (PL). This and other evidence suggests a hypothesis of pre-Lahontan age overflow of Lahontan Basin to the south. Below the railroad tracks historic shorelines occur (H), and above, poorly preserved primarily due to erosional activity, occur Lahontan age shorelines (L). Note that the point bar shore features are in a favorable position for prolonged preservation.

The evidence recognized here suggests a hypothesis of long-term regional downwarping to the north, with Rye Patch or earlier pluvial lakes spilling southward beyond the Lahontan age drainage divide to form a series of evaporite basins.

The pluvial paleohydrography as determined by this study, including overflows during Lahontan time and possible earlier overflow histories, provides additional perspective to the considerations of Hubbs and Miller (1948) on distribution of fish in the Great Basin. Findings of this study indicate overflow in Lahontan time is more limited in comparison to the data Hubbs and Miller worked with, and that lake distribution (as defined) was much more restricted. The opportunity for transfer of Lahontan fish to Alvord Basin by shifting drainage was not reflected in their sample analyses, but the affinity of the fish assemblages to the south of the Lahontan Basin with Lahontan Basin species was noted. The actual mechanism of fish transfer in the Great Basin, and time required for the development of distinct populations through isolation, are subjects warranting further consideration. Hubbs and others (1974) have further investigated eastcentral Nevada fish with respect to paleohydrography; however, results of this study indicate that a more accurate history of paleohydrography is possible with respect to distribution of pluvial lakes and timing of basin closures.

In summary, pluvial lake data given on plate 1 and the Appendix have been developed through application of a somewhat rigid set of criteria. The principal evidence used to recognize and map the pluvial lakes is the preserved shoreline features. In addition, attention has been given to the apparent age of the shore features through consideration of preservation, weathering, drainage history, and associated soils. Other lines of evidence have been considered but have not been judged reliable criteria. Numerous previous interpretation of pluvial lakes, basin closures, and "lacustrine" deposits have been judged in this study to be unreliable, and therefore, a number of previously mapped pluvial lakes have been omitted. As the following quantitative analyses will demonstrate, the developed pluvial lake data of plate 1 and the Appendix yield consistent results. Such consistency is not possible using the lake distributions of previous work.

## Modern Climate and Estimation of Pluvial Climate

When a comparison is made between the modern climate and the pluvial climate of a given basin or a given region of the Great Basin using Equation 4, the variables of the equation must be known. Scattered long-term modern climatic data are available in terms of mean annual precipitation and associated temperature; evaporation from a few deep bodies of water is fairly well known; and localized runoff is somewhat known in scattered parts of the Great Basin. The most successful approach in climate comparison is to consider the mean annual temperature, precipitation, and evaporation as the prime variables which describe the climates.

### Precipitation and Temperature

In most of the Great Basin there is one overwhelming aspect about modern precipitation, that is, precipitation is highly variable with respect to physiographic conditions and time. In high mountains there is clearly an orographic effect with much larger precipitation values occurring in the mountains than in the basins. The three types of precipitation, cyclonic, convective and orographic—as generated by some mechanism to lift air masses to produce cooling and associated condensation—are clearly operative in the Great Basin. Precipitation is more or less evenly distributed between warm and cold months in much of Nevada. Cold month precipitation is more important with respect to runoff and ground-water recharge; snowpacks in the high mountains store enough moisture to permit runoff to overcome high evaporation and transpiration rates in the warmer summer months. Much of the warm weather precipitation is lost to the atmosphere through "in situ" evaporation and transpiration in a matter of hours or days.

An important problem in the available precipitation/temperature data is the distribution of measurement stations with long-term records. Most stations are located in basin lowlands, only a few are in low passes or valleys within mountainous areas, and even fewer are on mountain ridges or crests. Areas receiving the most important amounts of precipitation are therefore those with the least data. Generally, piedmont and valley portions of basins in Nevada receive less than 8 inches of moisture per year. Most mountain ranges with more than 3,000 feet of relief. receive more than 14 inches per year, and the highest mountain ranges receive more than 20 inches per year in crestal portions.

Unfortunately, precipitation and temperature in the Great Basin are not consfstently dependent variables. Figure 22 is a plot of Climatic Division means of temperature and precipitation, with supplemental individual station data selected upon the basis of low mean annual temperatures to give some additional perspective to the meaning of the Climatic Division data plots. The scatter of the data makes estimation of expected precipitation with a temperature drop not particularly satisfying, and this problem is perhaps the weakest aspect of comparing modern climate with pluvial climates through the use of Equation 4. Since there is no better alternative, these data have been used to develop precipitation/temperature curves to estimate what might be expected with a temperature drop.

Careful study of the geographic and physiographic relationships of the data of Figure 22 yields some basis for developing the needed curves. By inspection, it can be seen that two trends seem to be established by the Climatic Division mean plots. The upper trend is best defined and in the 50°F to 45°F mean annual temperature range, depicts the moistest portions of the Great Basin; for example, southeastern Oregon, southcentral Utah, southcentral Oregon, and the northern interior basins of California. The supplemental stations that fall near this trend are mountain crest, mountain flank or mountain valley stations. Supplemental stations of special interest are Austin and Jiggs in northcentral Nevada. Austin is on the western flank of the Toiyabe Range at about 6,800 feet MSL, and Jiggs is at about 5,500 feet MSL in Huntington Valley near the foot of the Ruby Mountains.

The lower trend is not as well defined. It is established by the means of Climatic Divisions of northwest and northeast Nevada, and the High Plateau of Oregon. Most stations of these divisions are located in basin environments. The supplemental station plots in Nevada and Oregon are all within the intermontane valleys.

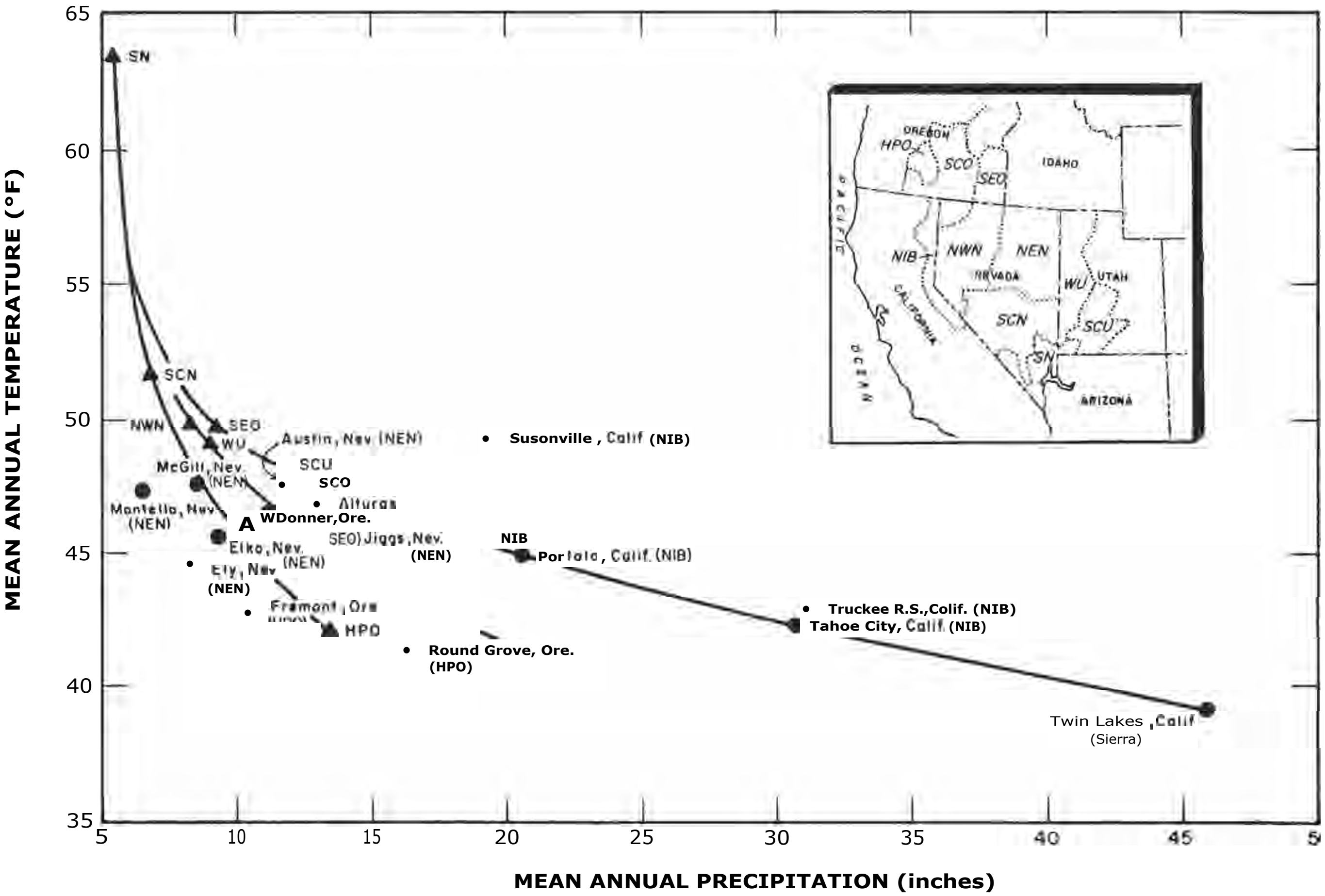

FIGURE 22. Relation of mean annual temperature to mean annual precipitation based on State Climatic Divisions, 1931-1960.

In considering these data and the typical basin configuration of the Great Basin, it is reasonable to suggest the lower Climatic Division trend represent what might be expected in the very intermontane basin environments; the upper curve represents less arid high mountain flank and crestal environments, and a few less arid basins in the north and east of Nevada. Many of the basin lowlands in this study are best related to the lower curve; however, three extreme northwestern basins of Nevada better fit the upper curve, as do parts of Lahontan Basin (the mountainous areas of the Sierra Nevada rivers and Humboldt River headwaters). Some of northcentral Nevada also may lie closer to the upper curve relationships than the lower curve, as indicated by the Austin and Jiggs data.

In analyzing Great Basin topographic configurations and requirements of precipitation values in Equation 4, it has been found that about 10 percent of the hydrographic basin can be considered high mountain terrain and the rest is intermediate or basin lowland. When precipitation is weighted according to terrain altitude using the precipitation map of Nevada, it is found that tributary basin precipitation ($P_T$) is usually about 25 percent higher than basin floor precipitation ($P_L$). This, of course, will vary in both directions depending upon the particular basin and associated mountain terrain; however, a more sensitive approach is not warranted because of the estimated nature of precipitation isohyetes in the precipitation maps of Nevada.

Figure 22 has been adopted as a guide in estimating expected changes in precipitation that seem reasonable if mean annual temperature varied during the pluvial climates. The direction of least climatic change necessary to provide more moisture is clearly toward lower mean annual temperatures; however, due to the spread of data represented by the upper and lower trends of the developed temperature/precipitation curve, judgment is necessary to use the curve for evaluating Equation 4. A conservative approach is to attempt to estimate the correct trend for several climatic zones of Nevada and also assume that the upper curve is more representative of tributary precipitation ($P_T$) where appropriate. The lower curve, because of the strong basin bias of the stations, seems reliable for lake precipitation ($P_L$) in the very arid basins. A median curve has been displayed and has been used in several cases, as discussed later. The adopted approach, using Figure 22, assumes the modern climate interdependency of precipitation and temperature in the Great Basin also applied to pluvial climates; it permits a departure from modern climate and adjusts esti: mates of pluvial climate to values of known variation of temperature and precipitation within the Great Basin. Other methods of estimating precipitation with a temperature drop seem less sensitive to the complex and relatively unknown characteristics of climate in the Great Basin. When searching for reasonable departure curves of precipitation and temperature for estimating pluvial climates, it was found that available long-term records do not show a clear correlation of a temperature decrease with more precipitation in the annual records of individual stations. Yet, data presented in Figure 22 clearly suggest interdependence of increased precipitation with lower temperatures in a geographic sense, and this basic observation leads to the underlying assumption that modern climatic variations within the Great Basin give an indication of what should be expected precipitation in Nevada for pluvial climates with lower mean annual temperatures.

### Runoff

Runoff is a function of precipitation and evapotranspiration; however, evapotranspiration is very dependent upon subtle parameters such as terrain conditions and distribution of precipitation in time and intensity. Thus, when evaluating climate from hydrologic conditions depicted by Equation 4, the right-hand term containing runoff is easier to use.

Runoff is also a dependent variable of temperature. Figure 23, adopted and modified from Schumm (1965, p. 784), clearly demonstrates just how important temperature is with respect to runoff from a given amount of annual precipitation. These curves by Schumm are based on runoff throughout the United States presented by Langbein and others (1949, p. 9). Mean annual runoff and precipitation is compared to weighted mean annual temperature. Weighted mean annual temperature refers to the temperature during the time of runoff, i.e., if the majority of runoff occurred during warmer months, a higher weighted mean temperature would result. In Nevada, where the majority of runoff occurs during spring and early summer from snow melt, weighted means should be close to the mean annual temperature. To aid evaluation in this study, trends were somewhat extended beyond Schumm's data supported curves into the region of low runoff and rainfall, as indicated by the question marks in Figure 23.

Collectively, the basins of northwest Nevada have a mean annual temperature of about 50°F and mean annual precipitation of only 8 inches. Using Figure 23, it would appear that something less than 0.1 inches of runoff theoretically should occur each year. All but a small percentage of the region has less than 1 inch of average annual runoff, as shown on an average annual runoff map (Nevada Hydrologic Atlas, 1972). The small areas where runoff exceeds 1 inch are localized areas of exceptionally high terrain where precipitation is much greater than 8 inches; for example, about 31 inches of precipitation at 43°F yields about 11 inches of annual runoff for a mountain station (Truckee Ranger Station, Calif.). This is a profound difference in availability of runoff and directly comparable to only small areas of the highest mountains in Nevada, such as the Carson Range near Reno, the Santa Rosa Range and Jarbidge Mountains in northern Nevada; also, the Ruby Mountains, Snake Range, and Schell Creek Range in northeastern Nevada, and the Toquima Range and Toiyabe Range in central Nevada. These mountainous areas locally yield more than 10 inches of runoff.

In comparing modern climatic conditions and associated runoff to pluvial climatic conditions and associated runoff, the obvious contrast is demonstrated by the existence of the pluvial lakes (plate 1). In other words, pluvial climatic conditions were clearly conducive to more runoff reaching the lower parts of many of the closed basins in Nevada.

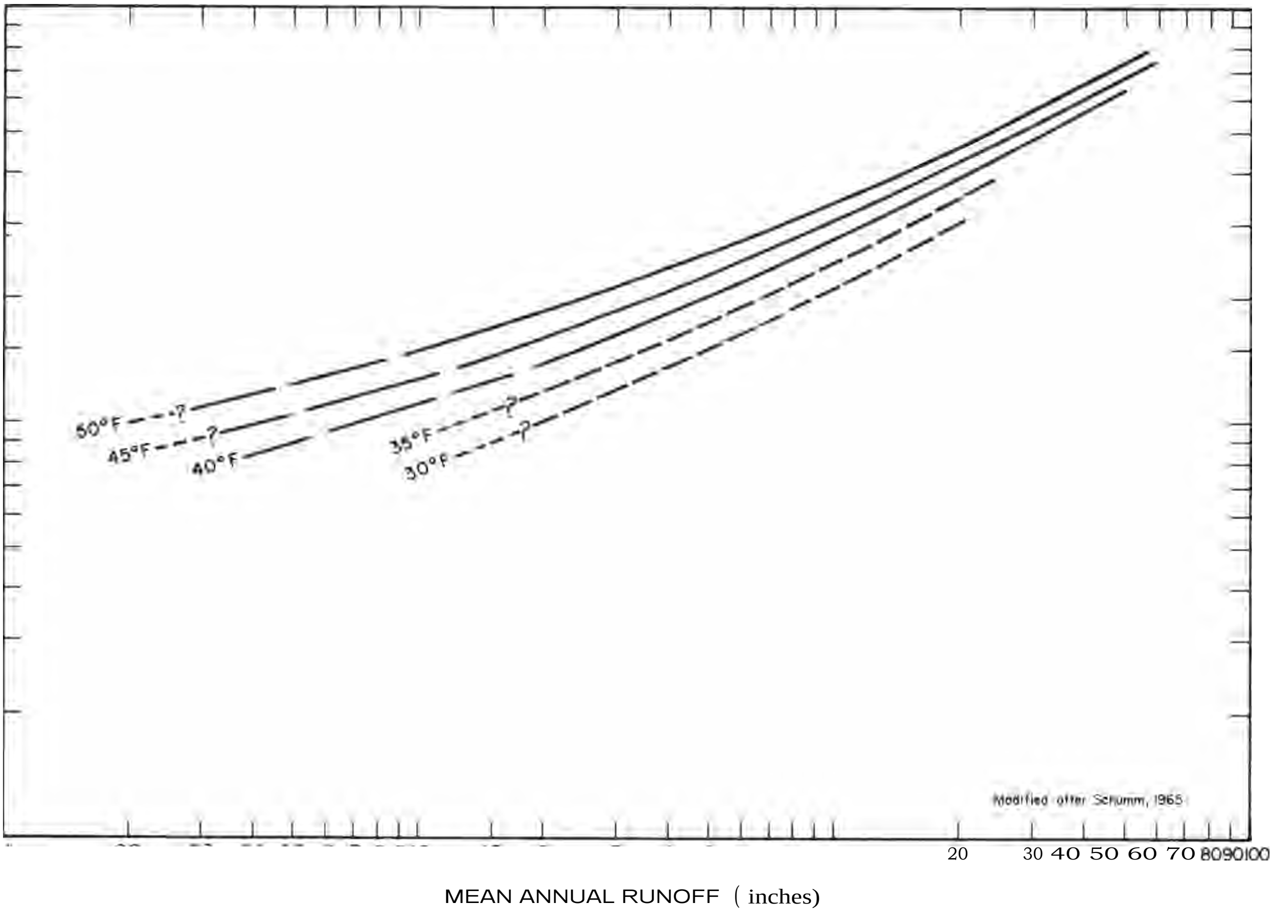

FIGURE 23. Relation between mean annual temperature, precipitation and runoff.

Figure 23 can be used to demonstrate how either a shift in precipitation or a shift in temperature could have increased runoff. In the modern Great Basin temperature regimens, 15 inches of precipitation at 50°F would yield only 1 inch of runoff, but if temperature dropped to 40°F, about 2.5 inches of runoff would occur. Conversely, if only an increase in precipitation occurred, from 15 inches at 50°F to 20 inches at 50°F, runoff would increase from 1 inch to 2.5 inches. In terms of human perception as well as biological and geological processes, the 10°F mean annual temperature drop is a greater change in climate than the 5 inches of increased precipitation. With respect to necessary climate shift, less change is required in precipitation to give impressive hydrologic results.

As demonstrated in Figure 22, it seems most likely that the general lowering of mean annual temperature in the Great Basin would result in an increase in precipitation, which in turn would produce more runoff from the combined effect of the temperature decrease and precipitation increase. This demonstrates, more or less, the direction of "least" change from modern climates that would produce the pluvial climate hydrology of the Great Basin.

### Evaporation

According to Linsley and others (1958, p. 91), evaporation is influenced by solar radiation, air temperature, vapor pressure, wind, and possibly atmospheric pressure. Of these variables perhaps differences in solar radiation and air temperature are the most important factors in producing differences in evaporation from deep water bodies in the Great Basin. All other influencing parameters are more or less similar throughout the Great Basin.

Numerous studies of evaporation from lakes in the Great Basin provide data to establish graphs for estimating evaporation rates from large lakes. Figure 24 has been developed from data presented by Harding (1965, p. 22), Phillips and Van Denburgh (1971, p. B1) and Langbein and others (1949). These data of lake evaporation demonstrate the effect of altitude (air temperature primarily) and suggest the lesser influence of latitude (solar radiation). Data of Figure 24 suggest no more than about 7.2 inches of variation in evaporation within a range of 6° latitude; however, each change in altitude of 1,000 feet generates as much as 10.8 inches (between 1,000 and 2,000 feet altitude) to as little as 3 inches of evaporation (between 6,000 and 7,000 feet altitude). Snyder and Langbein (1962, p. 2390-2391), in their study of pluvial Spring Lake in eastern Nevada, estimated evaporation rates decrease at about 6 percent per 1,000 feet rise in altitude in the Great Basin. In Figure 24, however, between 3,000 and 4,000 feet altitude, a 13.7 percent decrease is indicated [(51 inches per year) —(44 inches per year) ÷ (5 inches per year)] and between 5,600 and 6,600 feet altitude a 10.3 percent decrease is indicated. In the study by Snyder and Langbein (1962) their assumed 6 percent decrease appears to have been slightly low according to existing data, and the values and associated trend of Figure 24 are believed to provide a more viable departure for estimation of pluvial lake evaporation.

The pluvial lake evaporation rates can be approximated from modern rates by assuming a similar lapse rate as modern climate (3.5°F/thousand feet of altitude change) and adjusting the rate according to estimated mean annual temperature drop; for example, 4°F, 5°F, and 6°F temperature drops would represent increases in altitude of 1,143, 1,429, and 1,714 feet, respectively, and corresponding lesser rates of lake evaporation as taken from Figure 24.

### Comparison of Climates

Methods for estimating all necessary parameters of Equation 4 have been developed from either modern observations of climate and hydrology with associated extrapolations, or from the physical evidence of the pluvial lakes and their respective basin characteristics. Calculated hydrologic indices are sensitive to small differences in values of lake precipitation ($P_1$) and runoff (RT) produced by assumed amounts of precipitation increase due to a temperature drop. Lake evaporation remains at a fixed rate according to a temperature drop, although adoption of a different lapse rate or different initial modern departure values could make important differences in the calculated indices. In this study Figure 22 is the most critical in its assumptions and application in evaluations using Equation 4.

Climatic Division means depicted in Figure 22 are believed reasonable departure points to estimate the pluvial climates of the Great Basin. It is informative to adopt the procedure of assuming a lower mean annual temperature of some amount and then attempt to establish what the hydrologic responses in the basins would have been through the use of Equation 4. The magnitude of necessary temper-

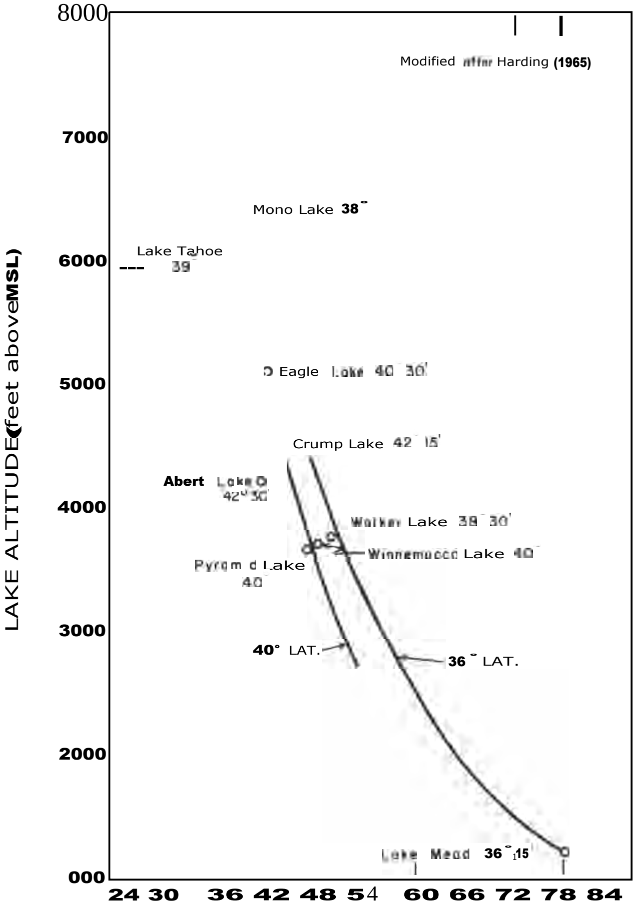

FIGURE 24. Mean annual evaporation from large lakes.

ature drop is of great interest, as suggested changes range from as little as 4.5 F (Antevs, 1952) to as much as 20 F (Galloway, 1970).

The relationships developed in the preceding sections permit trial and error calculation of pluvial indices until the calculated indices match the measured pluvial indices. Calculation of the indices for a given climatic zone of Nevada with Equation 4 has been performed in the following manner:

1) A mean annual temperature change is assumed and subtracted from the Climatic Division mean annual temperature of the zone of interest.
2) The corresponding increase in precipitation is established from one of the trends of Figure 22 to give either the lake precipitation $(P_L)$ or the tributary precipitation $(P_T)$.
3) The lake or tributary precipitation value is then calculated by adding or subtracting 25 percent.
4) Lake evaporation (EL) is determined from Figure 24 by establishing lake elevation and then correcting for the temperature drop by increasing the altitude according to the modern lapse rate of 3.5°F/1,000 feet.
5) Runoff, (RT) is determined by using Figure 23 with the adopted mean annual temperature and the tributary precipitation already determined.
6) Computation of the pluvial index (Z) of Equation 4 is made using the derived variables of the preceding five steps.

In order to facilitate the comparison of measured pluvial indices with calculated indices through the use of Equation 4, the basins representing climatic zones have been grouped together to establish the mean lake elevations and the mean pluvial index (Z) within each zone. The effect of this procedure is for generalized climatic relationships to be compared with generalized measured pluvial indices. Tables 2 through 6 group the basins according to the estimate of similar modern climate which more or less corresponds to the Weather Bureau Climatic Division. One should note that the measured values of the pluvial indices more or less vary in magnitude with respect to modern climate. The largest indices occur in the basins which now experience the coolest and moistest climates. This relationship supports the basic assumption made in this study of uniformity between the pluvial and modern climates; that is, the pluvial climates were closely related to modern climates of the Great Basin and the differences are probably the result of relatively small shifts in mean annual temperature with corresponding shifts in precipitation and associated hydrologic response. While indices vary in magnitude within the Climatic Division groupings, all measured pluvial indices seem to fit a general pattern established by the conditions of modern climate and terrain characteristics.

**TABLE 2. Extreme Northwestern Nevada (ENWN) pluvial data.**

| Basin/Lake | Plate I No. | Lake Altitude | Pluvial Index |
|---|---|---|---|
| Long/Meinzer | 43 | 5,800 | 0.91 |
| Macy Flat/Macy | 45 | 5,860 | 0.56 |
| Surprise/Surprise | 65 | 5,140 | 0.57 |
| | Mean | 5,600 Mean | 0.68 |

**TABLE 3. Northwestern Nevada (NWN) pluvial data.**

| Basin/Lake | Plate I No. | Lake Altitude | Pluvial Index |
|---|---|---|---|
| Antelope | 3 | 5,112 | 0 |
| Cold Spring/ Laughton | 14 | 5,120 | 0.19 |
| Dixie/Dixie | 18 | 3,600 | 0.13 |
| Gabbs | 25 | 4,085 | |
| Granite Springs/ Granite Springs | 29 | 3,856 | 0.04 |
| Kumiva/Kumiva | 38 | 4,400 | 0.04 |
| Lemmon/Lemmon | 41 | 4,990 | 0.19 |
| | Mean | 4,452 Mean | 0.084 |

The use of Figure 22 to establish lake and tributary basin precipitation (PL and PT) requires a certain amount of judgment to make the quantitative comparison of climates as meaningful as possible. Extreme Northwestern Nevada (ENWN) contains three basins with modern climates closer to the Southcentral Oregon Climatic Division and the Northern Interior Basins Climatic Division of California. It seems reasonable to adopt the upper trend of data in Figure 22 and consider it the tributary precipitation $(P_T)$ parameter. This judgment is made upon the basis of modern hydrology, distribution and type of vegetation. frequency of snow falls, and limited climate records, as well as the magnitude of the measured pluvial hydrologic indices of the three basins.

The grouping of basins assigned to the Northwest Nevada Climatic Division (NWN) is not very satisfying.

**TABLE 4. Northeastern Nevada (NEN) pluvial data.**

| Basin/Lake | Plate I No. | Lake Altitude | Pluvial Index |
|---|---|---|---|
| Antelope/Antelope | 4 | 5,724 | 0.16 |
| Big Smoky/Toiyabe | 6 | 5,585 | 0.19 |
| Butte/Gale | 9 | 6,250 | 0.28<br>(overflow ?) |
| Cave/Cave | 10 | 6,000 | 0.23 |
| Clover-Independence/ Clover | 12 | 5,674 | 0.53 |
| Edwards Creek/Edward | 21 | 5,280 | 0.34 |
| Goshute/Steptoe | 28 | 5,777 | 0.20 |
| Grass/Gilbert | 31 | 5,740 | 0.36 |
| Jakes/Jakes | 35 | 6,380 | 0.19 |
| Lake/Carpenter | 40 | 5,985 | 0.34 |
| Little Smoky/Corral | 42 | 6,500 | 0.23 |
| Long/Hubbs | 44 | 6,300 | 0.41 |
| Newark/Newark | 49 | 6,060 | 0.28 |
| Ruby/Franklin | 56 | 6,068 | 0.61 |
| Smith Creek/Desatoya | 58 | 6,230 | 0.41 |
| Spring/Maxey | 61 | 5,793 | 0.17 |
| Spring/Spring | 62 | 5,770 | 0.27 |
| Stevens/Yahoo | 63 | 7,320 | 0.11 |
| | Mean | 6,025 Mean | 0.295 |

**TABLE 5. Southcentral Nevada (SCN) pluvial data.**

| Basin/Lake | Plate I No. | Lake Altitude | Pluvial Index |
|---|---|---|---|
| Alkali Spring | 1 | 4,802 | 0 |
| Big Smoky/Tonopah | 7 | 4,800 | 0.05 |
| Clayton | **11** | 4,266 | 0 |
| Coal/Coal | 13 | 4,990 | 0.07 |
| Columbus Salt Marsh | 15 | 4,680 | 0.06 |
| Dry Lake/Bristol | 19 | 4,620 | 0.04 |
| Emigrant/Groom | 23 | 4,475 | 0.05 |
| Garfield/Garfield | 26 | 5,600 | 0.03 |
| Gold Flat/Gold Flat | 27 | 5,120 | 0.04 |
| Huntoon | 32 | 5,640 | 0 |
| Kawich/Kawich | 37 | 5,370 | 0.07 |
| Monte Cristo | 48 | 5,274 | 0 |
| Penoyer | 52 | 4,738 | 0 |
| Railroad/Railroad | 53 | 4,870 | 0.09 |
| Ralston/Mud | 54 | 5,280 | 0.05 |
| Rhodes/Rhodes | 55 | 4,432 | 0.07 |
| Soda Spring (Acme) | 59 | 4,373 | 0 |
| Soda Spring (Luning) | 60 | 4,439 | 0 |
| Stonewall | 64 | 4,649 | 0 |
| Teels Marsh | 66 | 4,904 | 0 |
|  | Mean | 4,866 | Mean 0.031 |

Two basins, Cold Spring and Lemon (14 and 41 in plate 1) are hydrologically influenced by an eastern spur of the Sierra Nevada, Peavine Mountain, which yields more runoff than most of the other high areas feeding other basins in this group. Another basin, Dixie Valley (18 in plate 1) has high bounding ranges with climate more similar to the northeastern Nevada grouping even though the basin floor is the lowest in the northern half of Nevada. The other four basins included in this group are extremely arid due to the rain shadow effect of the Sierra Nevada. In view of the variation in modern hydrology and climate of the basins in this group, two separate trends and associated values for lake and tributary basin precipitation have been adopted from Figure 22. Clearly, part of this region of Nevada is very arid, and the lower data trend of Figure 22 is most descriptive. The three basins mentioned, Cold Spring, Lemon and Peavine Mountain, seem to be more in a transitional climatic position between the two data trends of Figure 22, and thus the median curve has been developed and used to evaluate Equation 4. This dual approach also allows demonstration of the effect or sensitivity of use of Figure 22 with respect to estimating mean annual temperature differences between pluvial and modern climates.

The majority of the Northwestern Nevada Climatic Division is part of the Lahontan Basin (39 and 39 A through 39 G in plate 1). Lake Lahontan, however, has been omitted from this group for two reasons: 1) its size and subbasin hydrologic complexity during the pluvial climatic interval, and 2) the clear difference of climates in the two prime nourishment regions, the Sierra Nevada and the northeastern mountains of Nevada. These two aspects more or less defeat the evaluation approach being employed, and thus Lake Lahontan is treated separately.

Data on the Northeastern Nevada Climatic Division are problematic, as can be seen by the supplemental data points in Figure 22. The only two long-term high valley or mountain flank stations of Nevada are within this region and nicely plot along the upper data trend of Figure 22; however, McGill, Montello, Ely and Elko stations are also in this region and clearly demonstrate the aridity of at least some of the intermontane basins. Again, the median curve and the lower curve in Figure 22 have been used to develop precipitation values for use in Equation 4 and to provide a sensitivity test in the use of Figure 22.

The basins of the Southcentral Nevada Climatic Division (SCN) are quite arid with respect to modern climate, and the lower trend of Figure 22 has been adopted to establish precipitation values for Equation 4 evaluation. The Southern Nevada Climatic Division basins (SN) have been treated by using the upper part of the Climatic Division data trend in the temperature region where there is no divergence. While this approach yields no significant increase in precipitation from modern climate to estimated pluvial climate, when small temperature shifts are assumed, the absence of physiographic evidence for pluvial lakes in this climatic division supports aridity during the pluvial climate. To the extreme north of the southern grouping is a general decrease in magnitude of measured pluvial hydrologic indices to the smallest measured values (0.05 to 0.03) as basins become lower or more southerly in the Southcentral grouping (SCN) of closed basins. Nine of the 20 basins of the Southcentral grouping contain no recognizable pluvial lake features. In the Southern Nevada group (SN) the modern climate is much warmer, and accordingly, rates of evaporation and evapotranspiration are much greater. There is considerable evidence, however, that at least the higher mountains in southern Nevada received more moisture during the pluvial climate, and accordingly Figure 22 may not be very satisfactory for this part of Nevada.

**TABLE 6. Southern Nevada (SN) pluvial data.**

| Basin | Plate I No. | Altitude | Pluvial Index |
|---|---|---|---|
| Apex Dry Lake | 5 | 1,968 |  |
| Delamar | 16 | 4,538 |  |
| Desert | 17 | 3,206 |  |
| East Jean | 20 | 2,995 |  |
| Frenchman | 24 | 3,077 |  |
| Grapevine Canyon | 30 | 4,015 |  |
| Indian Springs | 33 | 3,014 |  |
| Ivanpah | 34 | 2,602 |  |
| Jean Dry Lake | 36 | 2,784 |  |
| Mesquite | 46 | 2,540 |  |
| Pahrump | 50 | 2,457 |  |
| Papoose | 51 | 4,569 |  |
| Sarcobatus | 57 | 3,939 |  |
| Yucca | 68 | 3,414 |  |
|  | Mean | 3,223 | Mean 0 |

This region deserves careful consideration as a result of the previously discussed Haynes (1967) interpretation of his careful stratigraphic study in the Tule Springs area and because of the many other reports of lacustrine sediments believed to be of Pleistocene age. Therefore, to make a test that is very liberal with respect to pluvial precipitation values, the lower curve of Figure 22 is assumed to begin its point of inflection, as it does at the Southcentral Nevada Climatic Division data point, and at the Southern Nevada Climatic Division data point. Table 7 illustrates the calculated results for mean annual temperature drops of 5°F, 10 F, and 15 F.

Even when using the exaggerated precipitation curve modification of Figure 22, a 10°F temperature drop is necessary to produce a calculated index that is nearly equal to the smallest measured index of Nevada. In addition, the physiographic evidence indicates that pluvial bodies of water much smaller than the small mapped pluvial lakes yielding the minimum value indices were too shallow and/or ephemeral to produce reliably recognizable shoreline features. Based on the necessity for more than double the mean annual temperature shift that will be demonstrated as necessary for the rest of Nevada and the absence of shoreline features, we can therefore conclude, that southern Nevada did not contain perennial lakes during the Wisconsinan pluvial; also, that the "lacustrine"-like sediments of this general age have a more subtle origin as previously discussed.

### Estimated Full Pluvial Climate

Table 8 gives the results of the evaluations of Equation 4, assuming 4°F, 5°F, and 6°F mean annual temperature drops, and compares the calculated pluvial indices (Z) with the regional mean values of the measured indices (Z). The results indicate a 5°F or 6°F mean annual temperature drop. The 6°F drop approximates the measured mean index three times, the 5°F twice, and in one case, a 4°F drop b.est approximates the measured mean index. With respect to the favored choice of curves from Figure 22, as indicated by asterisks in Table 8, the 5°F drop in mean annual temperature is the favored general measure of the difference between modern and full pluvial climates.

An important consideration is the sensitivity of the calculated index to the use of differing curves of Figure 22 with respect to necessary temperature drop. Generally speaking, when adjacent curves of Figure 22 are used for evaluating the index, the matching temperature changes by 1°F. In the case of the northeastern Nevada evaluation, the difference is 2°F due to the low initial Climatic Division temperature and the greater divergence of precipitation curve trends in this region of temperature. These relationships are comforting in that the choice of curves of Figure 22 is necessarily somewhat subjective.

TABLE 7. Evaluation of Southern Nevada (SN) with exaggerated precipitation.

| | AT | $P_L$ | $P_T$ | $R_I$ | $E_L$ | |
|---|---|---|---|---|---|---|
| 58.5 | 5°F | 8 | 10 | <0.1 | 46 | 0.0026 |
| 53.5 | 10°F | 12 | 15 | 0.8 | 41 | 0.028 |
| 48.5 | 15°F | 19 | 23.8 | 4 | 34 | 0.267 |

In the four evaluated regions of Nevada where pluvial lakes were present, the derived pluvial lake precipitation (EL) values are considerably greater than the modern basin precipitation values (Climatic Division data). These differences, calculated as percent increase over the modern data, are as follows: ENWN 77 percent, NWN 63 percent, NEN 80 percent, and SCN 52 percent. The calculated numerical increases range from 3.3 to 9.5 inches and average 6.5 inches of precipitation. Due to the manner in which the estimated climate shifts were derived, the calculated increases in tributary basin precipitation are of similar percentage, but 25 percent greater in numerical magnitude. Thus, the quantitative evaluations using Equation 4 yield, in general terms, a statewide shift of climates to mean annual temperature about 5°F lower, with an average of 68 percent more precipitation. Reduction in lake evaporation averaged 10 percent.

It is informative to compare the derived climate changes with the extremes of historic climate data in the same regions. Table 9 depicts the mean and extremes in annual temperature and precipitation between 1931 and 1960 for the Climatic Divisions used in the analysis. The largest recorded extremes in precipitation generally approach the pluvial lake values that were estimated as necessary. With the exception of northeastern Nevada, however, the lowest recorded temperatures are 2°F or more above the estimated pluvial climate temperature. These relations indicate hydrologically significant but rather small differences between modern and full pluvial climates. The shifts in climate are slightly more than the normal extreme variations in annual climatic conditions of the modern climates. Further, the estimated increases of precipitation seem very reasonable in view of the data comparisons in table 9. One important aspect of the annual records is that there is no correlation between wet years and lower mean annual temperature; they are sometimes warmer, average or cooler in temperature, and thus one might argue the basic assumption used in adoption of Figure 22 is without basis. Careful examination of Table 9 does illustrate the basis for this assumption, that lower temperature should yield more precipitation, at least in Nevada. The data of the four Climatic Divisions of Nevada illustrate this overall trend.

### Evaluation of Lake Lahontan

The Lahontan Basin presents a complex problem when an attempt is made to follow the preceding approach of hydrologic index generation. The basic problem stems from basin overlap into climatic zones which greatly differ from one another. In addition, subbasins with pluvial lakes which overflowed add to the complexity. Perhaps the greatest stumbling block is estimating the appropriate modern climatic parameters in appropriate climatic zones, such as the Sierra Nevada and the Susan River/Madeline Plains region, and then weighting them according to percentage of basin area involved. While possible and perhaps informative to perform, the latter would offer much room for error as compared to those derivations already performed. A more valuable approach is to solve for runoff (RT) and then consider whether or not such derived runoff reasonably could be generated with a 5°F drop in temperature. The following parameters are obtained from Figures 22 and 24, recognizing that most of the lake was restricted to the northwestern Nevada climatic zone, and the general lake

TABLE 8. Comparison of calculated indices with mean measured indices.

| | | AT | | $P_I$ | $R_T$ | $E_L$ | | $\bar{Z}$ | Fig. 22 Curve |
|---|---|---|---|---|---|---|---|---|---|
| ENWN<br>(5600')<br>(47.5°F) | 43.5 | 4°F | 18.75 | 25 | 6.8 | 35 | 0.42 | | |
| | 42.5 | 5°F | 21.75 | 29 | 9.2 | 34 | 0.751 | 0.68 | Upper |
| | 41.5 | 6°F | 25.5 | 34 | 15 | 33 | 2.0 | | $(P_T)$ |
| NWN<br>(4452')<br>(50°F) | 46 | 4°F | 10 | 12.5 | 0.77 | 39 | 0.027 | | |
| | 45 | 5°F | 10.5 | 13.1 | 1.05 | 38 | 0.038 | | Lower |
| | 44 | 6°F | 11.5 | 14.4 | 1.65 | 37 | 0.065 | 0.084 | |
| | 46 | 4°F | 12 | 15 | 1.48 | 39 | 0.05 | | |
| | 45 | 5°F | 13.5 | 16.9 | 2.25 | 38 | 0.092 | 0.084 | Median* |
| | 44 | 6°F | 15 | 18.8 | 3.3 | 37 | 0.15 | | |
| NEN<br>(6025')<br>(46°F) | 42 | 4°F | 13.5 | 16.9 | 3 | 34 | 0.15 | | |
| | 41 | 5°F | 15 | 18.8 | 3.6 | 33 | 0.20 | | Lower |
| | 40 | 6°F | 16 | 20 | 4.5 | 32 | 0.28 | 0.295 | |
| | 42 | 4°F | 19 | 23.8 | 6 | 34 | 0.4 | 0.295 | |
| | 41 | 5°F | 21 | 26.9 | 7.5 | 33 | 0.65 | | Median* |
| | 40 | 6°F | 23 | 29.4 | 11 | 32 | 1.29 | | |
| SCN<br>(4866')<br>(51.5°F) | 47.5 | 4°F | 9 | 11.25 | 0.5 | 39 | 0.017 | | |
| | 46.5 | 5°F | 9.5 | 11.9 | 0.64 | 38 | 0.022 | | Lower |
| | 45.5 | 6°F | 10.2 | 12.8 | 0.9 | 37 | 0.034 | 0.031 | |
| SN<br>(3223')<br>(63.5°F) | 59.5 | 4°F | 5.5 | 6.9 | <0.1 | 47 | 0.0024 | | |
| | 58.5 | 5°F | 5.5 | 6.9 | <0.1 | 46 | 0.0025 | 0 | |
| | 57.5 | 6°F | 6 | 7.5 | <0.1 | 45 | 0.0026 | | |

surface at maximum stage (before isostatic rebound) was approximately 4,360 feet MSL:

$$EL = 37 \text{ inches}$$

$$P_L = 11 \text{ inches (minimum curve from Figure 22)}$$

$$Z = 0.26$$

$$Z = 0.26 = \frac{R_T}{37 - 11} \text{ or } RT = 6.75 \text{ inches}$$

If the mean annual temperature within the basin was between 40°F and 45°F, approximately 23 to 26 inches of tributary precipitation would have been required to produce such runoff. Such an amount seems reasonable when compared to those tributary precipitation estimates derived for northwestern Nevada (13.1 or 16.9 inches), northeastern Nevada (18.8 or 26.6 inches), and extreme northwestern Nevada (29 inches). The moisture rich Sierra Nevada would have had even higher values and could have more than made up for the drier parts of the basin. Additionally, there would have been a greater opportunity for evapotranspiration of the large basin and subbasin pluvial lakes. While the evaluation lacks precision, the derived Lahontan Basin runoff value is slightly lower than the derived pluvial runoff mean of the three climatic zones that the basin straddles (6.8 inches to 7.1 inches). Therefore, the 5°F lower mean annual temperature is adequate to generate Lake Lahontan, and necessary runoff is consistent with prime nourishment-area runoffs derived from the same temperature change.

### Modern Hydrologic Indices

Examination of hydrologic conditions in most topographically closed basins once occupied by pluvial lakes, reveals the equivalent of very small indices. If indices are to be measured upon the basis of lake area, only a few have values exceeding zero. This approach is believed the most valid for direct comparison of modern hydrologic indices with pluvial indices; however, most basins do receive water through groundwater flow to areas of discharge in the lower parts of the bolsons. Further, most basins are occupied by playas which occasionally receive surface-water runoff from infrequent runoff events. Water on playas is spread out into thin sheets, often only a few inches or less in depth and usually evaporates within a matter of days or weeks even in winter months. There is little data on the percent of time or extent of inundations for playas in Nevada. Playas range from very small areas

**TABLE 9. Comparison of evaluated pluvial climates with annual extreme variations of Climatic Division means, 1931-1960.**

| Climate Division | Evaluated Climate Temp/ F $P_L$/inches | Annual Temperature (°F) High Mean Low | Annual Precipitation (inches) High Mean Low |
|---|---|---|---|
| SCO (ENWN) | 42.5 | 50.4 | 17.38 |
| | | 46.7 | 12.28 |
| | 21.75 | 44.5 | 6.86 |
| NWN | 45 | 53.0 | 12.75 |
| | | 49.8 | 8.30 |
| | 13.5 | 47.5 | 3.90 |
| NEN | 42 | 50.9 | 16.45 |
| | | 45.9 | 10.53 |
| | 19 | 42.6 | 7.47 |
| SCN | 45.5 | 55.0 | 12.77 |
| | | 51.7 | 6.72 |
| | 10.2 | 49.7 | 3.10 |
| SN | 58.5 | 67.3 | 11.37 |
| | | 63.5 | 5.10 |
| | 8* | 61.9 | 1.40 |

*Value from Table 7 based on adjusted curve of Figure 22.

to hundreds of square miles in extent, but even the largest playas receiving ephemeral runoff would be equivalent to very small areas of perennial lake surface yielding three or more feet of evaporation per year. Estimates of modern hydrologic indices based on ephemeral surface water on playas and groundwater discharge can be approximated by modifying Equation 4 to :

$$Z_M = A_E(E_P - P_B) = A_I(R_S + R_G)$$

or

$$Z_M = \frac{A_E}{A_T} = \frac{R_S + R_G}{- P_B} \qquad (5)$$

where, $A_E$ = Area necessary to evaporate the combined surface water ($R_S$) and ground water (RG) reaching the basin floor,

$E_P$ = Potential evaporation, and

$P_B$ = Modern basin precipitation.

Calculations over the tributary area always yield less than 1 inch per year and usually less than half inch per year where estimates of groundwater discharge have been made (Mifflin, 1968; Nevada Hydrologic Atlas, 1972). Examination of the surface-water runoff map of Nevada (Nevada Hydrologic Atlas, 1972) demonstrates a mean of less than 2 inches of surface runoff distributed over tributary basins; usually it is considerably less than 1 inch. Thus, a maximum modern hydrologic index for northeastern Nevada can be approximately evaluated as follows:

$$Z_M = \frac{R_S + R}{E_P - P_B} = \frac{1 + 0.5}{40 - 10.5} = \frac{1.5}{28.5} = 0.053$$

Ruby Valley (56 in plate 1), on the east side of the Ruby Mountains, constitutes one of the moistest closed basins in northeastern Nevada. This basin has a well-developed perennial paludal body of water called Ruby Marsh nourished by a number of large carbonate rock springs which yields a hydrologic index of 0.026 when the marsh area is used for a measured lake area in Equation 4. The marsh measurement provides a direct comparison to the pluvial index of Ruby Valley. This value omits about an equal amount of groundwater and surface-water discharge (hay meadows, areas of phreatophytes, playa and marsh) in the northern half of the valley north of Ruby Marsh. This northern Ruby Valley runoff is not as distributed in time nor as concentrated as the spring flow of the Ruby Marsh System. Thus, if the total runoff to the entire valley is considered, the modern hydrologic index would be about 0.05 or approximately that calculated as maximum hydrologic index for northeastern Nevada.

In northwestern and southcentral Nevada all modern indices are smaller, and only in a few extreme northwestern basins (and in a number of basins occurring just beyond the Nevada line in California) do conditions suggest modern hydrologic indices of similar magnitude. In these latter basins the playas are more frequently occupied by water or are playa lakes, and groundwater discharge from large areas of phreatophytes suggest a half inch or so of groundwater discharge.

In the drier areas, the following evaluation of Equation 5 gives an idea of a maximum hydrologic index for southcentral Nevada:

$$Z_M = \frac{R_S + R}{E_P - P_B} = \frac{.5 + .25}{44 - 8} = \frac{.75}{36} = 0.02$$

In southern Nevada, the following might be expected:

$$Z_M = \frac{R_S + RG}{E_P - P_B} = \frac{.5 + .25}{54 - 5} = \frac{.75}{49} = 0.012$$

All evaluations of modern hydrologic indices using Equation 5 yield values not directly comparable to the values obtained in Equation 4 for pluvial indices. The prime reason direct comparison is misleading is the artificial way in which the basin shape has been circumvented in Equation 5. All surface water ($R_S$) and groundwater runoff (RG) does not concentrate into one localized perennial body of water due to basin shape. If surface water runoff ($R_S$) and groundwater runoff (RG) could be measured at the edge of the playas, both would drop to very small values because of evapotranspiration losses upgradient; therefore, an important part of the numerator in Equation 5 would be embodied in ETT in Equation 4.

Mono Lake, west of the Nevada border in California, offers a larger modern lake to compare with a pluvial hydrologic index. Pluvial Lake Russell in Mono Lake

Basin yields a pluvial hydrologic index of 1.12. Using Equation 4 to establish a modern index, data from the Appendix yields:

$$Z_M = \frac{A_I}{A_T} = 0.17$$

It is informative to note the general order of magnitude of difference between the modern and pluvial indices of Mono Basin (0.17 and 1.11) and the somewhat larger order of magnitude change (0.0026, 0.029, 0.26) that was calculated when southern Nevada was tested the second time with 5°F, 10°F, and 15°F temperature drops and the shifted lower curve (table 7). With the liberalized precipitation, about one order of magnitude change of the calculated pluvial index represented a 5°F shift in temperature. The Mono Lake modern/pluvial hydrologic indices relationship supports the 5°F shift trend established in Equation 4 evaluations when using more conservative temperature/precipitation curve relationships. Note also that the Ruby Valley (Lake Franklin) pluvial hydrologic index is 0.61 and the approximated modern index is 0.05, or a difference of about one order of magnitude. Overflow from Butte Valley may have increased the Ruby Valley pluvial index somewhat, so the comparison is of uncertain value.

The modern index of Mono Lake corresponds to a number of pluvial indices observed in Nevada. The pluvial lakes in the following basins closely correspond to the modern Mono Lake, with a lake area of 87.5 square miles and a modern index of 0.17:

Lake Antelope; lake area 48 square miles, pluvial index 0.16

Lake Cave; lake area 69 square miles, pluvial index 0.23

Lake Jake; lake area 63 square miles, pluvial index 0.19

Lake Maxey (Spring Valley); lake area 81 square miles, pluvial index 0.17.

The basins of the listed pluvial lakes responded in the same hydrologic manner during the full pluvial climate as Mono Lake Basin is now responding to its modern climate. The Mono Lake Basin, however, is not believed to represent an exact "homoclimate" of the pluvial climates of the listed basins.

Figure 25 illustrates a series of hydrologic index graphs plotted with respect to runoff (RT = PT — ETT) on the ordinate and net evaporation (EL — PL) on the abscissa. Each index graph indicates the possible range in the two plotted variables which would produce the measured hydrologic index. Also plotted are the evaluated mean indices for each recognized climatic zone produced by a 5°F mean annual temperature drop as developed in the preceding sections. Further, the two modern indices discussed, Mono Lake and Ruby Valley, are also plotted for comparison. These data suggest the close similarity between the modern Ruby Valley climate and the estimated pluvial paleoclimates of Southcentral Nevada (SCN) and Northwestern Nevada (NWN). In other words, it seems the modern Ruby Valley climate is a near "homoclimate" of southcentral and northwestern Nevada's full pluvial climates.

Mono Lake Basin climate can be seen to be considerably different than that of Northeastern Nevada (NEN) average pluvial climate conditions where several basins responded in the same hydrologic manner, as previously

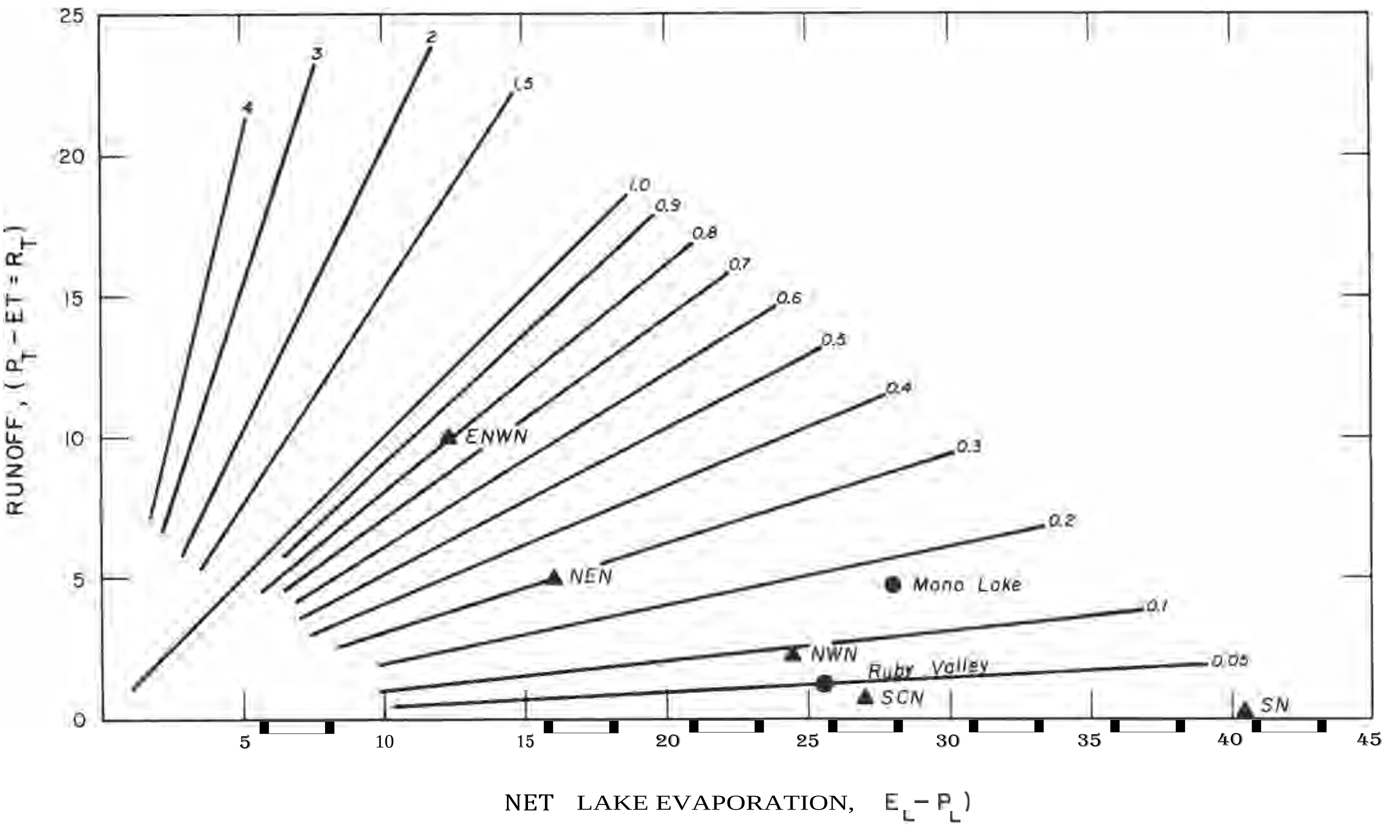

FIGURE 25. Comparison of full pluvial climates to modem climates using hydrologic indices.

noted. Due to warmer conditions in Mono Basin, more runoff from the high Sierra Nevada is necessary to produce the matching hydrologic index with greater net lake evaporation. Southern Nevada (SN) with significantly warmer pluvial climate temperatures creating large net lake evaporation rates and essentially no runoff, stands alone on the abscissa of Figure 25. This graphical depiction helps demonstrate how deficient the moisture input necessary for lake formation would have been in southern Nevada with a 5°F drop in mean annual temperature.

### Other Estimates of Pluvial Climates

Several investigators have suggested quantitative values of climate change for the Great Basin or southwestern United States. Most of the techniques used to arrive at the estimates are subject to as much or more error as embodied in techniques employed in this study, and sometimes there is little weight placed on modern relationships of climate and hydrology which are paramount to viable estimates. In this analysis, an attempt has been made to evaluate the paleoclimate giving rise to the highest lake levels experienced since Illinoian time, and perhaps the highest lake stages experienced during the Pleistocene in the Great Basin. This climatic condition is assumed the "full" pluvial climate; it represents a long-lasting maximum change in paleoclimate with respect to available moisture for runoff within the Great Basin.

Careful stratigraphic studies by Morrison (1964a) and Morrison and others (1965) indicate that a considerable number of lake fluctuations occurred below the maximum lake level in the Lahontan Basin. Further, study of paleosols and sedimentation patterns within the Lahontan Basin lacustrine sequence suggests to Morrison (1964b) that not only have there been cool—moist paleoclimatic conditions, but also there have been climate shifts, so there has been, at times, warm—moist and cool—dry conditions. The warm—moist conditions are believed by Morrison (1964b, pp. 134-135) to be evident from relatively short intervals which produced weak weathering profiles during limited lake drops. Morrison's interpretation is somewhat at odds with the fundamental assumption made in this study: when the climate changed, it changed in a pattern similar to that observed currently in the Great Basin, that of lower temperatures associated with increased precipitation and higher temperatures associated with reduced precipitation. Thus, the two basic parameters of climate are assumed more or less dependent variables as in the case in modern climates observed in the Great Basin. It is important to note that Morrison (1964b) believes 52°F mean annual temperature seems to mark the lower temperature limit of active soil formation (chemical weathering). The reconnaissance work indicated the well-developed Churchill Soil found in the lower elevations of Lahontan Basin (table 1), was not well developed or clearly identifiable in the higher central and northeastern Nevada basins. A continued effort was made to recognize the Churchill Soil equivalent to help establish relative age of the highest shorelines in all the basins visited, but the Churchill Soil equivalent was not recognized in the higher central and northeastern basins. In the lower basins elsewhere in Nevada, equivalent paleosols were sometimes recognized. Perhaps, if Morrison's suggested temperature cutoff for active soil formation is accurate, the interpluvial mean annual temperatures in the higher Nevada basins have never reached this value.

Morrison (1965a, p. 267) suggests the cooler and wetter pluvials were 8° to 15°F cooler than the present climate and appreciably less arid. From his extensive stratigraphic and soil studies, Morrison suggests the cyclic pattern of climatic change as follows: at the start of an interlacustral period cool—dry changing to warm—dry, then to warm—wet, then during the ensuing lacustral-glacial maximum, to cool—moist, then back to cool—dry. These interpretations are essentially based on sedimentation patterns and paleosol formation. Having worked closely with Morrison in some of his Lahontan studies we are familiar with much of the stratigraphic evidence upon which he has based his interpretations; however, we believe there are no sedimentation or soil relationships that demand paleoclimate models reversing modern trends in precipitation with respect to temperature.

The interpretation of the same evidence when considered within the context of this study, is warm—dry interpluvial conditions changing to slightly cooler conditions with more precipitation and runoff and less evaporation. The full pluvial climates were probably the coolest and wettest conditions, but only about 5°F cooler. Final stages of the pluvial periods are interpreted as times of reversal of the overall climate trends with less available nourishment for the existing pluvial lakes. If the pluvial climates were indeed similar to the modern Great Basin climates, there were more than likely, short and perhaps intermediate duration net reversals of long term trends in climate throughout pluvial cycles. It should be kept in mind that the very large, deep lakes such as Lahontan, once partly or fully formed, could persist with various rates of declining stage for rather long intervals of time. It would have been possible for relatively short-term reversals of climate to occur while the lakes were present, and the waters in shallow embayments would have warmed and weak weathering profiles would have formed in the lake margin deposits in the lower, warmer basins. With a termination .of the reversals, renewed inundation with lake rise would have occurred. The durations of these relatively short-term climatic reversals could have been several hundred years, with Lake Lahontan still persisting at lowered stages in the central subbasins where stratigraphic studies have been made. All of these suggested conditions are concordant with the stratigraphic and shore deposit evidence of Lake Lahontan.

Snyder and Langbein (1962) have made a detailed quantitative analysis of Spring Valley (61 and 62 in plate 1) pluvial lake (actually two adjacent pluvial lakes according to our detailed mapping) that also yields greater change in paleoclimate temperature than that arrived at in this study. They found that an increase in precipitation of 8 inches and a reduction of evaporation of 13 inches would have yielded pluvial Spring Lake. This differs from the findings in this study in that lake evaporation is reduced about 5 inches, lake precipitation is increased about 8.5 inches, and tributary basin precipitation increased about 10.7 inches. In effect, it appears that Snyder and Langbein call upon an 8 or 9°F drop in mean annual temperature and about the same increase in precipitation as is developed herein. They used more or less a similar continuity equation approach towards evaluating paleoclimate, but rather than using graphs to establish trends of observed climatic and evaporation data, they used statistics and probabilities of climatic data to demonstrate the most likely climatic change. In doing so, they arrived at a relationship of increased precipitation with lowered mean annual temperature that is also developed by Figure 22; however, they believed that mean annual lake evaporation under modern conditions is 44 inches, whereas Figure 24 suggests it may be closer to 39 inches. They also estimated a 6 percent decrease in evaporation per 1,000 feet of altitude change, and observed data of Figure 24 indicate an 8 percent decrease at that altitude. These differences account for much of the difference in results of the two paleoclimates analyses.

Broecker and Orr (1958, p. 1030) have suggested a 5°C (9°F) drop in mean annual temperature and an increase from an average basin precipitation of 10 inches to an average of 18 inches to restore Lake Lahontan to its maximum level. They arrive at these conclusions through the use of rather generalized approximations of precipitation, runoff, and evaporation relationships as well as the use of a continuity equation similar to Equation 4. Broecker and Orr additionally suggest a 30 percent decrease in evaporation, assumed to be 54 inches with modern climatic conditions based on data from Hardman and Venstrom (1941, p. 82). Figure 24, using primarily Harding's (1965) evaporation data, indicates the initial 54-inch evaporation value is considerably too high. It is interesting to note that the suggested 30 percent drop using their high initial value yields approximately the same suggested pluvial evaporation value as in the previously discussed evaluation of Lake Lahontan (38 inches to 37 inches, respectively). Further, their 8-inch increase in basin precipitation is more or less similar to the derived estimates of this study. Here again, initial departure data seem to generate some of the differences in actual suggested temperature drop; however, Broecker and Orr (1958) did not quantitatively show the derivation of their values of climate change; rather, they made approximations without showing how the suggested temperature drop was derived.

Reeves (1968, p. 124) has compiled a list of authorities citing estimates of Pleistocene temperature lowering, either for summer temperatures or mean annual temperatures. Out of 27 references to mean annual temperature change in various parts of the world, most are drops of 10°F or more and only two authorities have called for temperature drops of 5°F or less. One of these, Antevs (1952), favored about a 5°F drop in mean annual temperature from his prolonged and intensive studies in the southwestern United States, including the Great Basin. In the case of Lake Lahontan, he believed mean annual precipitation of 39 inches and a temperature drop of 5°F would explain the lake. This increase in precipitation seems unreasonably high. The calculations made in this study indicate 23 to 26 inches for basin precipitation. Almost every other authority seems to favor about twice as much temperature drop, or even more in a few cases. Galloway (1970, p. 252) goes to the extreme and estimates almost a 20°F drop in temperature, evaporation rates 50 percent less, and precipitation 10 to 20 percent less for the American southwest. While such climatic change could conceivably produce the pluvial lakes of the Great Basin (fig. 25), neither supporting evidence for such extreme drops in temperature nor indication of reduced precipitation were recognized in this study. On the contrary, there is geomorphic evidence which suggests more precipitation and attendant stabilized terrain conditions through increased vegetal cover.

Galloway builds his deductions of the cold, dry paleoclimate on interpretation of "periglacial solifluction deposits" in the Sacramento Mountains of New Mexico, and similar deposits at similar altitudes cited by others in the same general region. The deposits, which occur at 2,000 m and higher, are presently stabilized, and Galloway correlates them as Wisconsinan age on the basis of soil development, weathering, and preservation. He believes the deposits represent a paleoclimate July isotherm of 10°C (50°F) where the modern July isotherm is 20–21 C (68–70 F). Galloway derives the rest of his paleoclimate analysis on the size of pluvial lakes in southwestern United States, including several Nevada pluvial lakes; however, the solifluction deposits are neither firmly correlated nor are such deposits necessarily formed in the climatic environment he envisions. Cool, semi-arid climates of the Great Basin give rise to similar mass wasting deposits formed in much the same manner as classical solifluction processes of alpine environments; similar prerequisite conditions are essentially matched, with perhaps the differences being primarily in rates of development. Conducive conditions are sparse vegetation, slow or absent soil formation processes, freezing and thawing, periodic moisture availability, and slopes with rapidly disintegrating but slowly decomposing bedrock. Such conditions give rise to "periglacial solifluction" features in the Great Basin and can be found both as active and relic deposits. Galloway also recognized that such deposits could be formed in a dry climate, but believed the Sacramento Mountain deposits are periglacial.

It seems highly unlikely that temperatures creating past arctic conditions in the Great Basin would not yield widespread and readily detectable manifestations. With Galloway's postulated mean annual temperature decrease, all Climatic Divisions in Nevada, with the exception of southern Nevada, would have been characterized by a mean temperature below freezing. Rather, small climate shifts, as demonstrated in this study, appear sufficient to produce viable hydrologic results that equal pluvial paleohydrologic conditions, and the associated temperature and precipitation regimens support or at least coexist with the many other lines of evidence of past pluvial climates.

From extensive study of modern and prehistoric climatic variation in the Donner Pass area (the western edge of Lahontan Basin in the Sierra Nevada) Curry (1969, p. 38) concludes that snowfall during the Wisconsinan maxima could have been as little as 1.5 times that of the present climatic normal. This estimate is based on the assumption of cooler and cloudier summer conditions which are reasonable conditions attending a mean annual temperature drop and an increase in precipitation. The estimated change is of similar magnitude as the increased precipitation in the analysis of this study. On the basis of Curry's (1969, p. 42-43) analysis of the deglacial climate, he states:

> Glacial climates apparently characterized times of increased vigor of upper-atmosphere circulation with higher amplitude, longer wave length upper-atmosphere meander patterns and resultant more frequent frontal storms and more southerly extension of storm tracks.

Curry's view and observation support the implicit suggestion of this study of a more vigorous hydrologic cycle operating in the Great Basin during pluvial climates and not greatly differing temperature regimens.

In his study of clay mineralogy of middle and late Quaternary paleosols from the Donner Lake area down into the lowlands of the Lahontan Basin, Birkeland (1969, p. 289) found little evidence which would indicate drastic change of climate or vegetation patterns from those now persisting. While he recognizes several difficulties in the definitive interpretation of the soil—clay mineralogy, the most significant aspect is lack of intense leaching of the basin soils. Thus, he believes it is unlikely that there were periods of markedly increased precipitation. Although, on a percentage basis, quantitative results of our study show marked increase in precipitation, the actual pluvial climate precipitation values in basinward environs are still within the range of arid and semiarid conditions in the lower basins such as the Lahontan lowlands. Recall that Table 9 demonstrates the mean pluvial precipitation increases are similar to the modern extreme precipitation values. Thus, Birkeland's findings seem compatible.

One interesting investigation (Mehringer and Ferguson, 1969), with respect to derived estimates of pluvial climate in our study, is the analysis of twigs of *Pinus monophylla* radiocarbon dated at 12,460 ± 190 B.P. (about the latest high stage of Lake Lahontan) from a woodrat midden at 6,300 feet MSL on Clark Mountain, located about 40 miles southwest of Las Vegas. Comparison of tree-ring growth characteristics with 27 modern twigs from both Clark Mountain and the Spring Mountains (in Nevada near Las Vegas) demonstrates all modern samples, including those from favorable sites for moisture, had sloWer growth. Other lines of evidence of their study suggest at least 1,500 feet of vegetal community depression, and the rapid growth indicated by the width of the rings strongly indicate marked increase in moisture availability. Depressed vegetation zones in the Great Basin have long been postulated, but biological evidence which bears more directly on relative amount of precipitation is rare. Marked increase in precipitation during pluvial climates significantly decreases the amount of change necessary in mean annual temperature, and this cited evidence seems strongly supportive of the quantitative results of the current study.

Beaty (1970) believed the "Pleistocene climate" was not likely to have differed greatly from modern climate. after his study of the geomorphology of alluvial fans flanking the White Mountains on the California—Nevada border.

When using quantitative approaches based on Leopold (1951) and Snyder and Langbein (1962), Weide (1974) found that an average annual drop in mean annual temperature of 9°F and an increase in average annual regional precipitation of 4 inches would be sufficient to restore Lake Warner and adjacent pluvial lakes. While there is no disagreement that such a combination of temperature and precipitation could have produced pluvial lake restoration, the question of relative importance of chang in the two parameters is pointed out by comparing results of the two studies. Extreme northwestern Nevada borders the area studied by Weide, and the derived increase in lake precipitation is about 9.5 inches with the 5°F decrease in mean annual temperature.

Several of the earliest workers in Nevada came just about as close to the results of this study as the more recent investigators. Russell (1885; 1896, p. 132) and Jones (1925) estimated similar temperatures to those of present day and an increase of mean annual precipitation to about 20 inches in the Lahontan Basin to account for Lake Lahontan. We find the 5°F mean annual temperature change is necessary to generate the increase in moisture, associated increase in runoff, and decreased evaporation. Meinzer (1922) suggested that modern moisture conditions of northwestern Nevada were prevalent in southern Nevada during the pluvial paleoclimate. This is, in a quantitative sense, reasonably close to what has been found in this study.

## CONCLUSIONS

This study has been an attempt to translate carefully observed physiographic evidence of paleohydrologic conditions into quantitative estimates of the pluvial paleoclimates. We have determined that approximately a 5°F mean annual temperature decrease and corresponding increases in precipitation, as indicated by temperature/precipitation characteristics of modern climates of the Great Basin, would be sufficient climatic change. In the regions of Nevada that had pluvial lakes, the estimated increases of precipitation above modern basin values in the basins range from 52 to 80 percent and average about 68 percent. In addition, some of the more indirect evidence briefly touched upon seems to argue against major temperature differences between present climates and pluvial climates.

In this study, no quantitative evidence has been recognized to indicate the exact magnitude of change in either principal parameter of the pluvial paleoclimates; however, there is indirect evidence against significantly lower temperatures. The following suggest considerably lower temperatures were not likely to exist: 1) weak weathering profiles between moderate drops in Lake Lahontan levels; 2) general absence of ice marginal features at high levels of the pluvial lake shores; 3) presence of tufa precipitated by algae up to the highest levels of Lake Lahontan; 4) indigenous and unique fish well adapted to present water-temperature regimes in Pyramid Lake and in many thermal springs of the northern Great Basin, and; 5) palynological data indicating more or less similar flora (but somewhat different distributions). Further, there is no recognized evidence indicating the general characteristics of the pluvial climates were greatly different from the modern climate. In view of these considerations, it seems necessary to call upon more moisture input into the Great Basin to generate the observed pluvial hydrologic indices. The data indicate considerable hydrologic change should be expected with only small changes in mean annual temperature.

Some evidence is compelling enough to consider even less temperature change, and correspondingly more precipitation, should the analysis of this study be found to err in some manner. As it is, the results are essentially compatible with the sum total of evidence presently available within Nevada. Perhaps a more accurate evaluation of Great Basin pluvial paleoclimates will be possible using the same general approach when the modern climates of the Great Basin are better known. As has been pointed out, some of the differences between the results of this study and similar analyses in the Great Basin result from the initial departure in use of climatic and hydrologic data. At present, some aspects of modern climatic data are not very satisfying or sensitive with respect to the needs of the analytical approach.

A brief comparison of the general results of this study with contemporary ideas of pluvial climates seems warranted. Clearly, the idea of more northerly storm tracks which shifted southward from modern paths by cold air masses associated with continental ice fields is compatible with the results of this study. Several of the cited investigators have suggested such direct cause of the pluvial climates in the Great Basin. Using modern climate as a guide suggests that the Great Basin would be penetrated more frequently during winter months by frontal storms bringing significantly more moisture without major temperature change. Such winter moisture is rather significant with respect to runoff in the modern Great Basin climates. Further, the absence of important alpine glaciation in nearly the entire Great Basin suggests that summer temperatures were just too high for substantial annual carryover of mountain snowpacks even in the most favorable exposures, and possibly the summer climatic characteristics were not greatly changed. Net effect might be envisioned as many more storms in winter months with significantly increased precipitation and eventual runoff; also, summers with a few more frontal storms and a considerable increase in convectional precipitation triggered by more local Great Basin moisture; this is a possibility favored by Stidd (1968). Summer temperatures may have been slightly lower, but it seems unlikely the strong continental climatic influence would be weakened enough to cause significant shift in the temperature. The suggested increase in convectional precipitation would still be relatively insignificant with respect to generation of runoff. Presumably, runoff derived from summer month precipitation would remain a rather small percentage of annual runoff.

In general terms, the average winter would bring more snow, as well as more spring and fall storms, and in the higher basins snow cover should have been prolonged more than they are now. Summer might well have been very similar, but vegetation distribution should have been significantly different due to soil—moisture availability. It seems the sagebrush/grass and Pinyon/Juniper zones of Billings (1951) would have moved down in altitude as much as 2,000 feet in response to increased soil—moisture availability when the lake precipitation values of table 7 are examined. As Pinyon and Juniper begin to appear abundant at about 14 to 16 inches of precipitation and sagebrush at 8 to 10 inches, the sagebrush community should have been found in many of the basins now occupied by the shadscale community, and the Pinyon/Juniper communities should have moved down mountain flanks into many of the basins as they presently are in some parts of northeastern and extreme northwestern Nevada. Additionally, it seems likely that the sagebrush and shadscale communities would have moved southward and become more extensive in southern Nevada.

In a hydrologic sense, there should have been some additional differences besides development of the mapped pluvial lakes. In the drier basins, wet (phreatic) playas, playa lakes, and marshes should have been more common and areas of phreatophytes much more extensive. Drainage channels should have had perennial flow through more of their reaches and good evidence indicates that in regions underlain by carbonate rock terrain there was more vigorous or extensive spring discharge, and perhaps more large springs. It is also believed that there were likely a number of areas of marsh environments in southern Nevada due to concentrated groundwater and spring discharge considerably in excess of present discharge. In southcentral and southern Nevada significant differences in the amount and location of groundwater discharge seem apparent.

Another interesting observation is evidence for greater terrain stability in the basins during the pluvial climate. This aspect is demonstrated by relative age and development of alluvial fan deposits and shoreline features. Generally speaking, there appears much greater fan activity during post-pluvial and inter-pluvial times than during pluvial intervals. This is not surprising if one considers the net effect of higher density vegetal covers due to increase availability of soil moisture, but the normal manner of thinking is for increased runoff to produce more rapid rates of erosion and associated sedimentation. In the precipitation regimes of both modern and pluvial climates of the Nevada portion of the Great Basin, this is not and probably was not the case. Further, where pluvial shorelines occur in Nevada, the more arid and warmer the present modern climate, the more active the fans appear to have been since the last pluvial. Translated into shoreline preservation, the higher, well vegetated basins have the best shoreline preservation.

In summary, the pluvial lake evidence has been presented and the apparent paleoclimatic meaning in both qualitative and quantitative terms has been demonstrated. We conclude that full pluvial climates were not greatly different than modern climates, but differed enough when measured in hydrologic terms to greatly change the paleohydrology of the region. Some relatively untested basic assumptions have been made which permit quantitative estimation of the pluvial climates. Hopefully this analysis might stimulate further study of this problem, as it is clearly shown that regions of arid, hydrographically closed basins offer unique opportunities for understanding paleoclimates.

## REFERENCES

Anonymous (1972) Water planning report: Nevada Hydrologic Atlas, Office of the State Engineer, Carson City, Nev.

Antevs, E. (1952) Cenozoic climates of the Great Basin: Geol. Res., v.40, p. 94-108.

Beaty, C. B. (1970) Age and estimated rate of accumulation of an alluvial fan, White Mountains, Calif., U.S.A.: Am. Jour. Sci., v. 268, p. 50-77.

——— (1971) Climatic change: Some doubts: Geol. Society America Bull., v. 82, no. 5, p. 1395-1397.

Birkeland, P. W. (1964) Pleistocene glaciation of the northern Sierra Nevada, north of Lake Tahoe, Calif.: Jour. Geol., v. 72, p. 810-825.

——— (1969) Quaternary paleoclimatic implications of soil clay mineral distribution in a Sierra Nevada—Great Basin transect: Jour. Geol., v. 77, p. 289-302.

Billings, W. D. (1951) Vegetational zonation in the Great Basin of Western North America: Les Bases Ecologiques de la Regeneration de la Vegetation des Zones Arides, Series B, U.L.S.B., Paris, p. 101-122.

Born, S. M. (1972) Lake Quaternary history, deltaic sedimentation, and mud lump formation at Pyramid Lake, Nev.: Center for Water Resources Research, Desert Research Institute, Reno, Nev., 97 p.

Bowyer, B., Pampeyan, E. H., and Longwell, C. R. (1958) Geologic map of Clark County, Nev.: U.S. Geol. Survey, MF 138.

Broecker, W. S., and Kaufman, A. (1965) Radiocarbon chronology of Lake Lahontan and Lake Bonneville II, Great Basin: Geol. Society America Bull., v. 76, p. 537-566.

Broecker, W. S., and Orr, P. C. (1958) Radiocarbon chronology of Lake Lahontan and Lake Bonneville: Geol. Society America Bull., v. 69, p. 1009-1032.

Broecker, W. S., and Walton, A. F. (1959) Re-evaluation of the salt chronology of several Great Basin lakes: Geol. Society America Bull., v. 70, no. 5, p. 601-618.

Clark, W. O., and Riddell, C. W. (1920) Exploratory drilling for water and use of groundwater for irrigation in Steptoe Valley, Nev.: U. S. Geol. Survey Water Supply Paper 467, 70 p.

Curry, R. R. (1969) Holocene climate and glacial history of the central Sierra Nevada, Calif.: Geol. Society America, Special Paper 123,47 p.

Denny, C. S., and Drewes, H. (1965) Geology of the Ash Meadows Quadrangle, Nevada—California: U. S. Geol. Survey Prof. Paper 1181-L, p. 1-56.

Feth, J. H. (1961) Review and annotated bibliography of ancient lake deposits (Precambrian to Pleistocene) in the Western states: U. S. Geol. Survey Bull. 1080,119 p.

Free, E. E. (1914) The topographic features of the desert basins of the United States with reference to the possible occurrence of Potash: U. S. Dept. Agri., Bull. 54,65 p.

Frye, J. C., and Willman, H. B. (1960) Classification of the Wisconsinan Stage in the Lake Michigan glacial lobe: Illinois State Geol. Survey, Circ. 285,16 p.

Galloway, R. W. (1970) The full-glacial climate in the southwestern United States: Assoc. Amer. Geogr., Ann., v. 60, p. 245-256.

Gilbert, G. K. (1875) Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U. S. Geog. and Geol. Expl. and Surv. W. 100th Meridian (Wheeler Survey), v. 3, p. 17-187.

——— (1890) Lake Bonneville, U. S. Geol. Survey Monograph 1, 275 p.

Harding, S. T. (1965) Recent variations in the water supply of the western Great Basin: Univ. Calif., Berkeley, Water Res. Center Arch., Arch. Series Rept. No. 16,226 p.

Hardman, G., and Venstrom, C. (1941) A 100-year record of Truckee River runoff estimated from changes in levels and volumes of Pyramid and Winnemucca Lakes: Am. Geophys. Union Trans., v. 22, p. 71-90.

Haynes, C. V. (1967) Quaternary geology of the Tule Springs area, Clark County, Nev.: Nev. State Museum, Antho. Papers No. 13, 104 p.

Hewett,.D. F. (1956) Geology and mineral resources of the Ivanpah quadrangle, California and Nevada: U. S. Geol. Survey Prof. Paper 275,172 p.

Hubbs, C. L., and Miller, R. R. (1948) The zoological evidence: Correlation between fish distribution and hydrographic history in the desert basins of the western United States *in* The Great Basin, Part II, Bull. Univ. Utah, v. 38, no. 20, p. 18-166.

Hubbs, C. L., Miller, R. R., and Hubbs, L. C. (1974) Hydrographic history and relict fishes of the north-central Great Basin: Calif. Acad. Sci., Memoirs, v. VII, 259 p.

Jones, J. C. (1925) The geologic history of Lake Lahontan *in* Quaternary Climates: Cam. Inst. Wash. Publ. 352, p. 1-49.

King, C. (1878) Systematic geology: U. S. Geol. Explor. of the Fortieth Parallel, Washington, 803 p.

Langbein, W. B., et al. (1949) Annual runoff in the United States: U.S. Geol. Survey, Circ. 52,13 p.

Layton, T. N. (1970) High Rock Archeology, Ph.D. thesis, Harvard Univ., Cambridge, Mass.

Leopold, L. B. (1951) Pleistocene climates in New Mexico: Am. Jour. Sci., v. 249,p. 152-168.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H. (1958) Hydrology for Engineers: McGraw-Hill, New York.

Longwell, C. R. (1961) Geology of southern Nevada *in* Harrington, M. R., and Simpson, R. D., Tule Springs, Nevada with other evidence of Pleistocene man in North America: Southwest Museum Papers, No. 18, p. 47-50.

Maxey, G. B., and Jameson, C. H. (1948) Geology and water resources of Las Vegas, Pahrump and Indian Spring Valleys, Clark and Nye Counties, Nev.: U. S. Geol. Survey Water Resources Bull. 5,128 p.

Meinzer, O. E. (1922) Map of the Pleistocene lakes of the Basin and Range Province and its significance: Bull., Geol. Society America, v. 33, p. 541-552.

Mehringer, P. J., and Ferguson, C. W. (1969) Pluvial occurrence of Bristlecone Pine *(Pinus aristata)* in a Mohave Desert mountain range: Ariz. Acad. Sci. Jour., v. 5, no. 4, p. 284-292.

Mifflin, M. D. (1967) Hydrogeology *in* A reconnaissance of the technology for recharging reclaimed waste water into the Las Vegas Valley ground-water basin: Desert Research Institute, CWRR, Tech. Rept. Series H-W, Publ. No. 2, p. 14-29.

——— (1968) Delineation of groundwater flow systems in Nevada: Desert Research Institute, CWRR, Tech. Rept. Series H-W, Publ. 4,111 p.

Mifflin, M. D., and Wheat, M. M. (1971) Isostatic rebound in the Lahontan Basin, northwestern Great Basin: Geol. Society America 1971 Annual Meetings, p. 647.

Miller, R. R. (1946) Correlation between fish distribution and Pleistocene hydrography in eastern California and southwestern Nevada, with a map on Pleistocene waters: Jour. Geology, v.54, p. 43-53.

Morrison, R. B. (1964a) Lake Lahontan: Geology of southern Carson Desert, Nevada: U. S. Geol. Survey Prof. Paper 401, 156 p.

——— (1964b) Soil stratigraphy: Principles, applications to differentiation and correlation of Quaternary deposits and landforms, and applications to soil science: Univ. of Nevada Ph.D. dissertation, Reno, Nev., 178 p.

——— (1965a) Quaternary geology of the Great Basin *in* The Quaternary of the United States: Princeton Univ. Press, p. 265—285.

——— (1965b) Lake Bonneville: Quaternary stratigraphy of eastern Jordan Valley, south of Salt Lake City, Utah: U. S. Geol. Survey Prof. Paper 474,80 p.

Morrison, R. B., and Frye, J. C. (1965) Correlation of the middle and late Quaternary successions of the Lake Lahontan, Lake Bonneville, Rocky Mountain (Wasatch Range), southern Great Plains, and eastern Midwest areas: Nev. Bur. Mines Rept. 9,45 p.

Morrison, R. B., Mifflin, M. D., and Wheat, M. (1965) Rye Patch Dam: Badland Amphitheatre on the Truckee River north of Wadsworth *in* Guidebook for Field Conference I, Northern Great Basin and California: Int. Assoc. Quat. Research, VII Congress, p. 29-33; 38-43.

Phillips, K. N., and Van Denburgh, A. S. (1971) Hydrology and geochemistry of Abert, Summer, and other closed-basin lakes in south central Oregon: U. S. Geol. Survey Prof. Paper 502-B, 86 p.

Price, C. E. (1966) Surficial geology of the Las Vegas Quadrangle, Nevada: Unpublished Masters Thesis, Univ. of Utah, 60 p.

Reeves, C. C., Jr. (1968) Introduction of Paleoclimnology : Developements in Sedimentology, No. 11, Elsevier, 228 p.

Russell, I. C. (1883) Sketch of the geological history of Lake Lahontan: Ann. Rept. U. S. Geol. Survey, v. 3, p. 189-235.

——— (1884) A geological reconnaissance in southern Oregon: Ann. Rept. U. S. Geol. Survey, v. 4, p. 431-464.

——— (1885) Geological history of Lake Lahontan, a Quaternary lake of northwest Nevada: U. S. Geol. Survey Monogr., no. 11, 288 p.

——— (1889) Quaternary history of Mono Valley, Calif.: Ann. Rept. U. S. Geol. Survey, v. 8, p. 261-394.

——— (1896) Present and extinct lakes of Nevada *in* The Physiograph of the United States: Monogr. Nat. Geog. Soc., p. 101-132.

Schumm, S. A. (1965) Quaternary paleohydrology *in* The Quaternary of the United States, Wright, H. E., Jr., and Frey, D. G., eds.: Princeton University Press, p. 783-794.

Scott, D. H., and Trask, N. J. (1971) Geology of the Lunar Crater Volcanic Field, Nye County, Nev.: U. S. Geol. Survey Prof. Paper 559-1,22 p.

Simpson, J. H. (1876) Explorations across the Great Basin of the Territory of Utah: Washington, Engineering Dept. U. S. Army.

Snyder, C. T., and Langbein, W. B. (1962) The Pleistocene lake in Spring Valley, Nevada, and its climatic implications: Jour. Geophys. Res., v. 67, no. 6, p. 2385-2394.

Snyder, C. T., Hardman, G., and Zdenek, F. F. (1964) Pleistocene lakes in the Great Basin: U. S. Geol. Surv. Misc. Geol. Invest. Map 1-416.

Spurr, J. E. (1903) Descriptive geology of Nevada south of the Fortieth Parallel and adjacent portions of California: U. S. Geol. Surv. Bull. 208,229 p.

Stidd, C. K. (1968) Local moisture and precipitation: Desert Research Institute, Univ. of Nev. Preprint No. 45 A, 34 p.

Taylor. 1). W. (1967) Late Pleistocene molluscan shells from the Tule [illegible]g Area *in* Pleistocene Studies in Southern Nevada: Nevada State Museum. Anthrop. Papers, No. 13, p. 395-399.

Wahrhaftig. C.. and Sharp, R. P. (1965) Sonora Pass Junction to Bloody Canyon *in* Northern Great Basin and California Field Conference Guidebook, Conf. I Int. Assoc. Quat. Research, VII Congress, Nebraska Acad. Sci., p.71-84.

Weide, D. L. (1974) Postglacial geomorphology and environments of the Warner Valley—Hart Mountain area, Oregon: Unpublished Ph.D. thesis, Univ. Calif., Los Angeles, 263 p.

Whitney, J. D. (1865) Report of progress and synopsis of the field-work from 1860-1864: Geological Survey of California, v. 1, p.452.

Yen, Teng-Chien (1951) Fresh-water mollusks and ecological interpretations: Geol. Society America Bull., v. 62, p. 1375-1380.

Young, G. J. (1914) Potash salts and other salines in Great Basin region: U. S. Dept. Agr. Bull. 61,96 p.

# APPENDIX

## STATISTICS OF BASINS AND PLUVIAL LAKES SHOWN ON PLATE I

### LEGEND

| | |
|---|---|
| | Name applied by authors, no known previous name |
| (0.20) | Brackets around hydrologic index indicates surface overflow has occurred |
| PUB | Value adopted from published source |
| AP | Measurement from aerial photograph overlay |
| AMS | Measurement from Army Map Service 1:250,000 maps |
| GSa | Measurement from U. S. Geological Survey 1:24,000 advance sheets |
| GSb | Measurement from U. S. Geological Survey 1:24,000 maps |
| GSc | Measurement from U. S. Geological Survey 1:62,500 maps |
| BM | Bench Mark controlled measurement |
| Sd-p | Strongly developed; entensively preserved landforms |
| Sd-lp | Strongly developed; limited preservation of landforms |
| Wd-p | Weakly developed; limited preservation of landforms |
| (³) | Notation number |

| Basin Name | Pluvial Lake Name | Map No. | Hydro. Index | Lake Area mi² | Basin Area | Max. Lake Alt. ft., MSL | Basin Floor Alt. ft., MSL | Shore Develop-ment | Overflow Channel | Interp. Age of Shores or Playa | Field Recon. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Alkali Spring | | 1 | 0 | | 312 GSc | | 4802 GSa | none | none | ~~Recent~~ | ~~yes~~ |
| Alvord | Alvord | 2 | | | | | | (1) | | Lahontan | yes |
| Hawksy Walksy | Hawksy Walksy* | 2A | (0.20) | 12 AMS | 71 AMS | 5670 GSa | 5602 GSa | Sd-p | Wd-p | Lahontan | no |
| Summit | Parman* | 2B | (0.13) | 6.5 GSa | 57 AMS | 5857 GSa | <5836 GSa | Wd-p | Sd-p | (2) | yes |
| Antelope | | 3 | 0 | | 18 PUB | | 5112 GSb | none | none | Recent | yes |
| Antelope | Antelope | 4 | 0.16 | 48 AP | 344 GSc | 5724 BM | 5650 AMS | Sd-p | none | Lahontan | yes |
| Apex Dry Lake | | 5 | 0 | | 250 GSc | | 1968 GSb | none | none | Recent | yes |
| Big Smoky | Toiyabe | 6 | 0.19 | 203 AP | 1296 GSc | 5585 GSb | 5440 GSb | Sd-p | none | Lahontan | yes |
| Big Smoky | Tonopah | 7 | 0.05 | 90 AP | 2048 GSc | 4800 GSa | 4720 GSa | Sd-p | none | Lahontan | yes |
| Bonneville | Bonneville | 8 | (0.59) | 19940 PUB | 54000 PUB | 5188 GSa | | Sd-p | Sd-p (PUB) | (3) | yes |
| Butte | Gale | 9 | (0.28) | 159 AP | 722 GSc | 6250 AMS | 6161 AMS | Sd-p | (4) | Lahontan | yes |
| Cave | Cave | 10 | 0.23 | 69 AP | 366 GSc | >6000 AMS | >5900 AMS | Sd-p | none | Lahontan | no |
| Clayton | | 11 | 0 | | 540 GSc | | 4266 GSb | none | none | (5) | yes |
| Clover-Independence | Clover | 12 | 0.53 | 352 AP | 1019 GSc | 5674 GSb | 5578 GSb | Sd-p | none | Lahontan | yes |
| Coal | Coal | 13 | 0.07 | 69 AP | 1005 GSc | 4990 GSa | 4956 BM | Wd-p | none | Lahontan | yes |
| Cold Spring | Laughton | 14 | 0.19 | 6.9 GSa | 43 GSc | 5120 GSa | 5026 GSa | Wd-p | none | Lahontan | yes |
| Columbus Salt Marsh | Columbus | 15 | 0.06 | 79 AP | 1364 AMS | 4680 GSa | 4509 GSa | Sd-lp | none | Lahontan | yes |
| Delamar | | 16 | 0 | | 380 GSc | | 4538 GSa | (6) | none | Recent | yes |
| Desert | | 17 | 0 | | 1021 GSc | – | 3206 GSa | none | none | Recent | no |
| Dixie | Dixie | 18 | 0.13 | 276 AP | 2361 AMS (7) | 3600 GSa | 3370 GSa | Sd-p | none | Lahontan | yes |
| Fairview | Labou | 18A | (0.08) | 20 AP | 285 PUB | 4180 BM | 4148 BM | Wd-p | Wd-p | Lahontan | yes |
| Dry Lake | Bristol | 19 | 0.04 | 35 AP | 883 GSc | 4620 GSa | 4579 GSa | Sd-lp | none | Lahontan | yes |
| East Jean | | 20 | 0 | | 40 GSc | – | 2995 GSb | none | none | Recent | yes |
| Edwards Creek | Edwards | 21 | 0.34 | 102 AP | 396 GSc | 5280 GSa | 5114 GSa | Sd-p | none | Lahontan | yes |
| Eldorado | | 22 | 0 | | 530 GSc | | 1708 GSa | none | none | Recent | yes |
| Emigrant | Groom | 23 | 0.05 | 36 AP | 687 GSc | —4475 GSb | >4437 GSb | Sd-lp | none | Lahontan | no |
| Frenchman | | 24 | 0 | | 455 GSc | – | 3077 GSa | none | none | Recent | no |
| Gabbs | | 25 | 0 | | 1269 GSc | | ~4085 AMS | none | none | (8) | yes |

| Basin Name | Pluvial Lake Name | Map No. | Hydro. Index | Lake Area mi$^2$ | | Basin Area mi$^2$ | Max. Lake Alt. ft., MSL | Basin Floor Alt. ft., MSL | Shore Develop-ment | Overflow Channel | Interp. Age of Shores or Playa | Field Recon. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Garfield | Garfield | 26 | 0.03 | 3.3 | GSa | 100 GSc | —5600 GSa | 5577 GSa | Wd-p | none | Lahontan | yes |
| Gold Flat | Gold Flat | 27 | 0.04 | 26 | AP | 680 GSc | 5120 GSa | 5050 GSa | Sd-lp | none | Lahontan | no |
| Goshute (Steptoe) | Waring | 28 | 0.20 | 541 | AP | 3244 GSc | —5777 GSa | 5583 BM | Sd-p | none | Lahontan | yes |
| Granite Springs | Granite Springs | 29 | 0.04 | 40 | AP | 947 GSc | | 3856 AMS | Wd-p | none | Lahontan | yes |
| Grapevine Canyon | | 30 | 0 | | | 100 GSc | | 4015 GSa | none | (9) | Recent | yes |
| Grass | Gilbert | 31 | 0.36 | 155 | AP | 585 GSc | 5740 GSb | 5617 GSb | Sd-p | (10) | Lahontan | yes |
| Huntoon | | 32 | 0 | | | 115 GSc | – | 5640 GSb | (11) | none | Lahontan | yes |
| Indian Springs | | 33 | 0 | | | 624 GSc | | 3014 BM | none | none | (12) | no |
| Ivanpah | | 34 | 0 | | | 781 GSc | | 2602 GSb | none | none | Recent | yes |
| Jakes | Jakes | 35 | 0.19 | 63 | AP | 401 GSc | 6380 GSb | >5295 GSb | Sd-p | none | Lahontan | yes |
| Jean Dry Lake | | 36 | 0 | | | 90 GSc | | <2784 GSb | none | none | Recent | yes |
| Kawich | Kawich | 37 | 0.07 | 22 | AP | 334 GSc | 5370 GSb | 5311 GSb | Sd-p | none | Lahontan | no |
| Kumiva | Kumiva | 38 | 0.04 | 15 | AP | 346 GSc | – | 4400 AMS | Wd-p | none | Lahontan | no |
| Lahontan | Lahontan | 39 | 0.24 | 8440 | AMS | 44300 AMS | (13) | 3459 PUB | Sd-p | none | (13) | yes |
| Bawling Calf* | Paiute* | 39A | (0.44) | 4.2 | GSb | 14 GSb | —6200 GSb | <6165 GSb | (14) | (14) | Lahontan | no |
| Buffalo | Buffalo | 39B | (0.18) | 77 | GSb | 499 GSc | 4642 GSb | 4601 GSb | Sd-p | Wd-p | Lahontan | yes |
| Diamond | Diamond | 39C | (0.14) | 392 | AP | 3102 PUB | 6000 GSb | 5770 GSb | Sd-p | Sd-p | (15) | yes |
| High Rock | High Rock | 39D | (0.02) | —12 | AMS-GSb | 665 AMS | —5140 GSb | <4894 GSb | Wd-p | Sd-p | (16) | yes |
| Smith | Wellington | 39E | (0.11) | —117 | GSc | 1190 PUB | >4800 GSb | <4546 GSc | Sd-lp | Sd-p | (17) | yes |
| Tahoe | Tahoe | 39F | | – | | – | 6319 PUB | —5000 PUB | Wd-p | Sd-p | Lahontan | yes |
| Washoe | Washoe | 39G | (0.38) | 23 | GSb | 84 GSc | 5080 GSb | —5060 GSc | Wd-p | Wd-p | Lahontan | yes |
| Lake (Duck) | Carpenter | 40 | 0.34 | 134 | AP | 525 GSc | 5985 BM | 5915 AMS | Sd-p | none | Lahontan | yes |
| Lemmon | Lemmon | 41 | 0.19 | 13 | GSa | 82 GSc | 4990 GSa | —4920 GSa | Wd-p | none | Lahontan | yes |
| Little Smoky | Corral* | 42 | 0.23 | 9.1 | AP | 49 GSc | <6500 AMS | | Sd-p | none | Lahontan | no |
| Long | Meinzer | 43 | 0.91 | 344 | AMS | 720 GSc | 5800 BM | 5512 GSa | Sd-p | none | Lahontan | yes |
| Long | Hubbs | 44 | 0.41 | 195 | AP | 666 GSc | —6300 AMS | 6062 AMS | Sd-p | none | (18) | yes |
| Macy Flat | Macy | 45 | 0.56 | 9.3 | AP | 25 AMS | 5860 GSa | 5773 GSa | Sd-p | none | Lahontan | no |
| Mesquite | | 46 | 0 | | | 480 AMS | | 2540 GSb | none | none | (19) | yes |
| Mono | Russell | 47 | 1.11 | 316 | PUB | 600 PUB | 7070 BM | | Sd-p | (20) | (21) | yes |
| Monte Cristo | | 48 | 0 | – | | 283 GSc | | 5274 AMS | none | none | Recent | yes |
| Newark | Newark | 49 | 0.28 | 302 | AP | 1372 GSc | 6060 GSb | 5834 GSb | Sd-p | none | (22) | yes |
| Pahrump | | 50 | 0 | | | 961 AMS | – | 2457 GSb | none | none | (23) | yes |
| Papoose | | 51 | 0 | – | | 104 PUB | | 4569 GSb | none | none | Recent | no |
| Penoyer (Sand Spring) | | 52 | 0 | | | 647 GSc | | 4738 GSb | (24) | none | Recent | yes |
| Railroad | Railroad | 53 | 0.09 | 375 | AP | 4690 (25) | —4870 GSa | 4706 GSb | Sd-p | none | Lahontan | yes |
| Reveille | Reveille | 53A | | 41 | AP | — (25) | 4960 GSb | <4879 GSb | Sd-p | Wd-p | Lahontan | yes |
| Sand Spring | Lunar* | 53B | 0.01 | 6.3 | GSa | 502 GSc | 5755 GSa | 5742 GSa | Wd-p | none | Recent | yes |
| Ralston | Mud | 54 | 0.05 | 133 | AP | 2701 GSc | 5280 GSb | >5195 GSb | Sd-p | none | Lahontan | yes |
| Rhodes | Rhodes | 55 | 0.07 | 13 | AP | 205 GSc | 4432 GSa | 4366 GSa | Wd-p | none | Lahontan | yes |
| Ruby | Franklin | 56 | 0.61 | 483 | AP | 1280 GSc | 6068 GSb | 5939 GSb | Sd-p | (27) | Lahontan | yes |

| Basin Name | Pluvial Lake Name | Map No. | Hydro. Index | Lake Area mi$^2$ | | Basin Area | Max. Lake Alt. ft., MSL | Basin Floor Alt. ft., MSL | Shore Develop-ment | Overflow Channel | Interp. Age of Shores or Playa | Field Recon. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sarcobatus | | 57 | 0 | | | 1335 GSc | – | 3939 GSa | none | none | (28) | yes |
| Smith Creek | Desatoya | 58 | 0.41 | 168 | AP | 579 GSc | 6230□GSa | 6044 GSa | Sd-p | none | Lahontan | yes |
| Soda Spring (Acme) | | 59 | 0 | | | 126 GSc | | 4373 GSa | none | none | Recent | yes |
| Soda Spring (Luning) | | 60 | 0 | | | 237 GSc | – | 4439 GSa | none | none | Recent | yes |
| Spring | Maxey | 61 | 0.17 | 81 | AP | 550 GSc | 5880□GSb | 5751 GSb | Sd-p | (29) | Lahontan | yes |
| Spring | Spring | 62 | 0.27 | 233 | AP | 1107 GSc | 5770 GSb | 5532 GSb | Sd-p | none | Lahontan | yes |
| Stevens | Yahoo | 63 | 0.11 | 2.0 | AP | 20 GSc | –7320□GSb | 7209 GSb | Sd-p | none | Lahontan | no |
| Stonewall Flat | | 64 | 0 | – | | 346 GSc | – | 4649 GSb | none | none | (30) | (30) |
| Surprise | Surprise | 65 | 0.57 | 568 | AMS | 1560 AMS | 5140□AMS | 4460 GSb | Sd-p | none | Lahontan | yes |
| New Year | Crooks* | 65A | | –5.3 | GSa | | 5980□GSa | | Wd-p | Wd-p | Lahontan | no |
| Teels Marsh | | 66 | 0 | | | 307 GSc | | 4904 GSa | Wd-p | none | (31) | yes |
| Warner | Warner | 67 | | | | – | 4770□GSa | – | Sd-p | none | Lahontan | no |
| Yucca | | 68 | 0 | – | | 292 GSc | – | 3414 GSb | none | none | Recent | no |

**(1) Alvord**

We did not confidently locate shoreline features within Nevada as others have mapped the lake extent. If Lake Alvord extended into Nevada, the maximum shore was near the town of Denio.

**(2) Summit**

Well developed overflow channel to Virgin Creek drainage (Lake Alvord) and Lake Parman shoreline artifacts indicate Late Lahontan overflow, but with probable initial overflow in pre-Lahontan or Early Lahontan. Snow Creek landslide has blocked Soldier Creek drainage to the Lahontan Basin.

**(3) Bonneville**

Along western border of the lake high shore features appear similar to Late Lahontan features in adjacent basins. Most, but not all, investigators working the eastern margins of Lake Bonneville believe the highest shores are of Early Lahontan age or older.

**(4) Butte**

Highest bar closes this basin south of the possible overflow channel cut in alluvial fan deposits. Some overflow possible in Lahontan time, but age relationships not clearly definitive. Ruby Valley index (0.61) may be influenced by Butte Valley (0.28) overflow.

**(5) Clayton**

Age of part of the playa is Recent. The majority of the deposits believed to be playa deposits of Late Lahontan age.

**(6) Delamar**

A possible very weakly developed or preserved shoreline at 4,550 feet MSL forming a pluvial lake about 6 mi$^2$ , and a hydrologic index of 0.01. At 4,540 feet MSL (2 feet above playa level) recent or modern shore evidence.

**(7) Dixie**

Basin area includes Fairview Valley drainage. Index calculation includes Lake Labou.

(8) Gabbs

Deposits partly Recent and partly Lahontan in age.

(9) Grapevine Canyon

Basin closure probably formed after the Lahontan pluvial.

**(10) Grass**

Snyder and others (1964), as well as other geologists, believe Lake Gilbert overflowed. We measure 127 feet of basin closure between the Lahontan age bar and the pass to Crescent Valley.

**(11) Huntoon**

No shore features recognized. Careful fieldwork or better aerial photography than available might yield shore features of a shallow pluvial lake.

**(12) Indian Springs**

Recent playa and Lahontan age playa and paludal deposits present.

**(13) Lahontan**

Range of altitude of the highest Lahontan age shore features is 4,325 to 4,406 feet MSL. Highest shore features are mostly Early Lahontan, but in the northeast sub-basins are Late Lahontan (Mifflin and Wheat, **1971).**

**(14) Bawling Calf**

This basin has not been studied with aerial photography. Topographic closure and overflow channel indicate probable weak shorelines exist in the basin.

**(15) Diamond**

"Old" shoreline features of pre-Lahontan age between 6,080 and 6,000 feet MSL in the northern part of the basin. Strong soils developed on the pre-Lahontan shore features, and the highest could be of a Rye Patch equivalent age (Illinoian) or perhaps older. Lahontan age shore is near the same elevation as the overflow pass.

**(16) High Rock**

Lake High Rock was formed in Lahontan time by a landslide blocking Willow Creek drainage. Reconnaissance made in Fly Canyon area without elevation control.

**(17) Smith**

Lake Wellington is believed to be Early Lahontan in age based on well-developed soil (Churchill Soil) on the high bar and soil developed on lacustrine deposits. Stream capture of East Walker River headwater area near Sonora Junction may correlate with the time of earlier basin overflow at about 5,000 feet MSL.

**(18) Long**

The "old" bar at the south margin of the lake is believed to be pre-Lahontan. Regional basin tilt to the north may have permitted preservation. This interpretation is preferred on the basis of comparison of weathering and preservation of pre-Lahontan features in other basins.

**(19) Mesquite**

Playa is Recent and some playa and paludal deposits are of Lahontan age.

**(20) Mono**

Some investigators have claimed overflow. If so, it has not occurred during Lahontan time, and possibly not during Mono Lake time.

**(21) Mono**
High shore believed of Lahontan age. Some investigators have recognized "older" and higher shore features; in field reconnaissance we found no definitive evidence.

**(22) Newark**
**"Old"** shore features recognized in the southeast corner of the basin. Either Early Lahontan or Rye Patch equivalent features; preserved due to faulting or warping. Not visited in the field.

**(23) Pahrump**
Playa features of Recent age. Lahontan age paludal and playa sediments in several areas.

**(24) Penoyer**
Lacustrine tufa and well-sorted sediments found during reconnaissance, but no definitive high shore feature recognized in field or on aerial photographs.

**(25) Railroad**
Includes Lake Reveille drainage and lake area and Sand Spring drainage in computation of hydrologic index. Basin area of Reveille and Railroad is 4,690 $mi^2$. Drainage from 53A periodically spilled to Lake Railroad.

**(26) Sand Spring**
**Playa** lake shore features with basin closure apparently developing from post Lahontan volcanism. See Scott and Trask (1971) for relative age of volcanics and long history of volcanism in the area.

**(27) Ruby**
Hardman, in Snyder and others (1964), believed Ruby Valley overflowed to the north. There is considerable closure and no evidence of overflow in the suggested area of overflow.

**(28) Sarcobatus**
Playa of Recent age. Some paludal and playa deposits of Lahontan age.

**(29) Spring**
Minor groundwater seepage to Lake Spring.

**(30) Stonewall Flat**
Minor basin closure, possibly related to desiccation of Lahontan age groundwater discharge basin; deposits appear to be paludal or playa in origin.

**(31) Teels Marsh**
Lahontan and Recent paludal and playa deposits. No recognized shore features in aerial photographs or in field reconnaissance.

# LATE QUATERNARY PLUVIAL LAKES IN NEVADA

0 10 20 30 40 50 60 70 80 Kilometers
10 20 30 40 50 Miles

Hydrographic boundary, dashed where significant overflow has occurred between adjacent basins

**57** Reference number of hydrographic basin

Hydrographic boundary and direction of flow of surface water of uncertain age

Position and direction of surface-water transfer during full pluvial climates of Wisconsinan age

Late Quaternary lake extent, dashed where inferred from known shoreline evidence. All except 53B are correlated with Wisconsinan events

Base map: Nevada Bureau of Mines and Geology Map 43

Nevada Bureau of Mines and Geology
University of Nevada, Reno, NV 89557