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PART 1 ONE

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

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PROTEROZOIC TO RECENT STRATIGRAPHY, TECTONICS, AND VOLCANOLOGY, UTAH, NEVADA, SOUTHERN IDAHO AND CENTRAL MEXICO

Edited by

Paul Karl Link and Bart J. Kowallis

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.

Middle: Lake Bonneville shorelines west of Brigham City, Utah.

Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

High, Old Pluvial Lakes of Western Nevada

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OVERVIEW

The purpose of this field trip is to view new evidence for large lakes which stood at higher levels than the well documented later Pleistocene pluvial lakes in western Nevada. Early and early-middle Pleistocene stands of Lakes Lahontan (stops 1-1, 1-3, and 2-1 to 2-6, Figs. 1 and 2) and Columbus-Rennie (stops 3-3, 3-4, and 3-6) were 25 to 70 m higher than those of the Eetza- (late-middle Pleistocene) and Sehoo-aged (late Pleistocene) lakes. In addition, deposits of late Miocene and Pliocene lakes (stops 3-1, 3-2, and 3-5) extend more than 100 km south of Walker Lake and suggest connections among proto-Lakes Lahontan, Columbus-Rennie, Clayton, and possibly Tonopah (Fig. 2). Evidence for the extreme high stands includes: (1) sequences of tephra- and fossil-bearing lacustrine and deltaic deposits grading up into beach gravel, (2) remnants of V-bars and arcuate shoreline berms, and (3) bedrock benches that bear remnants of rounded, polished beach gravel well above previously known shorelines. The implications of a 1400-m (4600 ft) high stand of Lake Lahontan (Fig. 2) are staggering: for example, Reno, Carson City, and Battle Mountain are submerged and the lake would probably have flooded Dixie and Fairview Valleys (stop 1-2, Figs. 1 and 2). Reconstructing these lake levels has important implications for paleoclimate, tectonics, and migration of aquatic species in the Great Basin.

Part I of the guidebook presents a review and update of the stratigraphy and history of Lake Lahontan, with revised tephrochronologic ages. Part II discusses the new evidence for extreme high stands of Lakes Lahontan, Columbus-Rennie, and Russell, and for Pliocene connections among these and other lake basins. Part III is the road log and contains detailed descriptions of the field trip stops.

PART I: LAKE LAHONTAN STRATIGRAPHY AND HISTORY: AN UPDATE

Roger B. Morrison

INTRODUCTION

Lake Lahontan (Fig. 3) was the second-largest pluvial lake in the Western Hemisphere several times, beginning in the early Pleistocene. Its last two maxima, about 160,000 and 13,000 years ago (Fig. 4), nearly coincident in altitude, now range between 1318 and 1343 m (4324–4406 ft) due to later deformation (Mifflin and Wheat, 1979; Mifflin, 1988). During these high stands, Lake Lahontan inundated more than 21,000 km^2. Its greatest depths then were about 270 m at Pyramid Lake, 180 m at Walker Lake, and 150 m in the Carson and Black Rock Deserts. Its drainage basin, about 115,000 km^2, covers most of the northwestern Great Basin (Fig. 3). Although comparable to Lake Bonneville in overall length and width, Lake Lahontan always had a much smaller lake area, maximum mean depth, and volume.

"Lake Lahontan" is used here in two senses, areal and stratigraphic. Areally, Lake Lahontan comprises the area outlined by its highest strandline and consists of many interconnected intermontane basins. In a stratigraphic-chronologic sense, Lake Lahontan refers to all lake cycles within the area enclosed by this high strandline. In terms of exposed stratigraphic record, this definition includes about a dozen deep-lake cycles that range back beyond one million years (Fig. 4). This definition expands my former definition (Morrison, 1964) to that of Russell (1885), who regarded Lake Lahontan as a pluvial lake of the entire Quaternary Period.

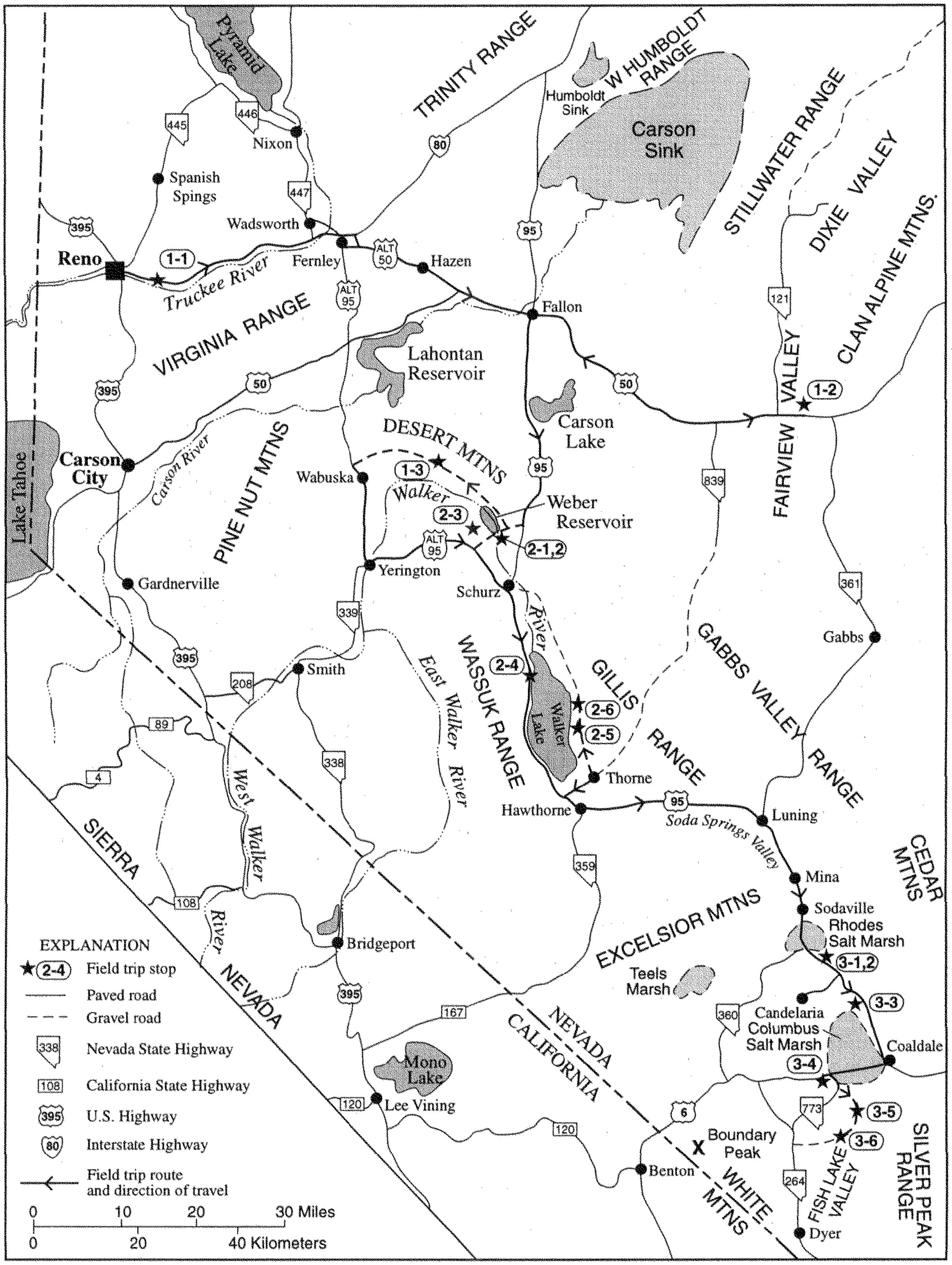


Figure 1. Highway map showing approximate route of field trip. See Table 1 for exact locations of stops. Total mileage from Reno and return is about 650 miles.

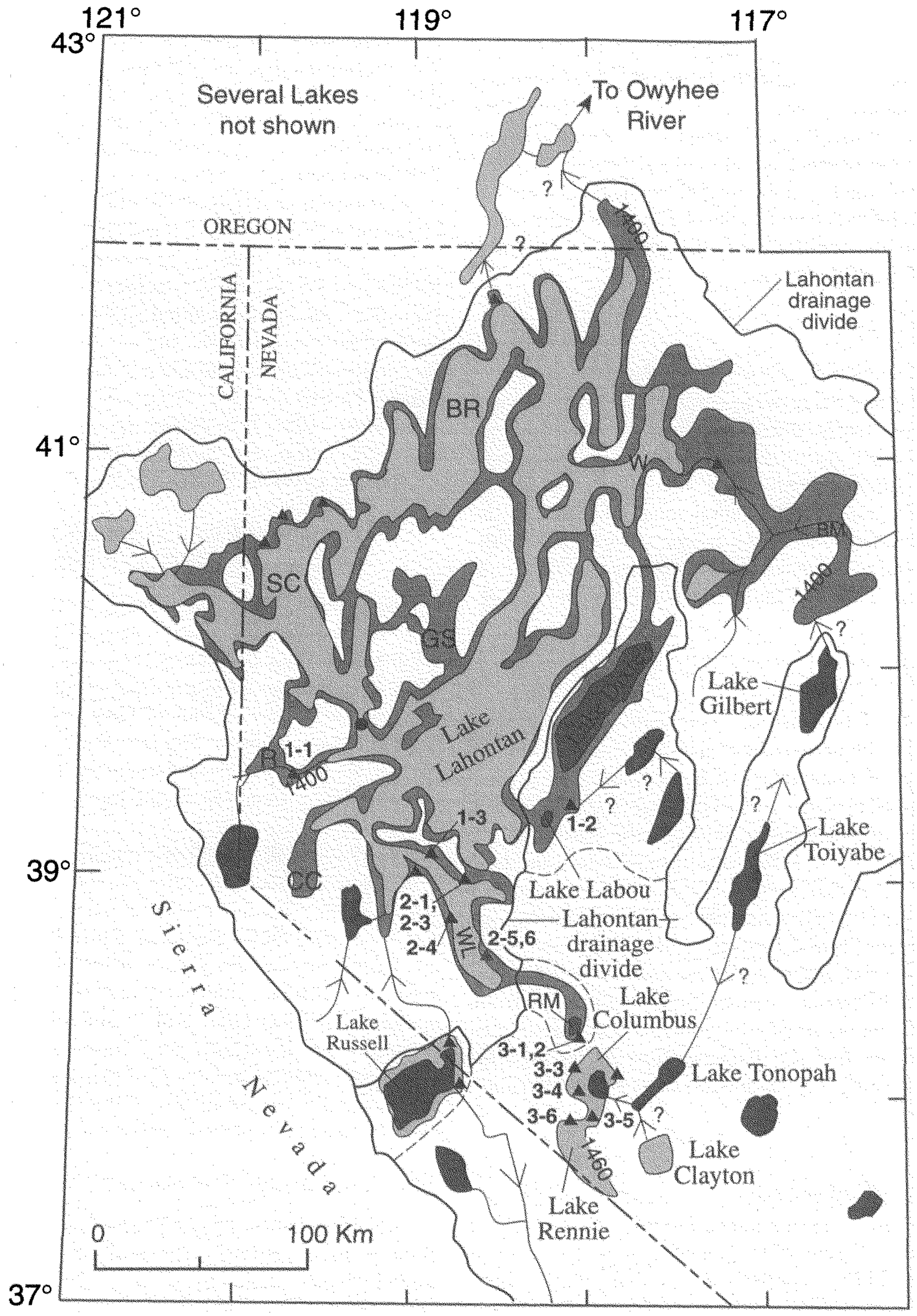


Figure 2. Regional map showing Lahontan basin and nearby pluvial lakes, selected shoreline elevations in meters, and areas of middle(?) Pleistocene (medium shading) and late Pleistocene lakes (light shading, Lahontan; dark shading, other pluvial lakes). Triangles show study sites in text; numbers are field trip stops (Table 1); queried arrows on drainages show possible links between basins during highest lake stands; dashed lines show possible enlarged area of Lahontan basin. BR, Black Rock Desert; SC, Smoke Creek Desert; W, Winnemucca; BM, Battle Mountain; GS, Granite Springs Valley; R, Reno; CC, Carson City; WL, Walker Lake; RM, Rhodes Salt Marsh.

Controls on lake history

Lake Lahontan did not overflow, nor was its basin breached, during the last 600,000 years. There were no sudden diversions of large rivers into or out of the Lahontan basin during this time. Although several small peripheral pluvial lakes overflowed into Lake Lahontan, they had minor effect on the total inflow. Cyclic climatic change was the principal influence on lake level, but other factors such as interbasin thresholds, river diversions, and tectonics have also affected lake levels.

Interbasin thresholds

As Lake Lahontan's water level oscillated for more than 1 Myr over a vertical range of more than 220 m, various minor and major interbasin thresholds (Fig. 3) were reached, repeatedly either opening or separating, expanding or contracting, different lake areas. As a result, the various subbasins have more or less independent histories for the times when lake levels were below critical thresholds. *There is no unique stratigraphy and history that applies to the whole area indicated by the highest strandline of Lake Lahontan.*

River diversions

Three of the four principal rivers that fed Lake Lahontan (Fig. 3) had significant interbasin diversions at various times during the Quaternary. Only the Carson River persisted in its present course to the Carson Desert. The Walker River may have ended in the Walker Lake basin until an outlet through Adrian Valley was formed when the lake rose to 1400 m (4600 ft) in early-middle(?) Pleistocene time (M. Reheis, written commun., 1997); afterward the Walker River frequently flowed through Adrian Valley to end in the Carson Desert, not into Walker Lake as it does now. The Humboldt River also commonly flowed into the Black Rock Desert, not via its present course to Carson Sink. In late Pleistocene time the Truckee River flowed at least once to the Carson Desert, instead of to Pyramid/Winnemucca Lakes.

Tectonism

Most of Lake Lahontan is in the Walker Lane tectonic belt and underwent local faulting and warping throughout the Quaternary Period. The Walker Lane belt is a broad northwest-trending complex zone of strike-slip faulting east of the Sierra Nevada (Stewart, 1988); recent geologic and geodetic studies indicate that 10–12 mm/yr of northwest-directed (right-lateral shear) plate-boundary slip is accommodated by the central part of the Walker Lane belt (Dixon et al., 1995; Reheis and Sawyer, 1997). Persistently downdropped basins include Pyramid, Winnemucca, and Walker Lake basins and Carson Desert; strongly uplifted mountain ranges include the Humboldt, Stillwater, and Wassuk Ranges (Fig. 3). The many changes in topography due to tectonism make it impossible to outline fully the highest strandlines of early Pleistocene deep-lake episodes and possible sites of very ancient overflow from the Lahontan basin.

Isostatic rebound since the late Pleistocene (Sehoo, Fig. 4) highstand is a maximum of 9 m (Mifflin and Wheat, 1979) or 18 m (Adams, 1996), centered in the Carson Desert. Mifflin and Wheat (1979) concluded that the whole Lake Lahontan area has been tilted slightly northward, so that north of latitude 41°N the highest strandline is of Sehoo age, and south of this latitude it generally is of Eetza (late-middle Pleistocene, Fig. 4) age. In contrast, Adams and Wesnousky (1996) believe that no northward tilting took place; this controversy rests on differing criteria for discriminating Eetza vs. Sehoo shoreline deposits.

SUMMARY OF LAKE LAHONTAN STRATIGRAPHY AND HISTORY

The following discussion centers on the Carson Desert and other northern terminal basins such as the Pyramid/Winnemucca Lake, Black Rock Desert, and lower Humboldt River basins.These were principal sumps, fed continually or intermittently by all four of Lake Lahontan's principal tributary rivers, Carson, Truckee, Walker, and Humboldt. Thresholds between these basins are low, so the whole complex has a common lacustrine history above these thresholds.

The Walker Lake basin has a significantly different lacustrine history. This is because (1) the high threshold of Adrian Valley (Fig. 3), about 20 m below the highest Eetza and Sehoo strandlines, separates this basin from the northern basins, and (2) the Walker River, the only important inflow to this basin, changed course several times, ending up either in Walker Lake or in Carson Desert. During part of middle and late Quaternary time Walker Lake was a playa, even while large lakes existed in the northern basins; hence, the pluvial-lake history of the Walker Lake basin is likely to be less complete than those of the northern basins.

Early Lake Lahontan time, chiefly >1 Ma

The oldest known exposed Lake Lahontan deposits are in the Walker Lake basin. The most fully studied exposures are in badlands about 3 km south and 6 km north of Weber Dam (Stops 2-1 and 2-3, Figs. 1 and 5; Morrison, 1991; Morrison and Davis, 1984a, b). Here are two lacustrine units older than the Rye Patch Alloformation (henceforth abbreviated AF), separated from each other and overlain by extensive, alluviated erosional unconformities. The 1-Ma Glass Mountain G tephra layer (Sarna-Wojcicki et al., 1987,

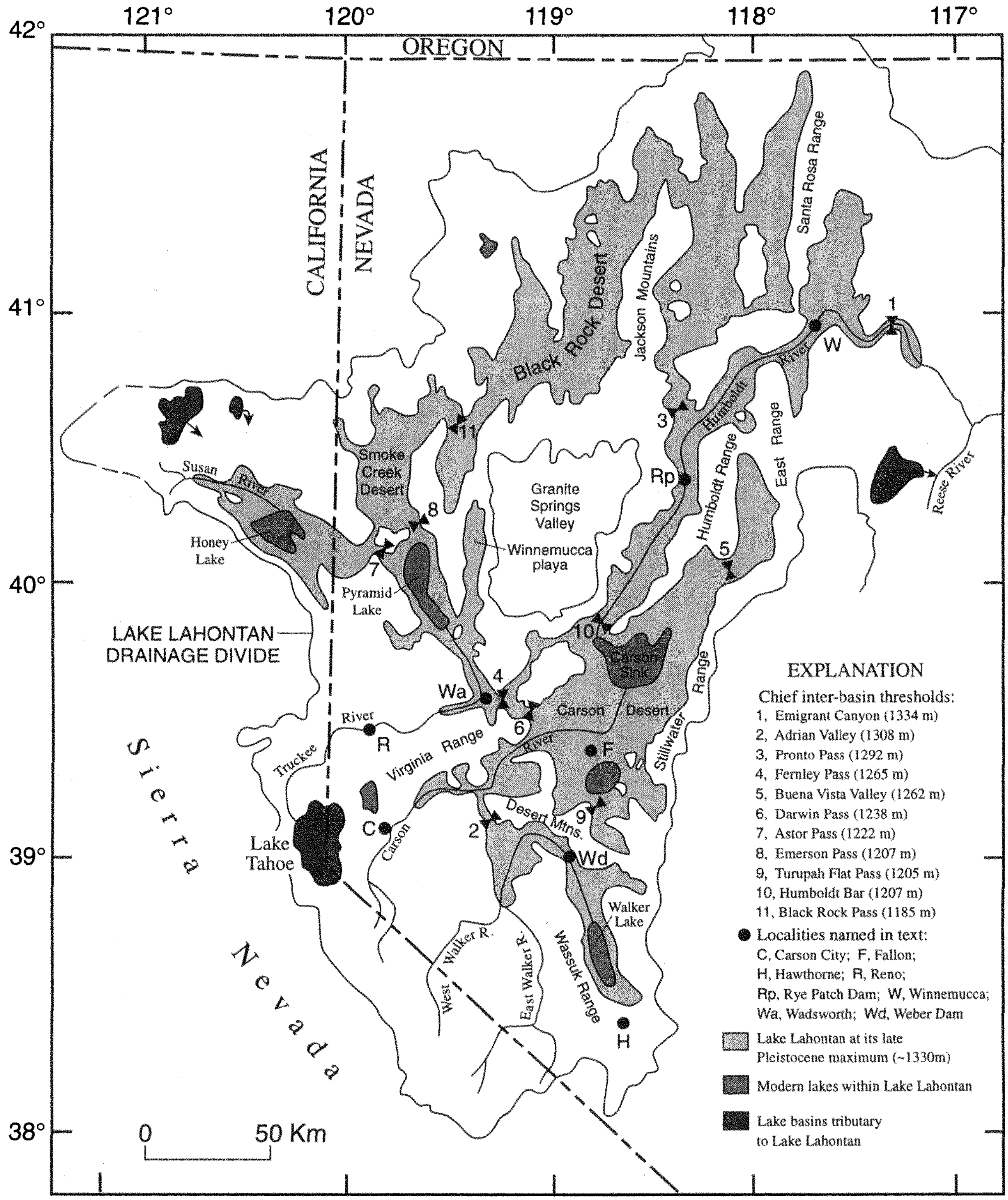


Figure 3. Lake Lahontan at its maximum late Pleistocene extent showing its subbasins, thresholds between them, and present courses of principal rivers (from Morrison, 1991).

1991) occurs in the middle of the upper lacustrine unit (Fig. 4). Ancient beach gravel and underlying lacustrine silt and sand, likely equivalent to these and younger units, is exposed at altitudes up to 1400 m (4600 ft) several km southeast of Weber Dam (Stop 2-2, Figs. 1 and 2) and on both sides of Walker River about 18 km northwest of Weber Dam (Stop 1-3; Reheis, Part II).

On the east side of Walker Lake, 15 km north of Hawthorne, is a polygenetic recurved spit complex known as the "Thorne bar" (Stop 2-5, Figs. 1 and 5). Above the late Pleistocene (Sehoo) highest strandline at 1332 m (4370 ft) and rising to 1400 m (4600 ft) altitude is an older, much more eroded spit complex whose gravel-on-gravel stratigraphy is ambiguous and unresolved. Four km north of Thorne bar (Stop 2-6), four generations of beach gravel separated by paleosols, all of early to middle Pleistocene age, are exposed (Reheis, Part II).

In the northern basins, tiny exposures at a few sites show lacustrine sediments, intercalated with alluvial-fan gravel, that may correlate with some of the ancient lake units in the Walker Lake basin. The remaining part of the discussion of Lake Lahontan stratigraphy refers to the northern basins.

Lovelock Alloformation and interlacustral, >800 to ~70 ka

The lowest widely exposed strata of the Lake Lahontan Allogroup in the northern basins comprise the Lovelock Alloformation (AF; Fig. 4). This unit represents a long interlacustral episode when the terminal basins were dry or held shallow lakes. It consists chiefly of alluvial sand and gravel intercalated with dozens of moderately to very strongly developed paleosols—a pedocomplex. In its upper part is a tephra layer (B? in Fig. 4) stratigraphically below the Brunhes-Matuyama geomagnetic boundary; although compositionally similar to the Bishop Ash, this tephra must be older because it is paleomagnetically reversed. Despite widespread alluviation during Lovelock time, alluvial fans this old are rarely preserved at the present land surface. Thus, this unit remains chiefly in the subsurface, exposed locally by deep erosion, notably in the Humboldt River valley below Rye Patch Dam (Fig. 3).

Rye Patch Alloformation and lacustral, ~700 to 650–600 ka

The Rye Patch Alloformation overlies the Lovelock AF and records a major lacustral with two principal lake cycles. It also is chiefly in the subsurface in the northern basins, exposed locally by deep erosion. Both members of this AF consist of lacustrine gravel, sand, silt, clay, and tephra layers. In the Humboldt River Valley near Rye Patch Dam (Fig. 3) the lower member has the ~670 ka Rye Patch Dam ash bed, and the upper member contains in its upper part

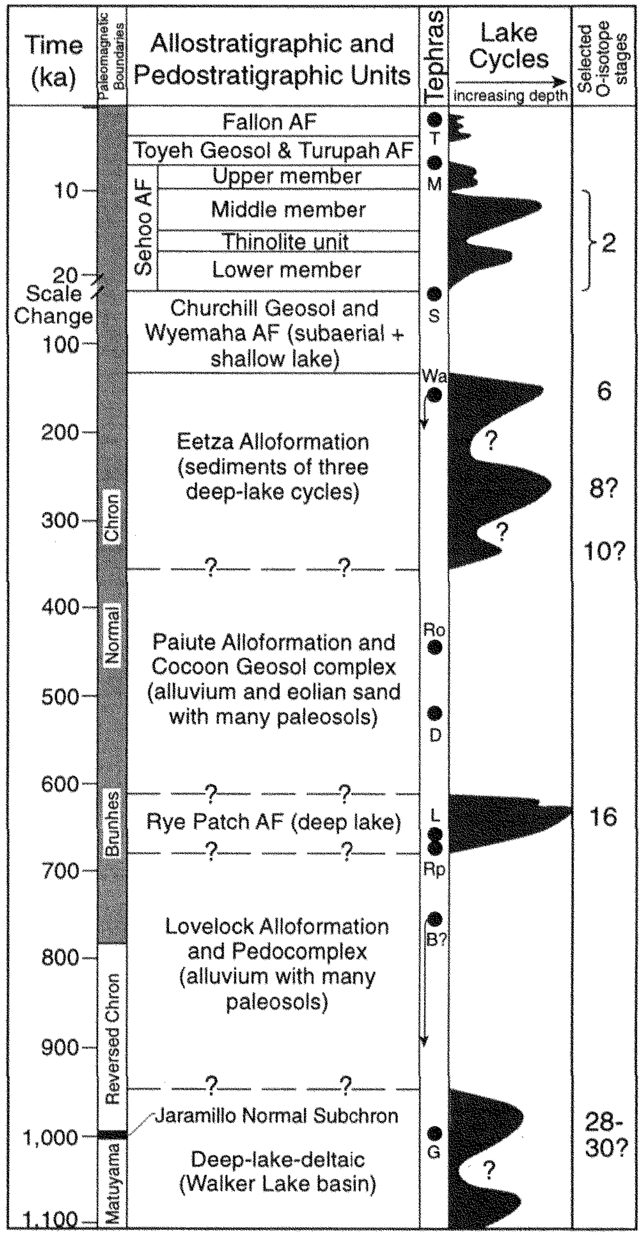


Figure 4. Lake Lahontan Allogroup as defined by Morrison (1991). Principal exposed allostratigraphic units (AF, Alloformation) and inferred fluctuations in lake level. Principal data from the Carson Desert, lower Truckee River, and Humboldt River areas. Letters in tephra column denote dated tephra layers (some tephra ages and unit boundaries are revised; A. Sarna-Wojcicki, 1997, written commun.): T-Turupah Flat, 1.2 ka; M-Mazama, 6.8 ka, and Tosoyowata, 7 ka; S-Mt. St. Helens C/Marble Bluff, about 35 ka; Wa-Wadsworth, about 150 to 200 ka; Ro-Rockland, 400–470 ka; D-Dibekulewe, about 510 ka; L-Lava Creek, about 665 ka; Rp-Rye Patch Dam, about 670 ka; B?-Bishop-like tephra, 760 ka or greater; G-Glass Mountain G, about 1 Ma.

the ~665 ka Lava Creek B tephra layer (Fig. 4). The next-higher dated tephra layer is the ~510 ka Dibekulewe ash bed in the lower part of the Paiute AF. Apparently the Rye Patch AF is equivalent to oxygen-isotope stage 16 and perhaps 18.

Gravelly sediments assigned to the Rye Patch AF are exposed at two sites at the northern front of the Desert Mountains (Fig. 3), at altitudes up to 1325 m (Morrison, 1991). Beach gravel, possibly in part correlative with the Rye Patch AF, lies above the highest Sehoo strandline (~1332 m, 4370 ft) and up to 1400 m (4600 ft) at several other sites in the northern basins (Fig. 2 and Table 1; Reheis, Part II). The configuration of Lake Lahontan during the Rye Patch lake maxima is not definitely known and probably never can be ascertained fully because of the highly disjunct exposure of the beach deposits and persistent tectonism in the Walker Lane.

Paiute Alloformation-Cocoon Geosol and interlacustral, 650–600 to ~340 ka

A thick, essentially non-lacustrine unit, the Paiute AF, overlies the Rye Patch AF. It represents an interlacustral when terminal basins were dry or held only shallow lakes. It is composed chiefly of alluvial gravel, although between the Carson Desert and Walker Lake the middle part of this unit has much eolian sand. Alluvial-fan building was widespread during Paiute time; many of the inactive alluvial fans seen today are of Paiute age. Many moderately to strongly developed paleosols typically are intercalated with the alluvial strata, making this unit another pedocomplex. The paleosols in its upper part, which commonly are amalgamated into a single soil profile, are called the Cocoon Geosol. The ~510 ka Dibekulewe tephra layer is in the lower part of the Paiute AF and the ~435 ka Rockland tephra layer is in the upper part (Fig. 4), indicating that the Paiute AF correlates with deep-sea oxygen-isotope stages 15 through 13.

Eetza Alloformation and lacustral, about 340 to 130 ka

The Eetza AF, overlying the Paiute AF, represents several lacustral periods and is as much as 45 m thick. It had three major lake cycles and at least three minor ones (Fig. 4). The highest Eetza lake maximum, mean altitude 1330–1335 m (~4360 ft), was within several meters above or below the Sehoo maximum depending on deformation that occurred between the two maxima.

On hills and piedmonts the deposits of Eetza age typically are boulder and cobble gravel. Offshore sediments are silt, clay and sand with lenses of pebble gravel in deltaic areas. The Wadsworth ash bed (Wa, Fig. 4), locally present near the top of this AF, was previously dated 155 ± 25 ka but now is thought to be about 200 ka (A. Sarna-Wojcicki, 1997, written commun). (I prefer the first date, because the stratigraphic position of this tephra layer in the Eetza AF suggests a correlation close to the maximum of oxygen-isotope stage 6.)

Locally intercalated with the lacustrine sediments of the Eetza AF are tongues of alluvial and colluvial gravel, commonly bearing weakly to moderately developed paleosols. They indicate that the Eetza lacustral consisted of at least six and possibly eight lake cycles, which are grouped into one unit for mapping purposes because most outcrops do not show this detailed stratigraphy. Only the last three cycles rose above intermediate shore levels, and apparently only one of these rose high enough to enter the Walker Lake basin. An exact chronology for these lake cycles remains to be determined. The ~160-ka Wadsworth tephra layer in the upper part of the Eetza AF and the ~510-ka Rockland tephra layer in the upper Paiute AF correlate the Eetza AF with deep-sea oxygen-isotope stages 6 to 10 (Fig. 4).

Wyemaha Alloformation and Churchill Geosol and interlacustral, ~130 to ~35 ka

The Wyemaha Alloformation and Churchill Geosol represent a ~100 kyr interlacustral between the Eetza and Sehoo lacustrals (Fig. 4). At elevations below about 1210 m (3970 ft) in the basins the Wyemaha AF is chiefly shallow-lake sand to clay, but at higher elevations it consists of eolian sand and alluvium with one or the other predominant depending on location.

Early Wyemaha time was one of extreme aridity and strong winds. Sand was blown into belts 10 to 30 km wide and as much as 120 km long, virtually drowning some low mountains in eolian sand (e.g. Blow Sand Mountains south of Fallon, F in Fig. 3). In later Wyemaha time climate became wetter and much less windy, promoting pedogenesis (the Churchill Geosol) at elevations above shallow lakes in terminal basins such as the Carson Desert.

The Wyemaha AF dates from the beginning of the last interglacial, about 130 to ~35 ka. The ~35-ka Mt. St. Helens C tephra layer marks the Wyemaha-Sehoo boundary, especially in lake-bottom sediments in the basin lowlands where it typically is less than a meter below the Mono Lake geomagnetic excursion, dated 27–29 ka (Liddicoat and Coe, 1997). Thus, the Wyemaha represents deep-sea oxygen-isotope stages 5 to 3.

Sehoo Alloformation and lacustral, ~35 to ~8 ka

The Sehoo AF records Lake Lahontan's last major lacustral. It is divided into lower, middle, and upper members on the basis of two major lake recessions (Fig. 4). The lower member dates from ~35 to 18 ka. Its shore deposits, sandy pebble gravel to small-boulder gravel, typically are smaller sized than the underlying Eetza gravel but record the strongest wave action of Sehoo time. The highest lake stage recorded by this member, ~1277 m (4190 ft), was reached about 20–19 ka. The following recession reached its lowest level at about 17.5 ka. It is marked by a major unconformity with deep river trenching, alluvium, and a weakly developed paleosol that has been traced as low as 1216 m (3990 ft) in Carson Desert and 1207 m (3960 ft) along the Truckee River (Fig. 3).

The middle or dendritic member of the Sehoo AF, dating from about 17 to 11.5 ka, records the highest Sehoo lake maximum, 1332 ± 5 m (~4370 ft) at about 13 ka. Its shore gravel is typically finer than that of the lower member, and much finer than underlying gravel of the Eetza AF. Strandlines exposed to strong wave action typically bear thick coatings of tufa deposited by blue-green algae as sheets and separate tufa heads. Just before the highest stage of this lake cycle, the lake level in the northern basins overtopped the 1308-m threshold into Walker Lake basin. The resulting flood changed the course of Walker River from the Carson Desert into Walker Lake, producing deep river trenching and the first deep-lake cycle in Walker Lake basin in more than 100,000 years. Also during the recession of the middle Sehoo lake cycle, the Humboldt River cut its present course south of Winnemucca to the Carson Desert (formerly it flowed to the Black Rock Desert; Figs. 2 and 3). The lake recession is represented by deep river entrenchment, alluvium, and a weak paleosol, traced as low as 1190 m (3905 ft) in the Carson Desert and 1165 m (3820 ft) along the lower Truckee River.

The last Sehoo lake cycle, recorded by the upper member of the Sehoo AF, rose only to about 1216 m (3990 ft) in the non-connecting Carson Desert and Pyramid/Winnemucca Lake basins. This minor lake cycle probably lasted from ~10 to ~8 ka. Apparently, human occupation of this region began in late Sehoo time, although archaeologic remains are few. A human mummy from a rock shelter in the Lahontan Mountains southeast of Fallon yielded a radiocarbon age of 9+ ka—the oldest mummy ever discovered in the Old or New Worlds.

Turupah and Fallon Alloformations; middle and late Holocene nonlacustral

During the remainder of Holocene time to the present, terminal basins such as the Carson Desert were dry or held shallow lakes. Middle Holocene time, represented by the Turupah AF, dating from ~8 to 3.5 ka, was the warmest part; at times, severe winds scoured the basin interiors and built large tracts of sand dunes. The dust settled eastward as a huge loessial blanket in places more than a meter thick. Alluvial deposition was infrequent and scanty. Late-middle Holocene time was warmer than now and had greater annual precipitation. Wind activity decreased greatly and plant cover increased; the increased landscape stability and wetter, warm climate produced the moderately developed Toyeh Geosol and locally, shallow lakes. The late Holocene, 3.5 ka to present and represented by the Fallon AF, had frequent climatic fluctuations within a small range of present values. Small lakes formed in the Carson Desert and Pyramid Lake basins. Fallon time has a rich archaeological record (Morrison, 1964; Davis, 1982).

Part II: LAKES IN THE LAHONTAN BASIN AND NEARBY BASINS IN WESTERN NEVADA DURING THE PLIOCENE TO MIDDLE PLEISTOCENE

Marith Reheis

INTRODUCTION

During its late-middle and late Pleistocene highstands (Fig. 4), Lake Lahontan covered more than 21,000 km^2 and extended more than 350 km, from northern Nevada to beyond the southern end of Walker Lake (Figs. 2 and 3). Deposits and altitudes of shorelines of these ages have been studied for over a century (e.g. Russell, 1885; Benson et al., 1990; Morrison, 1991). However, little information was available on older pluvial lakes and their high shorelines. In 1995, mapping was undertaken to investigate possible ancient extensions of Lake Lahontan to the south of Walker Lake and Mifflin's (1984) hypothesis of long-term northward tilting of northwestern Nevada. The mapping project resulted in the discovery of abundant sedimentologic and geomorphic evidence of lakes much older, and shorelines much higher, than the late Pleistocene lakes in western Nevada (Lakes Lahontan, Columbus, and Russell, Fig. 2). Altitudes of the earlier Pleistocene shorelines *in unfaulted locations* in the Lahontan basin are consistent and indicate little long-term northward tilting. Faulting has locally displaced shorelines at least 30 m, and possibly as much as 75 m along the west side of Walker Lake (stop 2-4, Figs. 1 and 2).

Morrison (1991, and Part I) summarized the current knowledge of Lake Lahontan's lake cycles, deposits (Fig. 4), and high shorelines. Little work has been done on other pluvial lakes in western Nevada (Fig. 2) except for Lake Russell (Benson et al., 1990, and references therein). Mifflin and Wheat (1979) found late Pleistocene shorelines for Lakes Dixie, Rhodes, Columbus, and Tonopah (Big Smoky Valley). Davis (1981) investigated late Tertiary lacustrine deposits in Clayton Valley. Gilbert et al. (1968) mapped Pliocene lacustrine deposits interbedded with volcanic rocks east of Mono Lake. Reheis et al. (1993) documented several Pliocene to middle Pleistocene cycles of pluvial Lake Rennie in Fish Lake Valley (Fig. 2) and thought that at about 760 ka, Lake Rennie may have merged with Lake Columbus to the north.

This discussion focuses on pre-Eetza (Fig. 4) pluvial lakes. Shoreline altitudes of the Eetza and Sehoo cycles of Lake Lahontan are nearly congruent (~1332 m, 4370 ft, where undeformed), although there is current debate on whether the highest obvious shoreline in the southern part of the Lahontan basin is Eetza (Morrison, 1964; Mifflin, 1984) or Sehoo (Adams, 1996) in age. The evidence for shoreline altitudes of pre-Eetza lakes is mainly sedimentologic. Classic shoreline morphologies such as wave-cut cliffs and beach berms are rarely preserved after half a million years or more of erosion. The highest altitude of beach-gravel beds or lag on bedrock slopes is taken as a minimum shoreline altitude. Finer-grained beds locally contain tephra layers; these are being identified by chemical correlation with tephra of known age by the U.S. Geological Survey Tephrochronology Laboratory (A. Sarna-Wojcicki, 1996 and 1997, written communs.). Ages of the units are also constrained by magnetostratigraphy and by vertebrate biostratigraphy (J. Honey and C. Repenning, U.S. Geological Survey). Site locations are in Table 1.

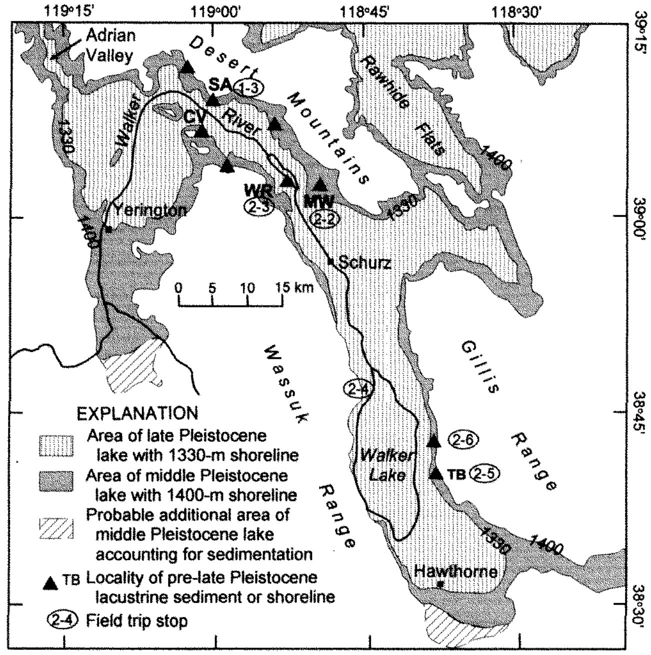


Figure 5. Map of Walker Lake basin and southernmost Carson Desert (Rawhide Flats) showing study sites, field trip stops, and lake areas. Area of lake at 1400 m is drawn using modern topography, acknowledging this is only an approximation of topography in the middle Pleistocene due to subsequent faulting, erosion, and sedimentation. SA, Sunshine Amphitheater; CV, Campbell Valley; WR, Weber Reservoir; MW, McGee Wash; TB, Thorne bar.

EVIDENCE FOR OLD PLUVIAL LAKES IN THE LAHONTAN BASIN

Walker Lake Basin

The Walker Lake basin (Figs. 3 and 5) contains much of the stratigraphic evidence of early and middle Pleistocene lakes with high shorelines in the Lahontan basin. The Walker River rises in the Sierra Nevada and presently feeds Walker Lake. However, at times in the past, the Walker River flowed north into the Carson Desert via Adrian Valley (Fig. 5; Morrison and Davis, 1984a; King, 1993). The Walker Lake basin trends north-south; it is bounded on the west by the Wassuk Range and the active Wassuk fault and on the east by the Gillis Range. At the north end of the Gillis Range, faults of the Walker Lane (Stewart, 1988) intersect the basin and cause a northwest shift in the trend of the basin. The Thorne bar and a nearby site lie in a tectonically quiescent area of the basin (Demsey, 1987). The following discussion is updated from Reheis (1996).

Sunshine Amphitheater and Campbell Valley

Sunshine Amphitheater (Figs. 2 and 5, Stop 1-3) is a large exposure of shallow-lake and sub-lacustrine deltaic deposits of five different lake cycles separated by unconformities and paleosols (see Fig. 8 in road log). Faults are present but strata are little displaced. Vertebrate fossils and paleomagnetic data indicate that the three oldest lacustrine units at Sunshine Amphitheater lie within the Matuyama Reversed Chron (~2.5–0.8 Ma); unit Qlo2 was deposited between 1.4 and 1.0 Ma, and unit Qlo3 was deposited beginning at about 1 Ma. Units Qlo4 and Qlo5 are thought to be middle Pleistocene in age; beach gravels of these units extend to altitudes of 1414 m (4640 ft) and 1378 m (4520 ft), respectively (Fig. 6).

Outcrops in Campbell Valley (CV, Fig. 5; Table 1) are cut by numerous northwest-striking lateral faults of the Walker Lane. The oldest lake unit, Qlo1, is mainly mudstone that is reversely polarized. Deposits in another outcrop, in uncertain stratigraphic relation to the mudstone, contain a tephra layer which is correlated with the Bishop-Glass Mountain family of tephra. Paleomagnetic measurements indicate normal polarity for the tephra layer but reversed polarity for sediment just above and below it; these data suggest that the tephra is a ~1-Ma Glass Mountain tephra within the Matuyama Reversed Chron (Sarna-Wojcicki et al., 1991). Units Qlo2 and Qlo3 consist chiefly of beach sand and gravel that extend to altitudes of about 1390 and 1356 m (4560 and 4450 ft) respectively (Fig. 6).

McGee Wash

The study site at McGee Wash (Stop 2-2, Figs. 2 and 5) extends from the Walker River eastward to U.S. Highway 95 (see Fig. 10 below). Deposits in this area are faulted and tilted (Morrison and Davis, 1984b), but the younger units

Table 1. Location information for field trip stops and other sites described in text.

Site Name	General Location	7.5-minute Map	Township and Range
		Lake Lahontan Basin	
Stop 1-1 (I-80 roadcut)	Truckee River canyon	Vista	NW/4 NW/4 SW/4 sec. 16, T.19N., R.21E.
Clark (arcuate features)	Truckee River canyon	Derby Dam	Most of sec. 1, T.19N., R.22E.
Stop 1-2 (Drumm Summit)	Fairview Valley	Drumm Summit	SE/4 sec. 27 and NE/4 sec. 34, T.17N., R.34E.
Stop 1-3 (Sunshine Amphitheater)	N Walker Lake valley	Parker Butte, Wild Horse Basin	Sec. 19 and adjacent edge of sec. 20, T.16N., R.27E.
Campbell Valley	N Walker Lake valley	Hinkson Slough	Sec. 6, T.14N., R.27E., and adjacent areas
Stop 2-1 (E of Weber Dam)	N Walker Lake valley	Weber Dam	Center sec. 28, T.14N., R.28E.
Stop 2-2 (McGee Wash)	N Walker Lake valley	Weber Dam	S/2 sec. 27 and NE/4 sec. 34, T.14N., R.28E.
Stop 2-3 (W of Weber Dam)	N Walker Lake valley	Weber Dam	SW/4 and NW/4 of SE/4 sec. 29, T.14N., R.28E.
Stop 2-4 (W of Walker Lake)	Central Walker Lake val.	Reese River Cyn.	NW/4 NE/4 and SE/4 NE/4 sec. 32, T.11N., R.29E.
Stop 2-5 (Thorne bar)	S Walker Lake valley	Walker Lake	NW/4 SE/4 sec. 4 and vicinity, T.9N.,R.30E.
Stop 2-6 (N of Thorne bar)	S Walker Lake valley	Walker Lake	SE/4 NW/4 SE/4 sec. 21, T.10N., R.30E.
Burro Mountain	NW Smoke Creek Desert	Salt Marsh	S/2 SW/4 sec. 21 and NE/4 NE/4 sec. 28, T.31N., R.19E.
Buffalo Slough	NW Smoke Creek Desert	Salt Marsh	NE/4 SW/4 sec. 34, T.32N., R.19E.
Freds Field	N Smoke Creek Desert	Wall Spring	NE/4 sec. 18, T.33N., R.22E.
Denio gravel pit	N Black Rock Desert	Denio Summit	SE/4 SE/4 NW4 sec. 24, T.46 N., R.30E.
Iron Point	East of Winnemucca	Iron Point	N/2 NE/4 sec. 6, T.35N., R.42E.
Emigrant Trail	East of Winnemucca	Iron Point	Center S/2 sec. 14, T.36N., R.41E.
		Southeast of Walker Lake Basin	
Stop 3-1 (roadcut)	Rhodes Salt Marsh	Candelaria	NW/4 NE/4 SE/4 sec. 35, T.5N., R.35E.
Stop 3-2 (Redlich Summit)	S of Rhodes Salt Marsh	Candelaria	Sec. 6 and parts of adjacent sections, T.4N., R.36 E.
		Lake Columbus-Rennie (Fish Lake Valley) Basin	
Stop 3-3 (The Big Hole)	N Columbus Salt Marsh	Rock Hill	SW/4 NW/4 NW/4 sec. 2, T.3N., R.36E.
Coaldale Junction	SE Columbus Salt Marsh	Coaldale	SE/4 sec. 17 and NW/4 sec. 20, T.2N., R.37E.
Stop 3-4 (Borrow pit)	S Columbus Salt Marsh	Columbus	NE/4 SW/4 sec. 24, T.2N., R.35E.
Columbus	W Columbus Salt Marsh	Columbus	Approx. NW/4 SW/4 sec. 25, T.3N., R.35E. (unsurvd.)
Stop 3-5 (The Gap)	NE Fish Lake Valley	Rhyolite Ridge NW	Approx. SW/4 sec. 9, T.1N, R.36E. (unsurveyed)
Stop 3-6 (Sinter mound)	N Fish Lake Valley	East of Davis Mtn.	Center S/2 sec. 17, T.1S., R.36E.

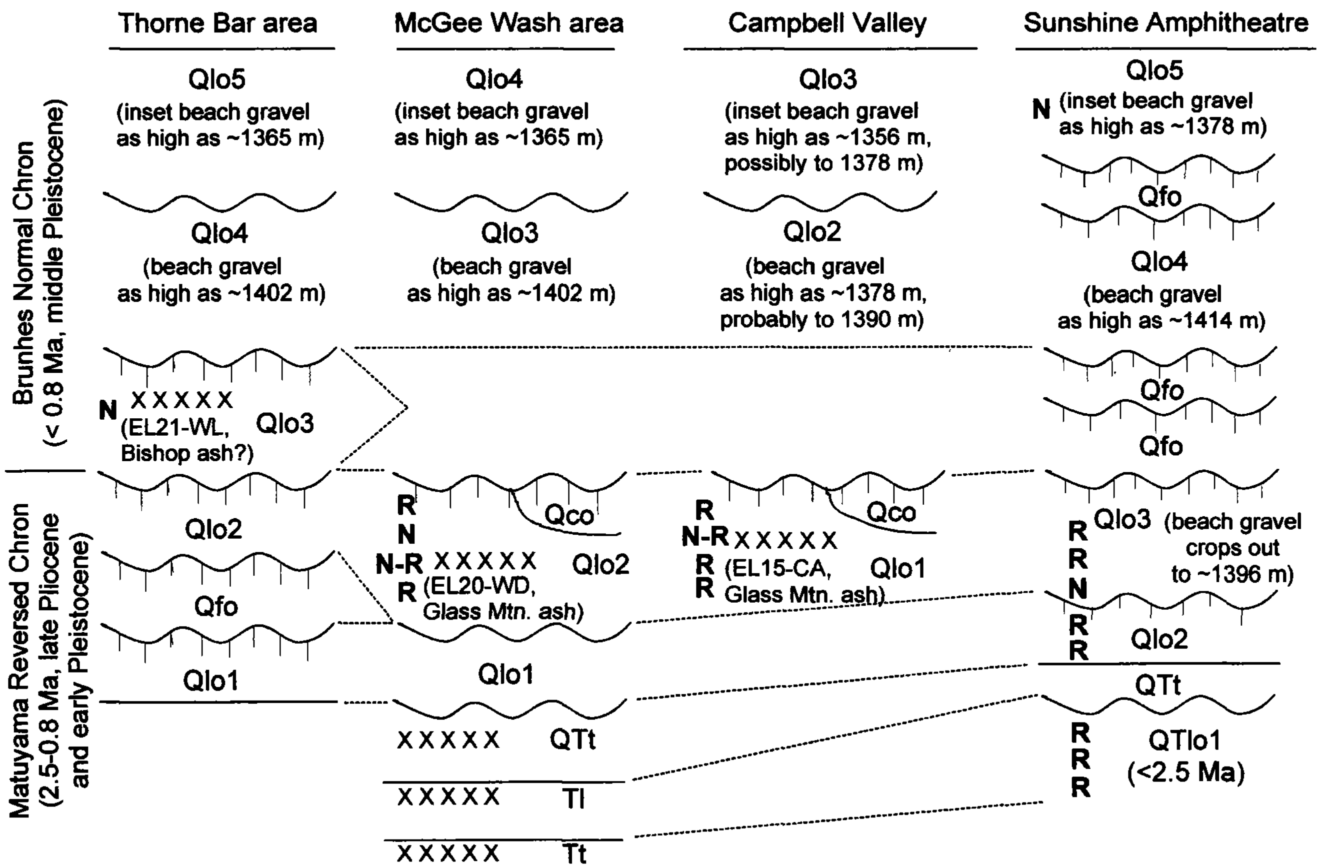


Figure 6. Preliminary stratigraphic correlations in the Walker Lake basin. Units and symbols are the same as in Figures 8, 10, and 11. Wavy lines represent unconformities.

are little displaced. Four pre-Sehoo lacustrine units separated by unconformities overlie a sequence of alluvial and eolian deposits containing numerous carbonate-enriched paleosols. Unit Qlo2 contains a Bishop-like tephra layer. Unit Qlo3 consists of loose sand and gravel with the morphology of a shoreline berm that rises to an altitude of 1402 m (4600 ft). The youngest, unit Qlo4, is inset into all older units and lies at an altitude of about 1365 m (4480 ft; Fig. 6).

Thorne bar area

The Thorne bar is a large V-shaped complex of shore gravel built at the mouth of a large canyon draining the Gillis Range (Stop 2-5, Figs. 2 and 5; Fig. 11 below). Other workers identified the Thorne bar as a site of pre-late Pleistocene shoreline deposits above the Eetza-Sehoo limit, but they attributed the elevated deposits to faulting along the Gillis Range (King, 1978) and (or) northward tilting of the Lahontan basin (King, 1978; Mifflin and Wheat, 1979; Morrison, 1991). Demsey (1987) found no evidence of faulting along the tectonically stable Gillis Range. I believe that the high altitudes of shore gravel in the Thorne bar area mark essentially undeformed shorelines of Lake Lahontan: the Sehoo-aged bar below 1330 m, pre-Sehoo barriers that reached altitudes between 1335 and 1365 m (unit Qlo5, Fig. 6), and at least one old bar that reached a minimum altitude of about 1402 m (Unit Qlo4, Fig. 6). North of the Thorne bar (Stop 2-6, Figs. 5 and 11), the 1402-m shoreline is underlain by four sequences of lacustrine gravel and sand. The second youngest unit contains 760-ka Bishop ash (Fig. 6).

Basins North of Walker Lake

When filled to the ~1332-m level of the Sehoo highstand, the northern basins of Lake Lahontan were connected to the Walker Lake basin only by the narrow Adrian Valley (Figs. 3 and 5; Davis, 1982). A lake that rose to 1400 m in the Walker Lake basin could have spilled to the northern basins through Rawhide Flats (Fig. 5) over a pair of sills at 1370 m. However, it is likely that in the early Pleistocene, Adrian Valley did not exist (King, 1993) and the sills leading into Rawhide Flats could have been higher than now. Hence, to establish that the very high shorelines found in the Walker Lake basin applied to Lake Lahontan as a whole, evidence of high shorelines north of the Desert Mountains is required.

Good evidence of high, old shorelines exists at three sites in the Smoke Creek Desert (Fig. 2, Table 1), where topographic contours define subtle benches and risers on the surfaces of volcanic flows. An upper bench terminates upward at about 1400 m and well rounded clasts are scattered over the bench. A lower bench at about 1365–1375 m is blanketed with abundant well-rounded clasts; one site preserves fragments of lacustrine tufa. In addition to these sites, a borrow pit in the northern Black Rock Desert exposes possible beach sand at about 1410 m (Fig. 2, Table 1).

Sites along the Truckee and Humboldt Rivers consist of rounded clasts on bedrock. Even if alluvial in origin, these clasts represent times when rivers were graded to levels far above the Sehoo shoreline. Arcuate geomorphic features with rounded cobbles occur in the Truckee River canyon at about 1400 m (Table 1), and one roadcut exposes sediment that may be lacustrine or deltaic at about 1355 m (Stop 1-1, Figs. 1 and 2). Very well rounded pebbles also occur on basalt slopes along the Humboldt River east of Winnemucca at altitudes from 1350 to 1370 m.

Summary for the Lahontan Basin

Several sites in the Walker Lake basin document early and middle Pleistocene shorelines that extend much higher than the Sehoo shoreline. Stratigraphic relations and minimum shoreline altitudes among four sites (Fig. 6) permit a conservative correlation that yields six lacustrine units (other correlations would increase this number) whose shorelines exceeded that of the Sehoo lake. The two youngest units postdate the 760-ka Bishop ash bed and have shoreline altitudes at about 1370 m (younger) and 1400 m (older); the next older contains the Bishop ash bed; and the three oldest are within the Matuyama Chron and thus are younger than 2.5 Ma.

Shoreline evidence from sites in the Smoke Creek Desert, including the unfaulted Freds Field site (Table 1) indicates high stands at altitudes of about 1400 and 1370 m. The sites lack age control, but the correspondence of these altitudes with those of shorelines at stable sites (near the Thorne bar) in the Walker Lake basin argues that they represent a continuous Lake Lahontan at two different times in the middle Pleistocene. In contrast, the high stands represented by four units containing and underlying the Bishop ash in the Walker Lake basin have no known analogs to the north. This suggests that the Walker River flowed into an isolated Walker Lake basin during the early Pleistocene, prior to the incision of Adrian Valley (Fig. 7; King, 1993). However, note that the presence of bones of Lahontan cutthroat trout in unit Qlo2 at Sunshine Amphitheater (Figs. 5 and 8 below) require a drainage connection between the Walker Lake basin and the northern basins at some time prior to 1 Ma.

The implications of a 1400-m shoreline are staggering (Fig. 2): such a lake would inundate Granite Springs Valley, would back up the Truckee and Carson Rivers to submerge all or part of present-day Reno and Carson City, would back up the Humboldt River at least to present-day Battle Mountain, and would extend 60 km southeast from Walker Lake to Rhodes Salt Marsh. If allowances are made for local tectonics and sedimentation in the past half-million years, the lake could have flooded into Dixie and Fairview Valleys and inundated many other flat-lying valleys whose floors are now only a few tens of meters above the 1400-m level.

Such projections permit specific hypotheses to be proposed and tested. For example, Hubbs and Miller (1948) postulated an "early pluvial" connection between Lake Dixie and Lake Lahontan (Fig. 2) on the basis of a subspecies of *Siphateles obesus* (a chub) that inhabits a present-day spring in Pleasant Valley, the northern extension of Dixie Valley. The 1400-m level of Lake Lahontan could have flooded Dixie, Fairview, and Pleasant Valleys, providing a continuous environment for the fish. An enigmatic outcrop in eastern Fairview Valley (Stop 1-2, Figs. 1 and 2) provides supporting evidence for such a connection. Thus, these high lake stands may prove key to understanding the distribution of native populations of fish and other aquatic species in the Great Basin (e.g. Hubbs and Miller, 1948; Hubbs et al., 1974).

EVIDENCE FOR OLD LAKES IN OTHER BASINS

Late Tertiary Lakes South of Walker Lake Basin

Lacustrine deposits are preserved along the range fronts both east and west of Mina in Soda Springs Valley (southeast of Walker Lake, Figs. 1 and 2), and at one site contain a probable late Miocene tephra and late Tertiary diatoms (J. Bradbury, 1996, written commun.). Younger deposits, probably about 2 Ma based on tephra correlation and diatoms (Fig. 7), crop out along the highway south of Rhodes Salt Marsh (Stop 3-1) up to an altitude of about 1423 m (4670 ft). These lake deposits are adjacent to (stratigraphic relation unclear) old fan gravel that overlies a thick sequence of late Miocene to late Pliocene lacustrine sediment at and north of Redlich Summit (Stop 3-2, Figs. 1, 2, and 12 below), the present-day divide between Rhodes and Columbus Salt Marshes.

In Fish Lake Valley, south of Columbus Salt Marsh and presently part of the same drainage area (Fig. 2), pluvial

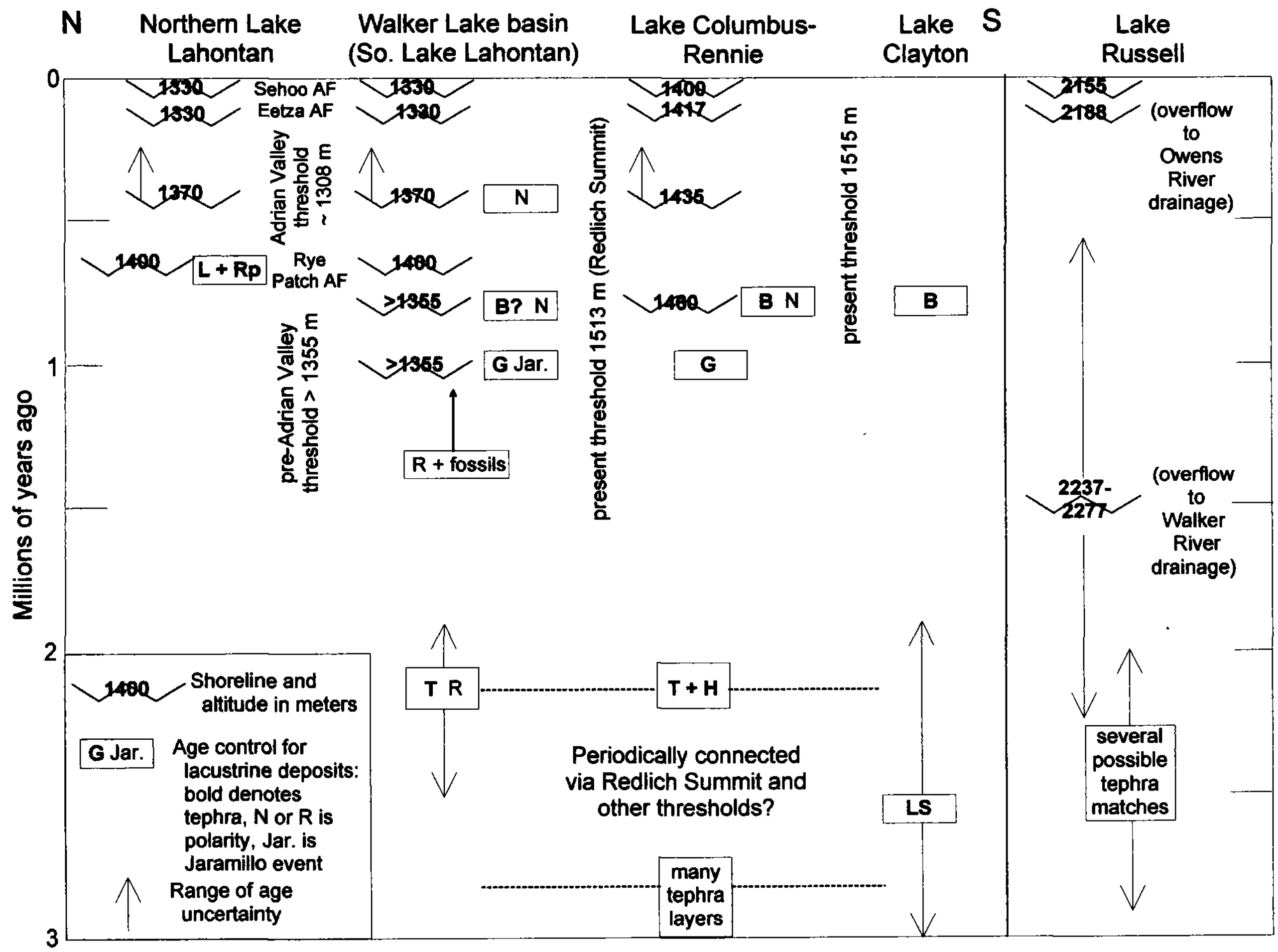


Figure 7. Preliminary correlation of late Pliocene and Pleistocene lacustrine deposits and shorelines in western Nevada. Bold letters are identified tephra layers. L, Lava Creek, Rp, Rye Patch; B, Bishop; G, Glass Mountain, T, tuff of Taylor Canyon; H, Huckleberry Ridge, LS, La Salida tuff of Kettleman Hills. Arrows indicate range of age uncertainties. AF, Alloformation.

Lake Rennie had at least two late Pliocene lake cycles (Reheis et al., 1993). Deposits contain tephra layers that document lake episodes from about 3.4–2.8 Ma and from about 2.2–2.0 Ma (Stop 3-5, Figs. 1, 2, and 13 below). Deposits of similar age have not yet been found in Columbus Salt Marsh.

Work in Clayton Valley (Fig. 2) by Davis (1981), including summaries of numerous well records, shows that Clayton Valley was periodically filled with fresh to saline lakes and playas. Exposures on the east side of the valley indicate at least two such intervals during the Pliocene, and recent analyses of tephra from the lower interval suggest an age of about 3–2 Ma. Thus, the record of Pliocene lakes in Clayton Valley is in accord with those in Rhodes Salt Marsh and Fish Lake Valley (fig. 7).

I infer that a lake basin that at least included Soda Springs Valley and Rhodes and Columbus Salt Marshes (Fig. 2), possibly extending north into the Walker Lake basin, was disrupted by faulting and (or) compression that lifted the area of Redlich Summit, the present-day divide underlain by Miocene to Pliocene lacustrine deposits. Two other lines of evidence permit the interpretation that lakes south and east of Walker Lake were connected during the Pliocene (Fig. 2): (1) the parallel histories of Pliocene lakes in Rhodes Salt Marsh, Clayton Valley, and Fish Lake Valley (fig. 7); and (2) the lack of sills or very low sills between Columbus Salt Marsh and Fish Lake, Clayton, and Big Smoky Valleys. Such “early pluvial” connections were first suggested by Hubbs and Miller (1948) on the basis of remnant populations of Lahontan fish south of the Lahontan basin. Mifflin and Wheat (1979) also thought that Rhodes and Columbus Salt Marshes and Clayton Valley had once had been part of a much larger body of water. Large lakes and relatively wet conditions during the middle (3.5–2.5

Ma) and latest (~2 Ma) Pliocene are well known from other parts of the western United States (Forester, 1991; Thompson, 1991).

Early and Middle Pleistocene Lakes South of Walker Lake Basin

Pluvial Lake Columbus-Rennie

New discoveries in the basin of Columbus Salt Marsh (Fig. 2 and Table 1) indicate at least four lake cycles higher and older than the late Pleistocene shoreline (altitude 1400 m, 4600 ft) of Lake Columbus. This area is essentially unaffected by Quaternary faulting. Progressively younger shorelines at about 1452–1457, 1435, and 1417 m (fig. 7) are recorded by berms and beach pebbles on bedrock slopes; outcrops at Stops 3-3 and 3-4 (Figs. 1, 2, and 13 below) expose sequences of lacustrine deposits, one containing Bishop ash. Lake Rennie existed in Fish Lake Valley at about 760 ka and probably at about 1 Ma (Reheis et al., 1993) and had a high stand at an altitude of about 1460 m (4800 ft). I infer that during the early and early-middle Pleistocene, Lakes Columbus and Rennie were contiguously connected through The Gap (maximum altitude 1430 m), the present-day drainage connection between the valleys.

Pluvial Lake Clayton

Clayton Valley playa (Lake Clayton, Fig. 2) has been cored numerous times (Pantea et al., 1982; mining-company data reported in Davis, 1981) due to the large brine pool containing lithium salts at depth. Most of these wells bottomed in the so-called "ash aquifer," as much as 10 m thick and between about 90 and 300 m below the playa surface. Sediments in the core holes consist of alternating beds of sand, mud, gypsum, and halite and include coarse tephra layers and glass-rich intervals. The mud is interpreted to reflect deeper, fresh-water conditions in the lake and the salt beds to reflect periods of saline water and desiccation. From a core sample obtained by Davis (1981) at a depth of 175 m, A. Sarna-Wojcicki (1992, U.S.G.S., written commun.) identified the "ash aquifer" as the Bishop ash. Thus, sediment beneath Clayton Valley records a long history of lacustrine deposition, including one lake at about 760 ka (fig. 7).

Pluvial Lake Russell

The late Pleistocene history and shoreline altitudes of pluvial Lake Russell (Figs. 1 and 2; present-day Mono Lake) are well known (summarized in Benson et al., 1990). The last overflow of Lake Russell southward into Adobe and Owens Valleys (Fig. 7) occurred at a highstand of about 2188 m (7180 ft) and is thought to be equivalent to the Tahoe glaciation (probably oxygen-isotope stage 6). Mono basin is a structural depression that probably began forming about 4–3 Ma; Pliocene lacustrine deposits containing abundant fossils are interbedded with volcanic flows on the east side of the basin (Gilbert et al., 1968). Miller and Smith (1981) and Hubbs and Miller (1948) used fossil and modern fish populations to show that fish had migrated southward into the Mono basin from the Lahontan basin, probably during the Pliocene, and later migrated southward into Owens Valley and Death Valley. Russell (1889) hinted, and Hubbs and Miller (1948) proposed, that the earlier connection between the Lahontan and Mono basins had been via the East Walker River (Fig. 2).

Recent discoveries around the east side of the Mono basin (fig. 2) suggest that at least one cycle of Lake Russell reached an altitude between 2237 and 2277 m. The former is the altitude of a sill composed of 1.5-Ma andesite (E. McKee, 1995, U.S.G.S., written commun.) over which Lake Russell could have drained north toward the East Walker River. The latter altitude is the highest occurrence of beach pebbles on the east side of the Mono basin. In addition, lacustrine deposits at a present altitude of about 2220 m contain tephra layers that are probably late Pliocene (2.5–2.0 Ma) in age. The fish fossils (Miller and Smith, 1981) imply that a connection to the Lahontan basin existed during the late Pliocene. The age of the andesite underlying the sill suggests that northward overflow may also have occurred after 1.5 Ma. Thus, the Mono basin may have been tributary to the Walker River in the late Pliocene and early Pleistocene (fig. 7). The additional input of water from this source, if confined to the Walker Lake basin, might help to account for the early Pleistocene highstands that exceeded the late Pleistocene highstand.

SUMMARY AND IMPLICATIONS

The lake basins discussed in this paper show abundant stratigraphic and geomorphic evidence of pluvial lakes during the Pliocene to early middle Pleistocene that were areally much larger, and had significantly higher shorelines, than the late middle and late Pleistocene lakes. Figure 7 summarizes the available information on the preliminary ages and shoreline altitudes of these old lakes. The shoreline altitudes are minimum estimates, and locally have been significantly affected by faulting or tilting. Nevertheless, broad correspondence among the basins is evident. These findings suggest that lakes in western Nevada were much larger during pluvial periods of the early and early middle Pleistocene than during those of the late middle and late Pleistocene. The reasons for these lake level changes may include: (1) increasing rain shadow through time due to uplift of the Sierra Nevada; (2) changes in position of the jet stream; (3) drainage changes that have changed the size of the Lahontan drainage basin (Fig. 2); and (4) more moisture crossing the Sierra Nevada in the early and early-middle Pleistocene due to the presence of Lake Clyde filling the Great Valley of California (Sarna-Wojcicki, 1995).

These new findings greatly expand our knowledge of deep-lake cycles of Lake Lahontan (Figs. 6 and 7). Deposits of the three pre-Eetza lake cycles identified by Morrison (1991) are the Rye Patch Alloformation, about 700–600 ka, and unnamed deposits containing and underlying ~1-Ma Glass Mountain tephra (Fig. 4). Deposits of Rye Patch age were known with certainty only from the northern basins (Rp, Fig. 3). I tentatively correlate deposits associated with the 1400-m shoreline of Lake Lahontan with the Rye Patch Alloformation. The 760-ka Bishop ash bed has not been found north of Walker Lake and was originally assigned to the interlacustral Lovelock Alloformation. However, the Bishop ash bed is now tentatively identified in lacustrine deposits in the Walker Lake basin (Fig. 6), indicating a deep-lake event also recorded by other lakes to the south, including lakes Columbus-Rennie (Reheis et al., 1993), Owens (Smith and Bischoff, 1993), Tecopa (Sarna-Wojcicki et al., 1987; Morrison, 1991), and Manley (Death Valley; Knott et al., 1996).

PART III: ROAD LOG

Marith Reheis and Roger Morrison

DAY 1, Reno to Yerington

Leave parking lot of MGM Grand Hotel in Reno, turn left on Glendale Road and immediately take northbound entrance to US-395. In 0.4 miles take east-bound entrance to Interstate 80 and set odometer at the interchange. See Figure 1 for approximate route and Table 1 for exact site locations.

Miles	Cum. Miles	
0.0	0.0	I-80 and US-395 interchange. From here eastward to the Vista exit, the highway crosses fluvial deposits of the Truckee River. This interchange and the MGM Grand at 2:00 are on eroded remnants of Tahoe outwash terraces with 1-m-thick argillic soils. The only age on nearby Tahoe outwash is a ^{14}C age of >40,000 yr on twigs from a depth of 30 m below the MGM Grand Hotel (Bell et al., 1984).
2.9	2.9	Leaving Sparks. Reno and Sparks lie in the Truckee Meadows, a structural depression filled with >1000 m of alluvium on the basis of gravity data. Pre-Tahoe deposits in the Truckee Meadows are buried. Ahead in the Truckee River Canyon, on the footwall block of the frontal fault of the Virginia Range, remnants of pre-late Pleistocene terraces are preserved.
5.0	7.9	Exit 33, Lockwood. The south side of the canyon is capped by McClellan Peak Basalt dated elsewhere at 1.14 ± 0.04 my. This basalt also crops out in several places on the valley floor (Bell and Bonham, 1987) and the distribution of the outcrops indicates that the flow probably filled the Truckee River Canyon.
0.6	8.5	Outcrop on north side of freeway exposes a possible deltaic deposit overlain by volcanic ash. This will be Stop 1-1. To reach it:
0.8	9.3	**Exit at Mustang, go beneath the overpass and head back west on I-80.**
1.2	10.5	**Pull right at the sign "Lockwood exit 1/2 mile" and park for Stop 1-1 (Table 1).** Walk west about 100 m to the outcrop. Stay behind the concrete barrier!

STOP 1-1—Alluvial and deltaic(?) deposits in Truckee River Canyon (45 minutes)

This small outcrop is above the 1330-m late Pleistocene (Sehoo) limit in the canyon. Alluvial deposits here are locally very well bedded and fine grained (deltaic or slack-water flood beds), contain lenses of coarse pumice, and overlie weathered rhyolite. The alluvial beds represent a deposit of the Truckee River graded to a base level much higher than that during Sehoo time; they may record a pre-late Pleistocene lake surface at about 1355 m (4445 ft). Chemical analyses of glass from the pumice beds do not yield firm correlations, but are similar in composition to upper Pliocene and upper Miocene tuffs; the pumice could be reworked from older deposits. The alluvial deposits are only 300 m upstream from a large outcrop of McClellan Peak basalt that extends down to river level, which suggests that the alluvial deposits postdate this 1.1-Ma basalt. The stratigraphic sequence is:

Thickness	Description
~200 cm	Interbedded coarse sand, silt, and mud with columnar structure to top of vertical exposure; interbedded lenses of well-washed coarse pumice. Locally contains isolated large clasts. Rounded gravel extends up slope about 5 m higher.
5–10 cm	Massive well-cemented $CaCO_3$; tufa or travertine?
30 cm	Thinly bedded well sorted silt and fine sand; fines upward.

45 cm		Well bedded and sorted fine to coarse sand, laterally continuous thin beds across about 15 m of outcrop; locally steep primary bedding.
25 cm		Imbricated pebble to cobble gravel
To base		Weathered rhyolite tuff.

Continue west on I-80.

0.6 11.1 **Exit at Lockwood, cross freeway, and head east on I-80 again.** South of the Mustang exit, the flood plain is studded by very large boulders laid down by glacial floods originating from the breaching of a glacier dam at Squaw Valley, California, and flowing down the Truckee River into Lake Lahontan (Birkeland, 1965). Two levels of these deposits are mapped as outwash of the Donner Lake and Tahoe glaciations (Bell and Bonham, 1987).

5.6 16.7 Derby Dam exit. The Giants Throne, visible to the south across the Truckee River, is a bench at 1365 m (4480 ft) cut on rhyolite. This may be a strath terrace of the Truckee River graded to a formerly much higher level of Lake Lahontan.

1.9 18.6 At 3:00 across the river, a basalt hill has two benches cut on it. The lower bench at ~1370 m (4495 ft) is above the Sehoo shoreline and has abundant subrounded clasts that may be pre-late Pleistocene terrace gravel of the Truckee River.

1.4 20.0 On the left, in road cuts for the westbound lane of I-80, light-colored deltaic sand and silt interfingers with dark-colored talus which rolled into a lake. On the right are scabland outcrops, including an island in the Truckee River, which have been scoured by glacial floods (Morrison and Davis, 1984a).

0.7 20.7 Tracy and Clark Station exit. South across the river is a broad bench between 1390 and 1410 m (4560–4625 ft) altitude (Table 1). This bench bears large arcuate features that seem to be scoured on bedrock and is thinly (~1 m thick) covered with subrounded to well rounded andesitic gravel; it may represent an abandoned meander of the Truckee River. The Eagle Picher diatomite plant at Clark is supplied from Miocene deposits about 9 km to the east (Bell et al., 1984).

10.5 31.2 Sehoo-aged lacustrine deposits are well exposed north of the road.

1.1 32.3 Wadsworth exit. Here the Truckee River turns from east to north and flows to Pyramid Lake. The Dodge Flat area consists of late Pleistocene deltaic sediments later trenched by the Truckee River. The top of the delta lies at about 1273 m (4200 feet; Morrison and Davis, 1984a).

4.6 36.9 **Exit 48, Fernley-Fallon. Exit south to US-50A.** Northwest-striking faults extend through Fernley to the south where they are truncated by northeast-striking faults of the Carson Lineament (Bell et al., 1984). These faults are within the Walker Lane, part of a broad zone of strike-slip faulting that accommodates part of the slip between the Pacific and North American Plates (Stewart, 1988).

1.3 38.2 **US-50A, turn east.** The hills to the south consist of well rounded alluvial gravel of diverse lithologies that probably represents deposits of the ancestral (Pliocene?) Truckee River; the gravel overlies Miocene alluvial and lacustrine beds.

6.0 44.2 Patua Hot Springs at 9:00. Gravel pits at 3:00 are in beach gravels of probable Eetza and Sehoo age separated by an argillic soil (the Churchill Geosol, Fig. 4; Bell et al., 1984). Ahead (southeast) near Hazen is a channel cut in middle(?) Sehoo time by the Truckee River when it drained into the Carson Desert.

11.1 55.3 **Junction US-50 and US-50A. Continue straight ahead on US-50.** A cluster of maars with gently sloping dark cones form a low dome-like ridge 5 km northeast. The two largest maars are occupied by Soda Lake and Little Soda Lake.

1.2 56.5 Ragtown was a welcome oasis on the Carson River for emigrants on the Humboldt Overland Trail. They stopped here to recuperate after the terrible 64-km trip bordering the barren Carson Sink from the last water on the Humboldt River.

5.0 61.5 Cross Carson River, named for the early explorer in this area, Kit Carson. The Carson River has formed a late Pleistocene and Holocene delta, at times flowing either northeast into the Carson Sink or southeast into the Carson Lake area.

2.1 63.6 **Williams and Maine Streets in center of Fallon. Continue straight on US-50.**

1.0 64.6 Rattlesnake Hill is composed of black to dark gray flows around a shallow summit

		crater (Morrison, 1964). The $\sim$1-Ma basalts are largely covered with Lake Lahontan sediment and young eolian sand.
9.2	73.8	Grimes Point Archeological Site and turnoff to Hidden Cave and Wyemaha Valley area, containing the type localities for the Eetza, Sehoo and Wyemaha Formations and the Churchill Geosol (Morrison, 1964).
1.2	75.0	At 9:00, at the south end of Rainbow Mountain, Tertiary basalts are coated with Lahontan dendritic tufa. Entering Eightmile Flat.
3.3	78.3	Salt Wells "Villa," originally a watering stop for the Fallon-Fairview freight and stage lines. Salt Wells is now a renowned brothel.
1.1	79.4	Windmill at 9:00 is near southern end of the Rainbow Mountain fault zone. Two earthquakes, M=6.8 and 6.6, ruptured this fault in 1954 (Bell et al., 1984). Sand Springs Range (site of AEC Project Shoal) at 12:00 to 1:00, Cocoon Mountains at 1:00–2:00, and Bunejug Mountains at 2:00 to 4:00.
6.8	86.2	Leaving Eightmile Flat, entering Fourmile Flat. Large sand dune complex (Sand Mountain) at 10:30 is 5 km from the highway and 180 m high.
1.4	87.6	Graves of pioneers at 9:00, said to be those of sisters who died of diphtheria.
2.0	89.6	At 9:00, just north of road, site of Pony Express and stage station. Sehoo shorelines are clearly marked by tufa on nearby basaltic ridge at 11:00. A prominent bench above these shorelines has the morphology of a wave-cut platform but no rounded clasts are present on it (altitude 1365 m, 4480 ft).
3.2	92.8	At 3:00 are the remains of Summit King gold mine and mill. This divide at altitude 1410 m between the Lahontan basin and the Fairview-Dixie Valley basin is about 8 m above the highest known Lahontan shoreline. Allowing for a small amount of uplift, the divide may have once been a sill between lakes in the two basins.
2.7	95.5	Panorama includes southern end of Stillwater Range at 9:00, Clan Alpine Range at 10:30 to 12:00, Desatoya Range at 12:00, and Fairview Peak at 1:30 beyond Labou Flat in Fairview Valley. Target and observation towers for Navy bombing range at 2:00.
1.6	97.1	Small fault formed during the Dixie Valley-Fairview Peak earthquakes crossed road at this point and had about 20 cm of displacement.
6.2	103.3	Junction with Nevada 121 to Dixie Valley. Continue east on US-50.
1.3	104.6	**Just east of a small saddle (Drum Summit), turn north through gate onto a dirt road.** Several en echelon scarps from the 1954 Fairview Peak earthquake cross the highway just east of here (Bell et al., 1984).
1.0	105.6	**Park for Stop 1-2 (Fig. 1 and Table 1) and lunch.**

STOP 1-2—Lake deposits and beach(?) gravel in Fairview Valley (2 hours)

Late Pleistocene pluvial lakes in Fairview (Lake Labou) and Dixie (Lake Dixie) Valleys were separate from Lake Lahontan (fig. 2). Lake Labou reached a highstand of 1264 m (4180 ft), about 120 m below this locality, and overflowed into Lake Dixie, which reached 1097 m (3600 ft; Mifflin and Wheat, 1979). Prospect pits along the east side of this small ridge show that the lower slope consists of flat-lying, gypsiferous lacustrine deposits containing at two tephra layers (EL59-FV and EL66-FV) of unknown age. Steeply dipping (20–25°) carbonate-cemented gravel beds crop out upslope in uncertain stratigraphic relation to the lacustrine deposits. The gravel beds grade up from coarse angular fan gravel to moderately sorted, moderately- to well-bedded pebble gravel. The steep dips and well-bedded upper layers suggest shoreface deposition. The gravel beds in turn are overlain to the ridge top, altitude 1384 m, by well rounded granule to pebble gravel with abundant discoidal clasts. If alluvial in origin, the gravel must predate present-day valleys because the present drainage length to the west is too short to accomplish such rounding and the underlying coarser gravel is dipping in an apparent upstream direction. These relations and the underlying lake beds suggest that the pebble gravel formed on a beach and may provide evidence of continuity with Lake Lahontan at 1400 m (Figs. 2 and 7).

		Retrace route to US-50, turn west and return to Fallon.
42.0	147.6	**Intersection of US-50 and US-95. Turn left (south) toward Las Vegas.**
9.9	157.5	The panorama is of the White Throne Mountains from 10:00 to 11:30, the Desert Mountains from 11:30 to 2:00, and the Dead Camel Mountains from 2:00 to 4:00. High beach barriers (note large gravel pits) on the north front of the Desert

Mountains are at 1334 m (4375 ft) altitude; these barriers are well developed because of the large fetch across the Carson Sink. Morrison (1964, 1991) interprets this shoreline to have been occupied during both the Eetza and Sehoo maxima, but Adams (1996) believes the high shoreline is only Sehoo in age.

4.3 161.8 Crossing the Wildcat Scarp, a semi-circular escarpment wrapping around the southern and eastern edges of the Carson Desert for 25 km (Bell, 1984). The scarp here is only 1–2 m high but further to the east it is up to 10 m high. Morrison (1964) interpreted the Wildcat Scarp to be a wave-modified fault scarp rejuvenated by two faulting events in post-Sehoo time.

2.9 164.7 Russell Pass. Russell Spit, a classic site for geologic debate, visible from about 3:00 to 4:00. Russell (1885) thought the highest shoreline here to be Sehoo in age based on morphology. Morrison (1964) assigned the high shoreline (here only 2–3 m above the Sehoo shoreline) to the Eetza. Chadwick and Davis (1990) described soils on purportedly different-aged features and agreed with Morrison's (1964) interpretation, but Adams (1996) found little difference in the soils on these features. In 1996, Russell Spit was in danger of becoming a landfill for the city of Fallon. Thanks to a letter-writing campaign by concerned geologists, the city of Fallon has transferred its application to a site on the east side of Russell Pass.

2.0 166.7 Allen Springs/Lee Hot Spring to the east. Allen Springs has long been an important watering site. Lee Hot Spring has near-boiling water and is marked by the lone cottonwood tree. Numerous tufa mounds attest to extensive spring activity during high stands of Lake Lahontan. East of the highway, the Blow Sand Mountains are so extensively mantled by eolian sand of Wyemaha to Fallon age (Fig. 4) that rock outcrops are rare. Ahead is Rawhide Flats, a small sub-basin attached to the Carson Sink by a sill at about 1230 m (4035 ft; Turupah Flat Pass, 9 on Fig. 3).

1.0 167.7 The Terrill Mountains are from about 10:00 to 1:00. These mountains are near the eastern margin of the Walker Lane tectonic belt (Stewart, 1988).

3.8 171.5 Entering the Walker River Paiute Indian Reservation.

5.1 176.6 Mineral County line.

0.7 177.3 **Turn west on graded gravel road toward Weber Reservoir.** (Continue south on US-95 1.2 miles to see the best outcrops of sequence described in next entry.)

1.3 178.6 Outcrops on the south side of the road expose Miocene volcanic rocks overlain by Miocene and Pliocene alluvium and gypsiferous Pliocene lacustrine deposits (Fig. 10 below). In turn these are overlain by Pliocene to Pleistocene alluvial and eolian deposits that underlie several lacustrine units in McGee Wash (Stop 2-2).

2.3 180.9 **Intersection with gravel road; turn north along east side of the Walker River.**

4.4 185.3 Two basalt buttes to the east. The Sehoo shoreline forms a clear trimline on the buttes; two higher subtler trimlines are best seen on the southern butte. The most prominent higher trimline at 1370 m has rounded beach gravel just below it; it is the lower of two pre-late Pleistocene shoreline altitudes in the Lahontan basin. A less obvious trimline is at about 1400 m. A rhyolite outcrop on the east side of the northern butte is covered by rounded beach gravel at about 1390 m.

6.0 191.9 Intersection with road to the northeast leading to the eastern side of Sunshine Amphitheater where the oldest lake unit is exposed. **Continue straight.**

0.6 191.3 **Park in the flats where the road bends 90° from northwest to southwest.** Hike due north about 1 km into Sunshine Amphitheater (Figs. 1, 5, and 8; Table 1).

STOP 1-3—Sunshine Amphitheatre, Walker Lake basin (2+ hours)

Sunshine Amphitheater is a large exposure of pre-late Pleistocene lacustrine deposits of five different ages (Fig. 8). It is notable for the abundance and preservation of vertebrate fossils. Faults are present but the strata do not appear to be greatly offset. This stop will be a walking tour through deposits of units Qlo2, Qlo3, and Qlo4, including fossil localities, unconformities, and paleosols (area of Sections 14 and 15, Fig. 8). *Please do not pick up any fossils!*

The three oldest lacustrine units are reversely polarized. The oldest unit, QTlo1, is overlain by alluvial and eolian deposits of unit QTt. Unit QTt is conformably over-

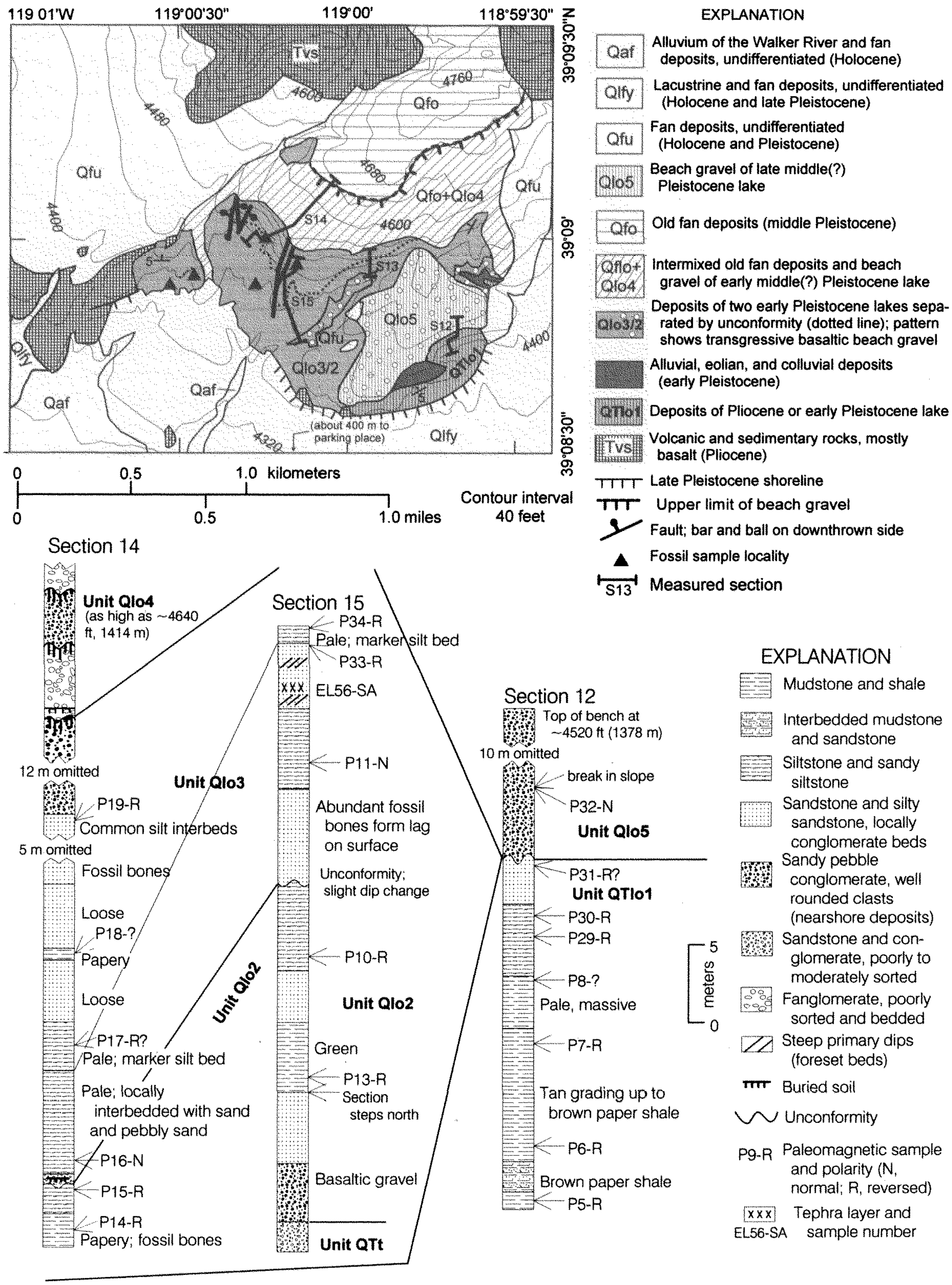


Figure 8. Geologic map of Sunshine Amphitheater (Stop 1-3, Fig. 5, Table 1) and selected measured sections. The field trip will visit the area of sections 14 and 15. That portion of 14 above the closely spaced contours (top of unit Qlo3) has not been measured and is schematic.

lain by unit Qlo2, which contained a distinctive horse bone and mammoth vertebrae that constrain its age to between 1.4 Ma and 1 Ma (C. Repenning, written commun., 1996). This unit also yielded the jaw of a Lahontan cutthroat trout (R. Miller, written commun., 1996). Unit Qlo3 has an interval about 2 to 8 meters above the base that has normal polarity and probably correlates with the Jaramillo Normal anomaly at about 1 Ma. Thus, the three oldest lacustrine units at Sunshine Amphitheater lie within the Matuyama Reversed Chron; unit Qlo2 was deposited between 1.4 and 1.0 Ma, and unit Qlo3 was deposited beginning at about 1 Ma. Unit Qlo3 at the top of the bluff (section 14, Fig. 8) bears a well developed argillic paleosol and is overlain by fan gravel forming a sloping bench. Exploratory soil pits on this bench indicate that the fan gravel is also capped by a paleosol and is buried by beach sand and gravel of unit Qlo4, another paleosol, and another fan gravel; unit Qlo4 rises to an altitude of about 1414 m (4640 ft) and is correlated with the Rye Patch Alloformation (Figs. 6 and 7). Unit Qlo5 consists of sandy beach gravel inset into the older units, and rises to an altitude of about 1378 m (4520 ft).

		Continue northwest along the Walker River (Figs. 1 and 5).
2.7	194.6	On the right (northeast) side of the road are pre-late Pleistocene lacustrine deposits grading up from sands and muds at the base to pink sandy foreset beds at the top, capped by a paleosol with argillic and calcic horizons. The paleosol appears to be truncated by gray clay beds which are dipping at about 10° to the south and may represent a unit of intermediate age. These are cut by a much younger unit, probably of Sehoo age, which bevels the top of the outcrop.
3.0	197.6	**Intersection with a road leading northeast; continue straight ahead.** Light-colored sediments are visible across the valley 5 km to the northeast. These are pre-late Pleistocene lacustrine sediments of two different ages; the younger extends as high as 1400 m (4600 ft) in altitude.
0.8	198.4	Intersection with graded road to Stanley Ranch.
2.6	201.0	Gravel pit to the right (north) is excavated into the Sehoo (late Pleistocene) highstand. Buried deposits in the pit and a nearby drainage ditch may represent Eetza-aged sediment. This stretch of the road lies just below the Sehoo high shoreline, in many places obliterated by young alluvial deposition.
3.4	204.4	**Intersection with US-95A. Turn south.** Buildings and vegetation southeast of the intersection mark Wabuska Hot Springs.
1.3	205.7	Crossing railroad tracks near hamlet of Wabuska. To the northwest, the railroad passes through a trough called Adrian Valley (Figs. 3 and 5), the pass between the Walker Lake basin and the Carson Sink. Walker River may have been confined to the Walker Lake basin during the early Pleistocene (see Reheis, Part II), but after formation of Adrian Valley the river has frequently drained north to the Carson Sink (King, 1993; Morrison and Davis, 1984b). This last occurred in the middle Holocene, when Walker Lake dried up (Bradbury et al., 1989).
8.3	214.0	McLeod Hill on the west. The road is at the approximate altitude of the Sehoo shoreline of Lake Lahontan.
2.3	216.3	**Intersection with Nevada 339. Turn east following US-95A into Yerington.** Cross bridge over Walker River.
1.0	217.3	**Stoplight. End of road log for DAY 1. Turn right (S) on Main Street (same as Nevada 208).** The Intown Motel is a few blocks down on the east side of the street near the Post Office.

DAY 2, Yerington to Hawthorne

0.0	0.0	**Begin mileage at intersection of Nevada 208 and US-95A at north end of Yerington. Follow US-95A toward Hawthorne (south, but direction leaving town is north and east).**
3.3	3.3	The highway is on the flat sandy delta plain of the Walker River, graded to the ~1330-m Sehoo shoreline.
7.7	11.0	To access exposures of pre-late Pleistocene lake deposits in Campbell Valley (CV, Fig. 5, Table 1) described in Reheis (Part II), turn northeast on a dirt road about 0.7 miles northeast of summit (a pass in the north end of the Wassuk Range).
2.4	13.4	Passing through a saddle. On the left (northeast), rhyolite is overlain by pale-colored ash-matrix alluvium and lacustrine(?) deposits of Miocene or Pliocene age and by Pliocene to Pleistocene alluvial-fan gravel.
3.5	16.9	**Intersection. Turn east on gravel road to Weber Dam and Reservoir.** West of the

highway is White Mountain, an outlier of the Wassuk Range. On its east flank, J. Yount (U.S.G.S., oral commun., 1996) has found well-rounded (beach?) gravel up to an altitude of about 1400 m (70 m above the Sehoo highstand) and alluvial-fan deposits that appear to grade to a lake at or just below 1400 m.

0.4 17.3 **Merge with gravel road; bear left.** Road crosses Reservation Hill, a horst of old fan gravel, then descends a bench underlain by beach deposits of Sehoo age. Badlands to the north expose early Pleistocene lacustrine deposits (Stop 2-3).

2.0 19.3 **Bear left at fork and cross Weber Dam. Continue up hill to the north.** From the dam, the view of the bluffs ahead is on the front cover of GSA's Geology of North America volume K-2 "Quaternary nonglacial geology; Conterminous U.S." Stop 2-1 is on the tip of the southern ridge atop these bluffs. The stratigraphic section you are seeing, shown in Figure 9B, probably represents at least 2 million years. The Walker River Paiute Tribe is developing camping areas along the reservoir; camping and fishing permits can be purchased in Schurz.

1.2 20.5 **Turn right (SE) on graded side road.**

0.2 20.7 **Pass through fence line and immediately park along road.** Walk southwest about 200 m to tip of ridge atop bluffs east of Weber Dam (Stop 2-1, Table 1).

STOP 2-1—Overlook from top of bluff east of Weber Dam and Reservoir (Figs. 1 and 5); summary of Pleistocene stratigraphy (30 minutes). Description by Roger Morrison.

Here is a fine overview of all the stratigraphy exposed in these badlands (Fig. 9A), extending back well into the Pliocene, and also a close view of some of the later Pleistocene units. We are in the central part of the Walker Lane tectonic belt. The older Pliocene and Pleistocene units are so faulted that in places they are a giant breccia. In order to decipher the stratigraphy of the badlands before you, one must also map the structure in detail: a 1:10,000 mapping scale is barely large enough. Of course, faults are more numerous in the older units. Not previously recognized in this area are the several episodes of widespread lateral erosion (pedimentation) that removed much of the record and truncated all but the youngest fault scarps.

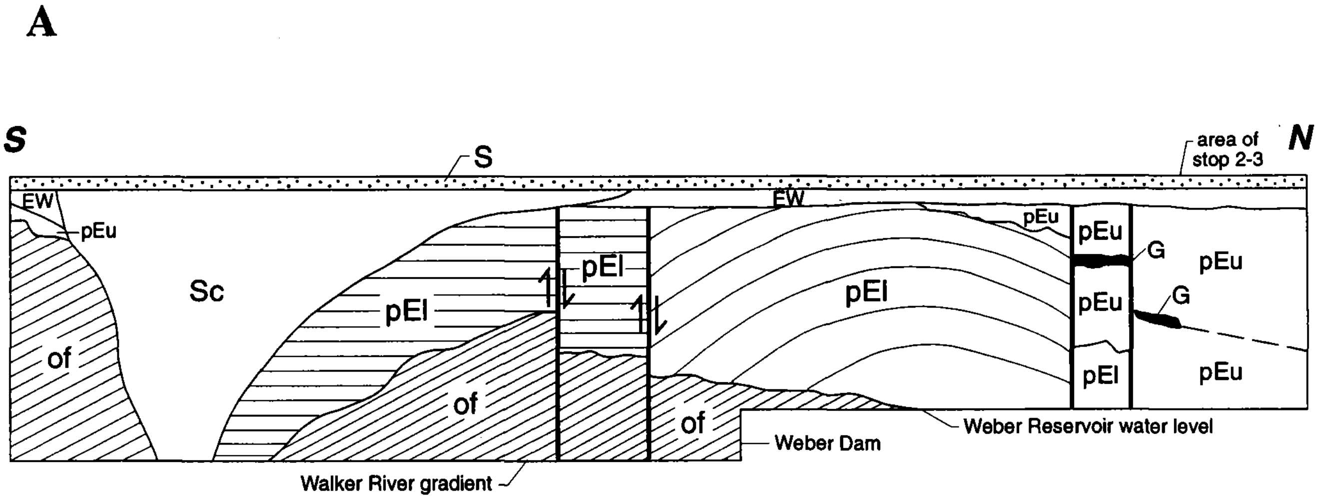
Pluvial-lake history in the Walker Lake basin is very different from that in the northern basins of Lake Lahontan, such as the Carson Desert and Pyramid-Winnemucca Lake basins. At times the Walker River fed Walker Lake as it does now, but at other times it went through Adrian Valley to join the Carson River and end in Carson Sink (Figs. 2 and 3). The Adrian Valley outlet was probably cut in Rye Patch time, ~700–600 kyr ago, or earlier. Until then, the Walker Lake basin was not directly connected to the northern basins. During episodes when the Walker River went through Adrian Valley, there were times when Walker Lake was a playa while substantial lakes existed in the northern basins.

In the badlands below us (Fig. 9) are thick lake-bottom deposits, chiefly silt and clay, of at least 5 pluvial-lake cycles, three of them dating from the Matuyama Reversed Chron and thus older than 780 ka (Fig. 4). They overlie Pliocene(?) fan gravel and are intercalated with younger alluvial gravel units. The oldest sediments visible from here are the pinkish bluffs in several fault blocks along the river below Weber Dam. They represent a thick fan-gravel sequence, likely of Pliocene age. The fan gravel has dozens of intercalated paleosols; although the gravel is gray, clay from the Bt soil horizons has washed over the cliff faces, giving them a reddish tint. A major unconformity separates this gravel from overlying units.

We will not visit the oldest exposed pluvial-lake sediments, but we can see them from here. This unit rests unconformably on the Pliocene(?) fan gravel. It is exposed west of the river and below the dam, and is ~20 m thick, chiefly lake-bottom mudstone with much gypsum and other salts. Similar gypsum-rich lacustrine deposits of probable Pliocene age are exposed about 6 km to the east along US-95 (see road log for Day 1).

The next-overlying lacustrine unit, the "lower pre-Eetza unit" of Morrison and Davis (1984b), can be seen in mid-distance across the river both above and below the dam (unit pEl, Fig. 9A). It is about 20 m of lacustrine silt, clay, and some sand, resting unconformably on a thick fan-gravel unit of pre-Lovelock age (Fig. 4). It is best exposed in the badlands within 1 km northwest of Weber Dam, albeit truncated there by a pediment-like erosion surface.

The "upper pre-Eetza unit" is well exposed in badlands west of Weber Reservoir starting about 1 km northwest of Weber Dam (unit pEu, Fig. 9A, Stop 2-3), where it is separated from the lower pre-Eetza unit by a pediment-like erosional unconformity. It is chiefly sand, sandy silt, and pebbly sand. In its central part is a white volcanic-ash bed identified as the ~1 Ma Glass Mountain G tephra layer. Sediments above and below the ash bed have reversed (Matuyama) polarity, but the ash bed and immediately adjacent strata have normal or indeterminate polarity and likely represent the 1-Ma Jaramillo Normal Subchron. (A chemically similar tephra layer in a similar paleomagnetic sequence crops out above the Sehoo highstand in Camp-



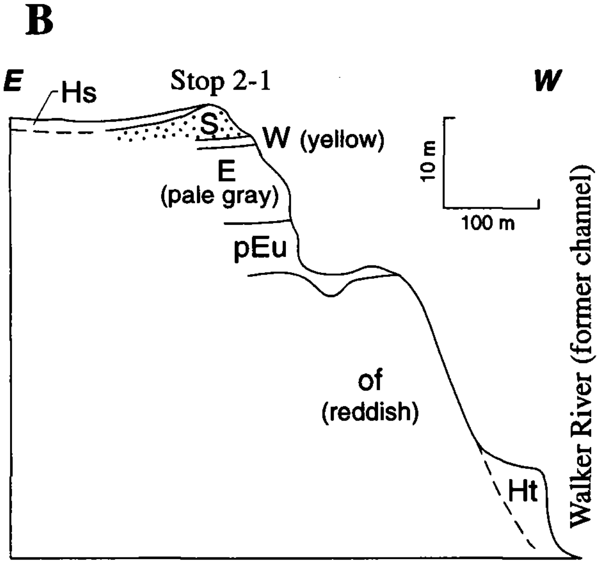


Figure 9. Sketches of stratigraphic cross sections around Weber Dam. ***A****, schematic north-south section west of Weber Reservoir and the Walker River (view from Stop 2-1).* ***B****, east-west section through the bluffs east of Weber Dam (view from dam). Units are: Ht–Holocene alluvial deposits in terrace and flood plain; S–Sehoo Alloformation, middle member, lake pebble gravel and pebbly sand; Sc–Sehoo Alloformation, middle member, channel-fill sand and pebbly sand; W–Wyemaha Alloformation, eolian sand and alluvial sand and gravel bearing truncated Churchill Geosol; E–Eetza Alloformation, lake silt and sand; pEu (upper) and pEl (lower)–pre-Eetza lacustrine silt, sand, and gravel; of–Pliocene(?) fan gravel with many paleosols.*

bell Valley northwest of Weber Dam; CV, Fig. 5.) On the basis of gravelly near-shore beds in its middle part, this unit may represent two lake cycles.

A major erosional unconformity separates the pre-Eetza units from a lacustrine unit that is presumed to be equivalent to a part of the Eetza Alloformation in the northern basins. The unconformity truncates the more faulted and locally tilted pre-Eetza units. The erosional periods are represented in this area only by local alluvial gravel with one or more paleosols. During this interval, Walker Lake was a playa or remained below these badlands.

The Eetza Alloformation is the near-white band, typically 5 to 10 m thick, near the top of the bluffs and badlands on both sides of the river (unit E, Fig. 9). It is chiefly sublacustrine deltaic silt and sand, with a basal gravel and locally an intermediate gravelly/pebbly sand bed. In this basin it probably represents a single deep-lake event caused by overflow via Adrian Valley from the northern basins during the highest Eetza lake maximum. The highest Eetza strandline is at 1330 m on the west side of the Walker River at Reservation Hill.

Overlying the Eetza Alloformation is the Wyemaha Alloformation (Fig. 4), a strong-yellow unit of eolian sand and sandy slopewash (unit W, Fig. 9). Typically it is one to several meters thick, but where wave action of the ensuing Sehoo lake was strong it is completely eroded. It bears the Churchill Geosol and dates in a broad sense from the last interglacial, probably including oxygen-isotope stages 5 through 3. An excellent exposure of this paleosol crops out nearby. Walker Lake was a playa during Wyemaha time.

The lower member of the Sehoo Alloformation (Fig. 4) is missing in this basin, as well as sediments of the transgressive phase of the middle member, because Walker River then flowed to the Carson Desert and Walker Lake basin remained essentially dry. When lake level in the northern basins rose above the 1,308 m threshold (no. 2, Fig. 3) in southern Adrian Valley, water from the northern basins overflowed into Walker Lake basin and the Walker River changed course into the desiccated Walker Lake basin. The river trenched deeply into sediments in this area, almost as deep as the present river valley below Weber Dam. The trench then rapidly filled with gravel and sand during the ensuing lake rise (unit Sc, Fig. 9B; see Morrison and Davis, 1984b, p. 36–37). The flood episode and trench filling occurred during the highest middle Sehoo lake levels in the northern basins, about 13 ka.

The highest Sehoo strandline is at 1330 m, congruent with the Eetza high strand-line at Reservation Hill (west of Walker River). It is at the same elevation at McGee Wash (east of the river; Fig. 5), but at McGee Wash the Eetza high strandline is higher due to faulting. We are standing on a spit of pebbly sand and pebble gravel formed during the late Pleistocene maximum near the end of middle Sehoo time. Note the clam shells (*Anodonta californiensis*) near the base of the Sehoo Alloformation beneath us.

The stratigraphy is complicated by a long history of faulting, surface erosion, and river incision. For example, looking south and east from this ridge, note the marked erosional unconformity on the pre-Lovelock fan gravel unit and how the pre-Eetza and Eetza units thin southward and especially eastward so that 0.4 km east of here both have pinched out entirely. At the start of pre-Eetza lake deposition, a rather wide valley about as deep as the present one had eroded into the Pliocene(?) fan gravel. We are on the eastern margin of this valley. Its axis, marked by the thickest pre-Eetza sediments, is west of the present Walker River. The present inner valley of the Walker and the badlands before us were eroded during the recessional phase of the middle Sehoo lake cycle, about 12,500 years ago.

		Return to vans. Bear left at fork in road and continue south.
0.7	21.4	**McGee Wash. If conditions are favorable, turn left (E) and drive up wash.**
0.3	21.7	**Park in wash (if no storm clouds) for Stop 2-2.** Walk east up wash about 2 km to view the exposure sequence around sections 8a and 8b (Figs. 5 and 10; Table 1).

STOP 2-2—McGee Wash, pre-late Pleistocene lacustrine and alluvial deposits (2 hours)

The study site at McGee Wash (Fig. 10), informally named for WH McGee of the Russell expedition, extends from the Walker River just below Weber Dam eastward to U.S. Highway 95. The outcrops in this area exhibit numerous faults and tilted sediments (Morrison and Davis, 1984a, b); only the larger faults are shown on Figure 10. Dips are generally greatest on the eastern side of the area near US-95 and decrease to the west. Younger units are less deformed. The overall structure appears to be that of a block or horst tilted progressively westward with time. This block was periodically partly or entirely covered by lakes that prograded eastward and by alluvial and eolian deposits that prograded westward. The field trip will examine deposits of four pre-late Pleistocene lakes exposed above the Sehoo level (1330 m, 4360 feet; see inset map on Fig. 10). Much of the lower part of the wash is shown as a stratigraphic cross section in Morrison and Davis (1984b, Figure 2-7).

A sequence of alluvium and eolian deposits (unit QTt) containing numerous carbonate-enriched paleosols and at least two tephra layers is exposed at the base of the upper part of McGee Wash (Fig. 10, Section 8a). Unit QTt was assigned to the Lovelock Formation by R. Morrison; preliminary tephra analyses (EL57-WD) suggest a Pliocene age in part of the unit. Four pre-Sehoo lacustrine units, consisting mostly of well bedded silt and pebbly sand and separated by unconformities, overlie unit QTt. The oldest, Qlo1, is preserved in only 2–3 small outcrops. Unit Qlo2 locally includes a thick lenticular bed of mud that may have accumulated behind a barrier bar, and contains at least one tephra layer. Two samples (EL20-WD, EL58-WD) have been identified as Bishop-like tephra layers. Preliminary paleomagnetic data do not yet confidently discriminate between a correlation with the Bishop Ash or an older Glass Mountain tephra (Fig. 10, Section 8b). Unit Qlo3 unconformably overlies unit Qlo2 around the head of McGee Wash and consists predominantly of loose sand and beach gravel forming a curving berm-shaped feature. The berm rises to an altitude of 1402 m (4600 feet), the same altitude as the highest shore gravel at the Thorne bar (Stop 2-5); unit Qlo3 is correlated with the Rye Patch Alloformation (Figs. 6 and 7). The youngest of the four pre-Sehoo lacustrine sequences, unit Qlo4, is inset into all older units. It consists mostly of pebbly sand, but in McGee Wash it overlies a gray clay layer that Morrison and Davis (1984b) assigned to the Eetza Alloformation. This unit lies at a maximum altitude of 1360–1365 m.

1.1	22.8	**Retrace route. Intersection with main road; turn left (west) and recross dam.**
1.1	23.9	**Turn right (north) on dirt road on west side of Weber Reservoir.** Many faults displace Quaternary sediment in this area, but they commonly do not offset the youngest deposits and do not appear on the surface as fault scarps.
0.5	24.4	**Bear left (west) at Y in the road. Brief intermediate stop (view from road).**

We see the best, thickest exposure of the main lower pre-Eetza unit in the erosional amphitheater west of the road (WR, Fig. 5). Here we are at the axis of a

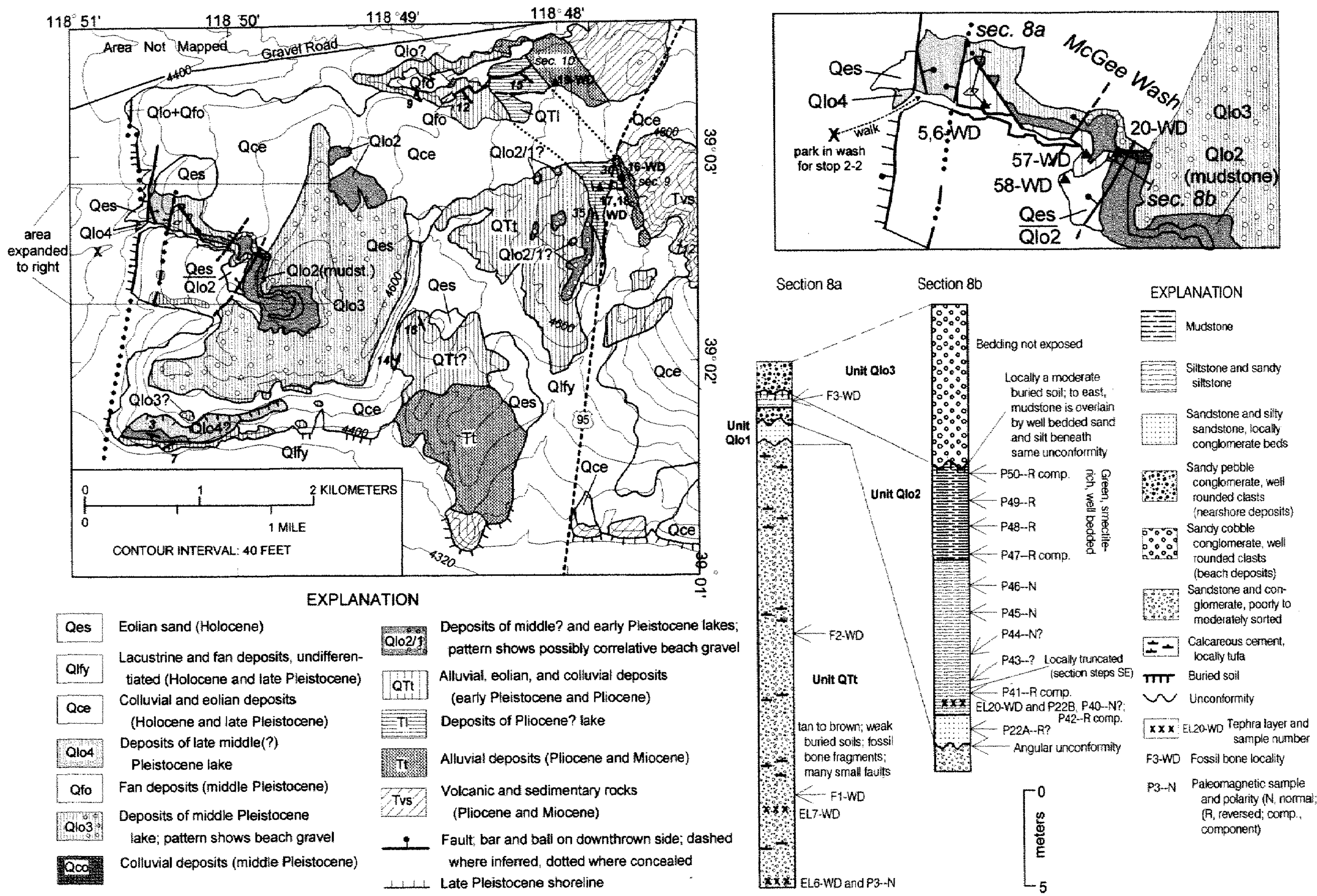


Figure 10. Geologic map of area around McGee Wash (Fig. 5 and Table 1), east of Weber Dam, and selected measured sections. Stop 2-2 is in the area of the inset map.

broad low anticline in unit pEl that is truncated by late pre-Eetza erosion (Fig. 9A). In a thickness of 20–25 m are twelve stratigraphic subunits, chiefly lacustrine clay and silt, some sand, and a basal pebble gravel, resting unconformably on moderately indurated alluvial-fan gravel of pre-Lovelock age (Fig. 4).

0.3 24.7 **Continue west; park along road for Stop 2-3 (WR, Fig. 5, Table 1).**

STOP 2-3—Pre-Eetza units northwest of Weber Dam (1 hour). Description by Roger Morrison

The upper pre-Eetza unit crops out here. A white volcanic ash bed in unit pEu is correlated to the 1-Ma Glass Mountain G tephra layer; a shore-gravel zone above this ash layer likely divides this unit into two lake cycles. (The upper-cycle part becomes much thicker eastward from here, in an ancient valley of the Walker River.) We then walk up over deposits of Eetza age onto gravelly shore sediments of middle Sehoo age.

0.8 25.5 **Retrace route toward dam; turn right (west) and immediately left (south).**

0.4 25.9 **Take right fork; continue 0.2 mile down to picnic area by river for LUNCH.**

0.6 26.5 **Retrace route to north and turn left (west); return to highway.**

2.4 28.9 **Intersection with US-95A. Turn left (south) toward Hawthorne.** For the next 35 miles the road follows the base of the Wassuk Range, one of the most active range fronts in the Lahontan basin in regard to both tectonics and fan deposition. Demsey (1987) identified two Holocene ruptures with a total of 6–7 meters of vertical separation. She surveyed the altitudes of shoreline scarps cut into alluvium on the Wassuk Range and across the basin on the presumed stable Gillis Range front. Her results indicate that the Wassuk Range has risen by about 1.5 m in the Holocene, or about 20 to 25% of the total displacement of the fault.

7.0 35.9 **Intersection of US-95A with US-95. Turn right (south) on US-95 toward Hawthorne and Las Vegas.**

1.5 37.4 To the east (left) is the present course of the Walker River. Walker Lake has dropped 45 m since 1885 (Adams, 1996), mainly due to diversion and damming of the Walker River for agricultural purposes. The Walker River Paiutes are concerned over the rapid headward incision of the river upstream toward Schurz as the river adjusts to its new base level (J.Yount, 1996, oral commun.). No water flowed into the lake for 7 years during the recent (~1985–1993) drought.

1.8 39.2 A fault scarp on the west side of the road at 9:00 exposes ledges of cemented lacustrine gravel. The light-colored layer near the top of the exposure contains probable 760-ka Bishop ash (Davis, 1978, and new paleomagnetic data) which serves as a matrix for the coarse beach gravel.

2.0 41.2 For the next few miles, the highway lies on historic shorelines of Walker Lake. The historic shorelines are less vegetated and have virtually no soil development when compared to those of Sehoo and older age.

5.0 46.2 **Pull over and park for short roadside stop (Figs. 1 and 5, Table 1).** The town of Hawthorne and the Army Ammunitions Depot is at the south end of Walker Lake. Hawthorne lies near the level of the Sehoo highstand, about 1329 m in this area (Adams, 1996).

STOP 2-4—Very high, uplifted shorelines on the Wassuk Range front (15 minutes)

In view about 1 mile south are two levels of tufa-cemented beach gravel on the footwall block of the Wassuk fault. The lower level, previously noted by Bob Bucknam (U.S.G.S.) during fault mapping, is a moderately preserved wave-cut bench overlain by 1–2 m of tufa-cemented beach rock; it extends up to an altitude of about 1400 m (4590 feet). The upper level, seen as an orange-capped hill behind the lower bench, is an eroded remnant of tufa-cemented beach rock with foreset beds, overlying bedrock (sheared granitic rocks); the highest outcrop is at 1452 m (4765 ft). If this remnant corresponds to the 1400-m (unfaulted) shoreline of Lake Lahontan, it records at least 50 m of uplift of the Wassuk Range since the early middle Pleistocene.

1.2 47.4 Mt. Grant (3426 m, 11,240 ft), the highest peak in the Wassuk Range, is in view. The relief between Mt. Grant and the surface of Walker Lake is over 2100 m. Tufa and beach rock are abundant along this section.

2.1 49.5 Turnoff to 20-Mile Beach. Straight west (right), the late Pleistocene shoreline is a bench cut on older alluvial-fan and lacustrine deposits. The fan deposits contain a

		tephra (being analyzed). In the ridge on the north side of this canyon, four beds of beach gravel interbedded with fan gravel are exposed above the late Pleistocene shoreline; the highest caps the ridge at 1475 m (4840 ft) altitude. Copper Canyon is at about 2:00. Copper Canyon fan has had three major floods since 1975.
2.4	51.9	For the next 0.5 miles or so, a well-developed, cemented shore gravel zone of late(?) Pleistocene age overlies wave-beveled bedrock.
4.8	56.7	Town of Walker Lake. Parts of this small town are built on historic shorelines.
10.3	67.0	**Turn left (east) on Thorne Road at flashing light opposite main entrance to US Army Ammunition Depot. Proceed easterly through the Ammunition Depot.** The Gillis Range lies on the east side of Walker Lake.
5.4	72.4	**Thorne siding. Cross the railroad tracks and bear left (north) at the "Y"; pavement ends; continue north.**
5.1	77.5	Road bears to right and begins to climb the southern slope of the Thorne bar.
0.8	78.3	Cross Sehoo highstand shoreline (Fig. 11).
0.3	78.6	**Park on the crest of the Thorne bar for Stop 2-5 (Figs. 5 and 11; Table 1).**

STOP 2-5—Thorne bar, Walker Lake basin (45 minutes)

The Thorne bar is a large V-shaped barrier complex of shore gravel (Fig. 11) built at the mouth of a large canyon draining the Gillis Range. The part of this complex above the Sehoo shoreline was previously described as pre-Sehoo lacustrine gravel elevated by northward tilting of the Lahontan basin (King, 1978; Mifflin and Wheat, 1979; Morrison, 1991). There appears to be no Quaternary deformation on this side of the Walker Lake basin (Demsey, 1987). I interpret the altitudes of the bar and its subdivisions to represent essentially undeformed shorelines. The degree of morphologic preservation and three reconnaissance soil pits indicate the presence of at least three and probably more lacustrine units above the historic limit: the late Pleistocene Sehoo barrier at 1330 m (4360 ft), at least two higher older barriers that reached altitudes between 1350 (4430 ft) and 1365 m (4480 ft), and at least one old bar that reached a minimum altitude of 1402 m (4600 ft). This highest bar is correlated with unit Qlo4 at Stop 2-6 and with the Rye Patch Alloformation (Figs. 6 and 7).

The cars are parked on a barrier with a moderately preserved surface at an altitude of about 1350 m (4430 ft); a pit on this surface about 250 m to the west exposes a soil with an incipient argillic horizon to about 15 cm depth underlain by a duripan (carbonate- and silica-cemented horizon; Adams and Wesnousky, 1996). The Sehoo barrier encloses a small playa below and just north of this pit. East of the cars is a higher, more eroded barrier that reaches an altitude of about 1365 m. A pit about 200 m west exposes a soil with an argillic horizon to about 30 cm depth. A trimline on basalt hills 1 to1.5 km northwest of the vehicles marks the 1402-m shoreline.

		From the crest of the Thorne bar, continue north on main road.
2.4	81.0	**Park at intersection with 4WD road heading up towards Gillis Range front.** This road was washed out by storms in 1996. Follow the road directions on foot (unless you have 4WD). **Walk 0.5 mile along 4WD road to T-intersection with power line road. Turn left (north).** **Walk 0.5 mile, then bear right at fork to road on east side of power line. Walk 0.1 mile up to range front and east up arroyo.** Exposure is on north-facing side of wash (Stop 2-6, Figs. 5 and 11, Table 1).

Stop 2-6—Pre-late Pleistocene lake deposits north of Thorne bar (2 hours)

This excellent small outcrop exposes four sequences of lacustrine gravel and sand separated by paleosols and alluvium (Fig. 11, Section 1) overlying bedrock well above the Sehoo shoreline. The second youngest lacustrine unit includes a tephra (EL21-WL) that is chemically correlative with the Bishop-Glass Mountain family of tephra. Paleomagnetic measurements on the silty layers of this tephra indicate normal polarity; thus, the tephra is probably the 760-ka Bishop ash bed. The youngest unit consists of about 38 m of tufa-cemented pebble and cobble shore gravel, commonly steeply bedded (backset beds), that rises to an altitude of about 1393 m. Beach pebbles continue upward as lag on bedrock to an altitude of about 1395 m (4580 ft). Because the outcrops here and of the oldest unit at the Thorne bar are similar in cementation and preservation and rise to about the same altitude, I infer that they are equivalent. Thus, the oldest and highest shoreline in this area is underlain by deposits of four different lakes: two that predated 760 ka and one that culminated at about 760 ka, all of which reached minimum altitudes of about 1355 m (4450 ft), and one after 760 ka that rose to a minimum altitude of about 1400 m (Figs. 6 and 7; correlated with the Rye Patch Alloformation). The four paleosols formed in units Qlo1 and Qlo2 and the intervening fan deposits (Fig. 11) have moderately to well developed argillic horizons that

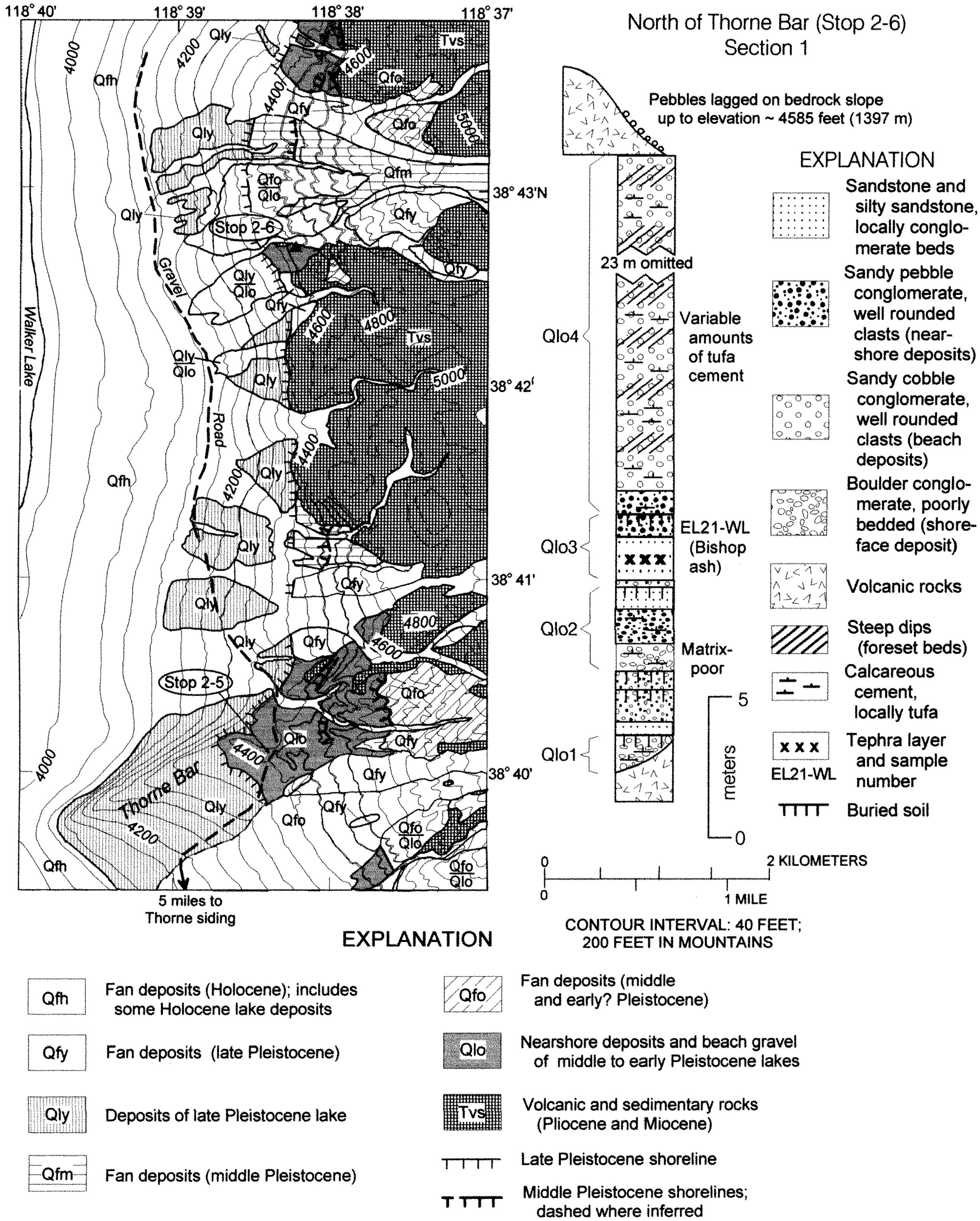


Figure 11. Geologic map of area around Thorne bar (Stop 2-5, Fig. 5 and Table 1) and measured section north of Thorne bar (triangle in northern map area; Stop 2-6).

are 50–90 cm thick. This degree of development indicates lengthy (>50 kyr) periods of nondeposition and thus a relatively long stratigraphic record prior to 760 ka.

14.0	95.0	**Retrace route back to US-95. Turn left (south) toward Hawthorne.**
1.7	96.7	**Intersection with US-95 bypass. Bear right on main road.**
0.7	97.4	**Intersection with Nevada 359 toward Lee Vining. Turn left (east), staying on US-95. El Capitan on the left.**
0.5	97.9	**Turn left into parking lot of Sand and Sage Motel. END OF DAY 2.**

DAY 3—Hawthorne to Fish Lake Valley

0.0	0.0	**From Sand and Sage Motel turn left (east) on US-95.**
5.7	5.7	Approximate level of the Sehoo highstand. Borrow pits to the right (south) expose Holocene alluvial-fan deposits over beach gravel. Beginning with the Gillis Range at 9 to 11:00, several ranges to the north and east are bounded or cut by northwest-trending right-lateral faults of the Walker Lane (Yount et al., 1993).
2.9	8.6	The approaching bedrock pass is below 1400 m (4600 ft) altitude, as is the valley to the left (north). A middle Pleistocene lake at 1400 m would have extended from Walker Lake basin into Soda Springs Valley to the southeast. However, no remnants of lacustrine deposits have yet been found around this pass.
4.2	12.8	Passing into the northern end of Soda Springs Valley, a long linear depression with small playettes. At 9:00 is a prominent scarp of the Indian Head fault, which extends into the alluvial fans.
9.3	22.1	Gabbs Valley Range extends from 10:00 to 12:00 with the Benton Spring fault running along the base of the range. Shaded scarp of Benton Spring fault at 11:00–12:00 is visible in morning light (Yount et al., 1993).
2.1	24.2	Intersection with Nevada 361 to the Berlin Ichthyosaur State Park; enter Luning.
6.9	31.1	Marsh deposits of Southern Pacific Spring at 9:00 contain a 30–50 ka tephra (Yount et al., 1993). Light-colored areas around the spring are diatomaceous (Miocene or Pliocene; J. Bradbury, U.S.G.S., 1995, written commun.) lake beds and contain a late Miocene(?) tephra from the Snake River Plain. The spring area lies on the northwest-trending, right-oblique Benton Spring fault zone bounding the Gabbs Valley Range and Pilot Mountains. The principal scarp of this fault vertically displaces late Pleistocene and middle Holocene deposits (Yount et al., 1993).
2.4	33.5	Outskirts of Mina. At about 3:00 is a light-colored area of lacustrine and alluvial sediments which are probably correlative to the Miocene(?) deposits across the valley near Southern Pacific Spring.
3.7	37.2	Passing Soda Springs. Ahead is Rhodes Salt Marsh, which held a small late Pleistocene lake (shoreline altitude 1350 m, 4430 ft; lake depth about 20 m; Mifflin and Wheat, 1979). Past Rhodes Salt Marsh to the southeast is dissected fan gravel that overlies lacustrine deposits within the pass between Rhodes and Columbus Salt Marshes. Because the two marshes contain anomalous concentrations of salts, Mifflin and Wheat (1979) speculated that they once had been part of a much larger body of water.
5.3	42.5	Intersection with Nevada 360. **Continue south on US-95.**
3.0	45.5	**Pull over and park in road cut for Stop 3-1 (Figs. 1 and 2, Table 1).**

STOP 3-1—Latest Pliocene lacustrine deposits, Rhodes Salt Marsh (30 minutes)

This road cut exposes lacustrine sediment dipping about 25° south, truncated by much younger fan gravel. The sediment includes two sequences of sand, silt and tephra separated by gravelly deltaic(?) beds, and contains diatoms of Pliocene age (J. Bradbury, U.S.G.S., 1996, written commun.). The chemistry of the lower tephra, EL2-RM, matches that of a tephra layer collected by J. Liddicoat to the west within lacustrine sediment on the south end of Teels Salt Marsh (Fig. 1). The chemistry of the upper tephra, EL26-RM, matches that of the ~2-Ma tuff of Taylor Canyon. These deformed, 2-Ma lake deposits crop out intermittently to the east and south up to an altitude of about 1423 m (4670 ft). They border and may underlie more gently dipping old fan gravel that blankets the hills to the south along and east of the highway. If so, these lake deposits may represent the upper portion of the lacustrine sequence better exposed at Stop 3-2.

1.7	47.2	**Continue southeast on US-95.** Bend in the road. View to the left of deep-water greenish mudstone, shallow-water pink sandstone, and overlying fan gravel.

0.7 47.9 **Pull off and park in paved area to right for Stop 3-2 (X, Fig. 12; Table 1).**

STOP 3-2—Late Tertiary lacustrine deposits underlying Redlich Summit (30 minutes)

Lacustrine deposits crop out across a wide area north of Redlich Summit, the divide between Rhodes and Columbus Salt Marshes (Figs. 2 and 12). Reconnaissance mapping and several measured sections indicate two or more lacustrine units separated by unconformities or periods of desiccation. Outcrops northeast of the highway suggest an upward sequence of deltaic sandstone, diatomaceous siltstone, green massive mudstone, and near-shore sandstone with oscillatory ripple marks. The outcrop on the southwest side of the highway (near us) exposes upward-coarsening deposits overlain by fan gravel. Tephra layers near the top of this section exhibit inverse grading of pumice clasts, which indicates a beaching line (shoreline). Chemical analyses of numerous tephra layers indicate correlations ranging in age from late Miocene to late Pliocene (possibly as young as 1.8 Ma; EL29-RM, Fig. 12). I infer that a Miocene to Pliocene lake basin that included parts or all of Rhodes and Columbus Salt Marshes, and perhaps extending north to the Walker Lake basin, was disrupted by faulting and (or) compression that lifted the area of Redlich Summit. The present threshold altitude is 1494 m (4900 ft).

1.0 48.9 **Continue southeast on US-95.** Small valley on the right contains the highest known exposure of Miocene-Pliocene lacustrine deposits in the pass.

0.9 49.8 Intersection with road to Candelaria, a large active mining district. The spoil piles are visible to the west.

1.6 51.4 Redlich Summit, altitude 1540 m (5050 ft). The saddle west of here is the present threshold between Columbus and Rhodes Salt Marshes at about 35 m above the altitude of the highest known shoreline (1457 m, 4780 ft) of Lake Columbus.

2.2 53.6 Rounding a bend, view is southeast to Columbus Salt Marsh and a low saddle that leads into Clayton Valley (Fig. 2). Farther down the road the White Mountains are in view to the southwest across the Silver Peak Range.

1.3 54.9 **Turn right (W) at historical marker, cross cattle guard and park on right for Stop 3-3 (Fig. 2, Table 1).** About 5 miles to the southwest is the ghost town of Columbus, which supported both hard rock mining and borate mining in the salt marsh. Chinese workers were imported for the borate operations.

STOP 3-3—Lacustrine deposits and tephra in the big pit in Columbus Salt Marsh (1 hour)

This large pit intersects the groundwater table and apparently provided water to nearby mines. The exposure includes three sets of alluvial-fan deposits interbedded with two lacustrine units, first sampled and described by J. Whitney and P. Glancey (U.S.G.S.) in 1985. The lower lake unit consists of pebbly sand in an offshore bar and marl containing Bishop ash on the south side of the bar. The upper lacustrine unit consists of sand and gravel, including foreset beds and tufa on the north side of the pit. The upper unit extends northward into beach deposits of the late Pleistocene shoreline of Lake Columbus at a maximum altitude of about 1400 m (4600 ft). The youngest alluvial-fan deposits contain Holocene tephra erupted from Mono Craters.

In view about 0.5 km due west are small gravel bars protruding from low bedrock knobs. These bars consist of beach gravel at a maximum altitude of about 1417 m (4650 ft), well above the late Pleistocene shoreline. Surface soils on these berms are moderately developed with argillic horizons that are not present on late Pleistocene deposits of Lake Columbus. Remnants of berms at the same altitude are also preserved on the west and south sides of the basin.

0.2 55.1 **Turn right on US-95 and proceed south.**

9.0 64.1 **Intersection with US-6 at Coaldale Junction. Turn right (west) on US-6.** The garbage dump behind the buildings cuts into a shoreline bar at 1430 m (4690 ft), 30 m higher than the late Pleistocene shoreline of Lake Columbus. This bar was first observed by J.O. Davis (Univ. Nevada Reno) on a satellite photo.

2.4 66.5 Straight ahead are Mount Montgomery (left) and Boundary Peak (right) in the White Mountains. The California-Nevada state line runs through the saddle between the peaks. White Mountain Peak, the highest point in the White Mountains, is only slightly lower than Mount Whitney.

3.9 70.4 Intersection with Nevada 773 south to Fish Lake Valley. **Continue west on US-6.**

0.7 71.1 A low basalt hill due south (9:00) in the foreground has a prominent bench on it. The bench is a shoreline marked by well-rounded basaltic clasts forming a pavement; the altitude of the bench is 1430 m, coincident with the berm at Coaldale Junction. The top of the hill at ~1445 m also bears a few rounded clasts.

1.1 72.2 **Turn left (south) at trash barrels; proceed toward borrow pit.**

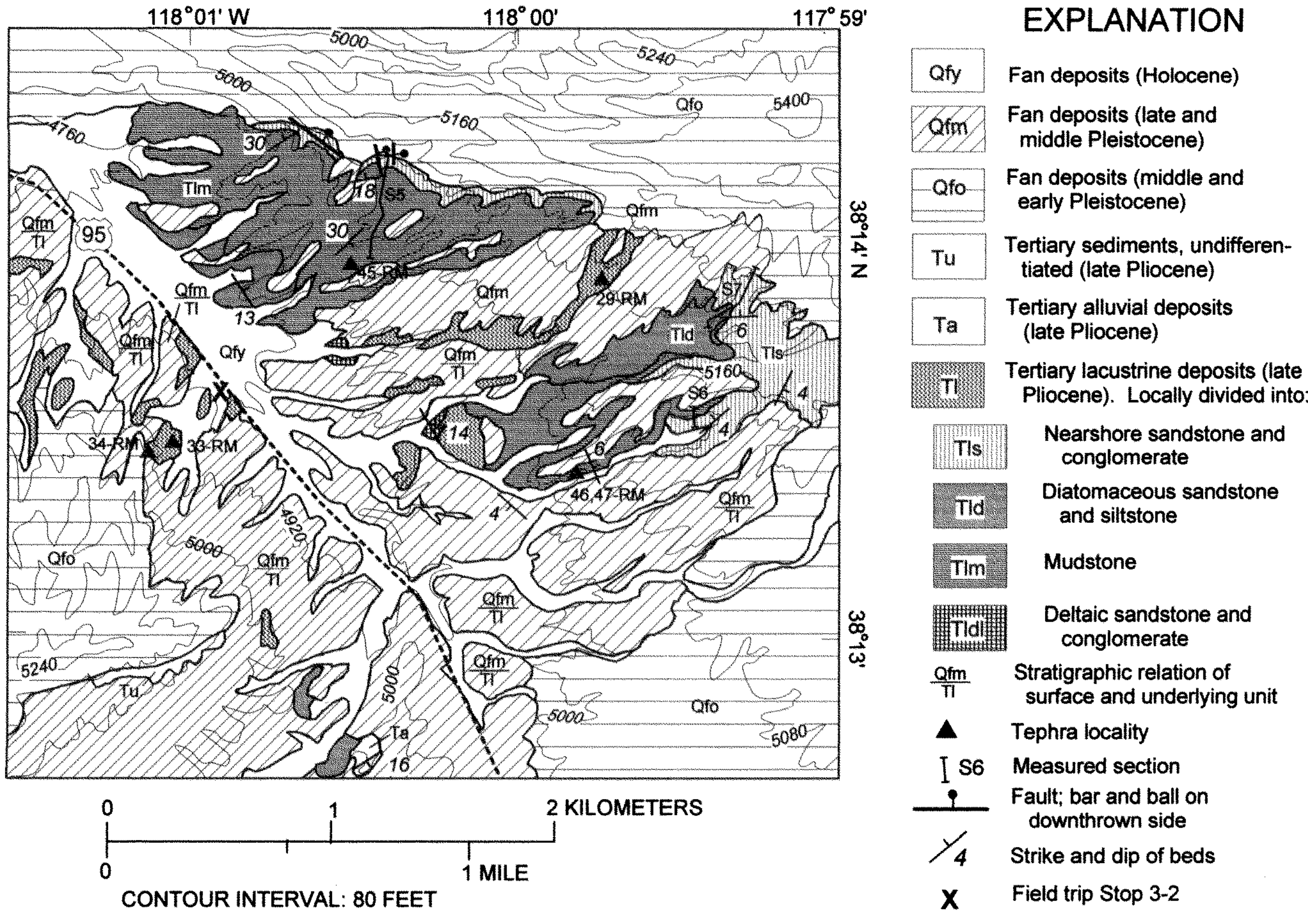


Figure 12. Preliminary geologic map of area northwest of Redlich Summit between Rhodes and Columbus Salt Marshes. X shows field trip Stop 3-2 (Figs. 1 and 2, Table 1).

0.2	72.4	Borrow pit on left is cut in beach gravel of the late Pleistocene (Sehoo equivalent) shoreline of pluvial Lake Columbus at 1400 m (4600 ft).
0.3	72.7	**Park next to small hill among gravel piles for Stop 3-4 (Figs. 1, 2, and 13; Table 1) and lunch.**

STOP 3-4—Pre-late Pleistocene deposits and shorelines of pluvial Lake Columbus (1 1/2 hours)

This small hill preserves evidence of at least four lacustrine units higher and older than the late Pleistocene shoreline of Lake Columbus (Fig. 2). Outcrops on the west side show that the hill is cored by Tertiary basalt and fluvial conglomerate, but these rocks are covered by lacustrine deposits best exposed on the southeast, including three units of lacustrine gravel, sand, and silt separated by paleosols (Fig. 13, Section 3). The uppermost unit in this section consists of tufa-cemented gravelly foreset beds that underlie a prominent berm which protrudes from the south side of the hill at an altitude of about 1435 m (4710 ft; same as unit Qlo3, Fig. 13). This altitude is similar to that of beach berms initially identified by J. O. Davis on the southeast side of the basin at Coaldale Junction. Very well-rounded gravel clasts and tufa are preserved as lag on the slope above the berm to the top of the hill at 1452 m (4765 ft), suggesting a yet higher lake stand. A similar gravel-covered bedrock bench on the west side of Columbus Salt Marsh extends to an altitude of 1457 m (4780 ft). Evidence of the youngest lacustrine unit here has been destroyed by gravel operations, but in 1991, excavations exposed gravelly foreset beds with a moderate argillic soil in a berm at about 1417 m (4650 ft). This altitude corresponds to those of small berms on the north side of the basin (Stop 3-3). In summary, deposits and berms at several locations around the marsh indicate at least four lake cycles older and higher than the late Pleistocene shoreline: the two oldest extended at least to 1420 m and probably to 1457 m, an intermediate shoreline

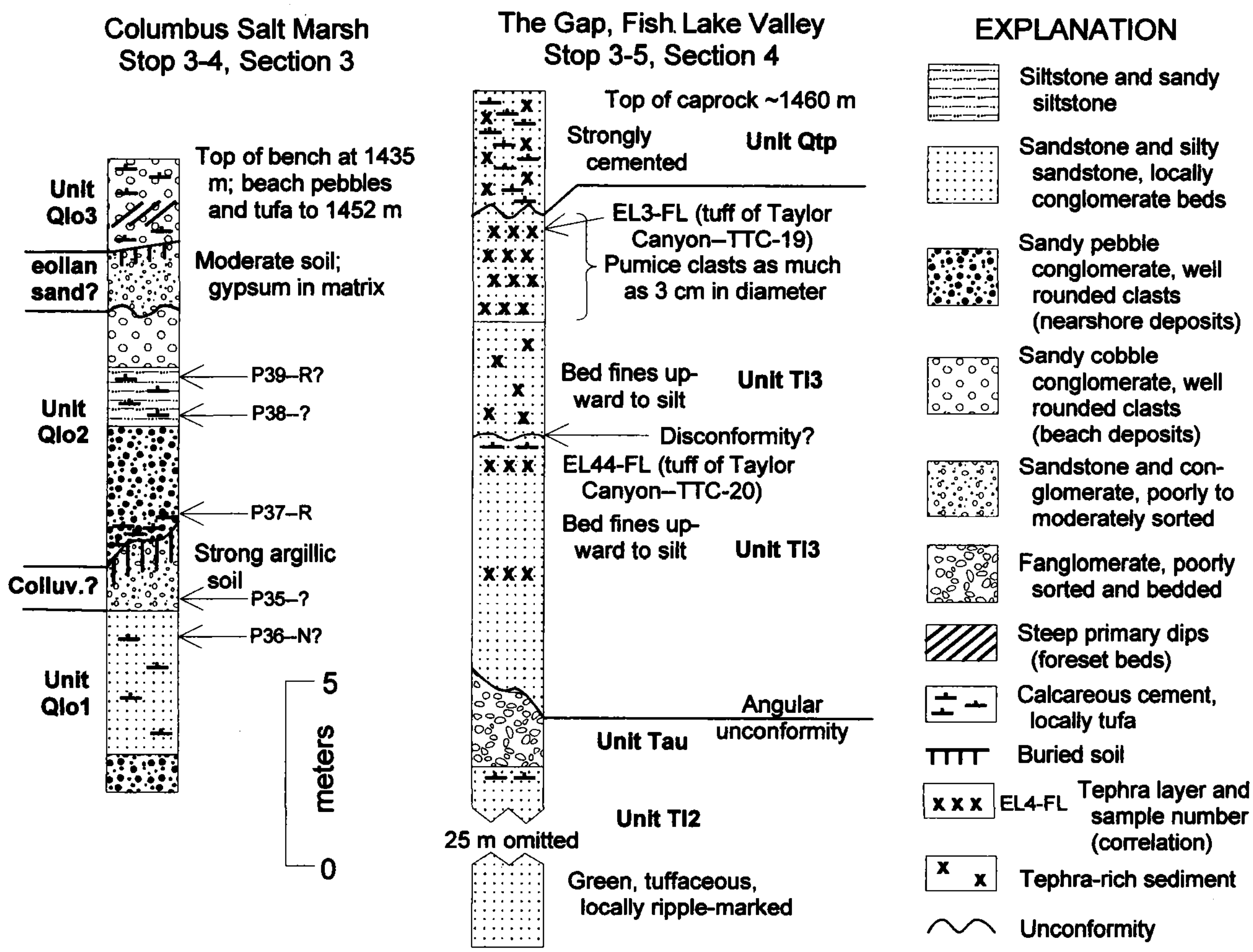


Figure 13. Measured sections at field trip stops 3-4 (Columbus Salt Marsh) and 3-5 (The Gap; Figs. 1 and 2, Table 1).

to about 1435 m, and a younger shoreline to 1417 m. One of the older three lake cycles probably occurred about 760 ka (Bishop ash bed at Stop 3-3), the age of Lake Rennie in Fish Lake Valley at its 1460-m (4800 ft) shoreline (Reheis et al., 1993). This level is very close to that of the highest preserved shoreline in Columbus Salt Marsh at 1457 m, indicating that Lakes Columbus and Rennie were contiguous at that time.

Retrace route to intersection of US-6 and Nevada 773.

2.3 75.0 **Turn right (south) on Nevada 773 toward Fish Lake Valley; prepare to turn.**

0.3 75.3 **Turn left onto a gravel road toward The Gap.** Fish Lake Valley drains through The Gap into Columbus Salt Marsh in big storms. Lake Columbus at 1435 m (4710 ft) would back well into Fish Lake Valley and cover the modern playa.

1.2 76.5 S curves through sandy, pebbly mounds which are late Pleistocene beach ridges of Lake Columbus. At this level Lake Columbus reached the mouth of The Gap and Fish Lake Valley had no lake (Reheis et al., 1993). Just past the curves at 9:00 (east) are low active spring mounds. Travertine beds extending from these mounds interfinger with late Pleistocene shoreline sediment of Lake Columbus.

1.1 77.6 At the mouth of The Gap to the right (west) is a massive spring mound that has been prospected for hydrothermal minerals. The Gap transects a colorful complex of Miocene volcanic rocks and is boggy throughout.

0.8 78.4 At 9:00 (east) is a blocky rhyolite hill with a bench on it about two thirds of the way up at an altitude of 1457 m. The bench may be a landslide, though intact bedrock seems to underlie it, or it may be the remains of a wave-cut platform at the time that pluvial Lake Columbus-Rennie stood at about 1460 m.

0.6 79.0 In the distance to the southeast are dissected fan gravels interbedded with sediment of four lake cycles that range from >3.4 Ma to 0.76 Ma. The two oldest lake units consist of pale-colored sediment beneath fan gravel in brown-capped hills. The greenish-striped lake unit contains ca. 2-Ma tephra including the Huckleberry Ridge Ash and several tephra of the tuff of Taylor Canyon (Reheis et al., 1993).

1.0 80.0 Left fork. **Continue straight ahead (south).**

1.1 81.1 **Park along the right edge of the road for Stop 3-5 (Figs. 1, 2, and 13; Table 1).**

STOP 3-5—Pliocene lacustrine deposits and tephra of pluvial Lake Rennie in The Gap

Deposits in this hill represent three lacustrine units of pluvial Lake Rennie interbedded with two alluvial units (Fig. 13, Section 4). Unit Tl1 (not shown in Fig. 13) is exposed on the north side of the hill; the middle and upper units Tl2 and Tl3, separated by an angular unconformity and coarse fan gravel, are exposed on the north side of the hill. Unit Tl2 here may be equivalent to deposits about 1 km southeast that contain a tephra possibly correlative to one erupted from the Mt. Jackson area at about 2.9 Ma. Unit Tl3 here contains two tephra (EL3-FL and EL44-FL), both of which are correlative to layers of the ca. 2-Ma tuff of Taylor Canyon. The upper tephra layer is 2–3 m thick and contains pumice clasts as much as 3 cm in diameter. The caprock, which is probably unconformable on unit Tl3, consists of tufa-cemented gravel with abundant large weathered pumice clasts likely derived from rhyolite flows in the hills to the west. This tufa caprock crops out for several kilometers to the south at about 1460 m (4800 ft) in altitude, coincident with the 760-ka shoreline of pluvial Lake Rennie (Reheis et al., 1993).

END OF DAY 3. Return to Reno (about 225 miles).

OR, continue on 6 miles to Fish Lake hot spring and sinter mound containing Bishop ash.

2.0 83.1 Cresting a hill. To the east is Fish Lake playa, which was mined for borates in the past. Across the playa is the Emigrant Peak fault zone, a system of north-striking normal faults with very high slip rates. The early Holocene deposits on this fan complex have been displaced about 23 meters (Reheis and Sawyer, 1997).

2.5 85.6 **Road forks; bear right (southwest).** To the left and right are low hills of fan gravel capping 2-Ma lacustrine deposits.

1.0 86.6 **Road forks; bear right (northwest) to the hot spring parking lot. OR, bear left (west) to the sinter mound.**

1.2 87.8 **Park where road crosses rock outcrop (Stop 3-6, Figs. 1 and 2 and Table 1).**

OPTIONAL STOP 3-6—Sinter mound of Bishop ash and 1460-m shoreline of Lake Rennie

This sinter outcrop protrudes through gently sloping late Pleistocene and Holocene fan gravel. The outcrop consists of about 18 m of reworked Bishop ash and lapilli tuff and opaline silica beds that overlie altered green mudstone (Reheis et al., 1993). Iron and manganese were leached from some beds and precipitated as cement in other beds. The uppermost bed contains pumice clasts as much as 2 cm in diameter admixed with rhyolite and basalt pebbles derived from the adjacent hills. Siliceous root casts litter the upper part of the outcrop. The sand-sized tuff beds commonly display load casts. The silica-rich beds are finely but irregularly laminated and resemble opaline sinter formed by primary hot-spring discharge.

Reheis et al. (1993) inferred that the sinter mound formed at the edge of a lake just after the eruption of the Bishop ash for the following reasons. The mound consists mainly of well-sorted tephra; no fluvial sedimentary structures are present but load casts are common. The siliceous deposits overlie green mudstone that is probably lacustrine. Pumice grains in most of the mound contain flattened vesicles, but near the top of the mound vesicles are spherical. This change suggests a sort of grading in which the lighter, air-filled pumices floated, whereas heavier pumices with flattened vesicles sank. Siliceous root casts in the upper beds probably reflect rooting depth in shallow water. The uppermost bed of the sinter mound is interpreted to represent the paleoshoreline of Lake Columbus-Rennie at about 1460 m.

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