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Timing of the last highstand of pluvial Lake Wellington, Smith Valley, Nevada

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TIMING OF THE LAST HIGHSTAND OF PLUVIAL LAKE WELLINGTON, SMITH VALLEY, NEVADA

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ABSTRACT

TIMING OF THE LAST HIGHSTAND OF PLUVIAL LAKE WELLINGTON, SMITH VALLEY, NEVADA

By Heidi L. Stauffer

Smith Valley, in west-central Nevada, was occupied by pluvial Lake Wellington, which reached its final highstand of approximately 1,477-m elevation during late Pleistocene time. Evidence for Lake Wellington includes lacustrine deposits and shorelines, whose surface geomorphology, sedimentology, and stratigraphy were used to interpret lake history. Based on modern valley topography and Geographic Information Systems (GIS) modeling, Lake Wellington had a surface area of approximately 217 km^2 at its last highstand.

On the basis of soil development on lacustrine sediment, and a tephra layer within the sequence, the 1477-m highstand of Lake Wellington occurred between 80 and 60 ka. Timing of this highstand approximately corresponds to Marine Isotope Stage (MIS) 4. Smith Valley provides the most complete evidence of a pluvial lake highstand in Nevada during MIS 4.

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INTRODUCTION

Smith Valley is located in west-central Nevada, about 35 km southeast of the Carson Valley and the towns of Minden and Gardnerville (Fig. 1). During the Pleistocene, Smith Valley was occupied by pluvial Lake Wellington; its shorelines and deposits are preserved within the valley. Until this project, although these features had been studied, no chronology had been developed for Lake Wellington, and no correlations with neighboring Lake Lahontan had been made.

Purpose

The purpose of this study was to determine the timing and assess the extent of the last highstand of Lake Wellington, and to compare that timing with other lake and proxy climate records. To that end, a study of shorelines, lacustrine deposits, and soils was conducted in Smith Valley to characterize the final highstand of Lake Wellington. Shorelines were mapped from aerial photographs, and additional topographic and geomorphic data were collected in the field using Global Positioning System (GPS) technology. Terrain analysis was conducted using

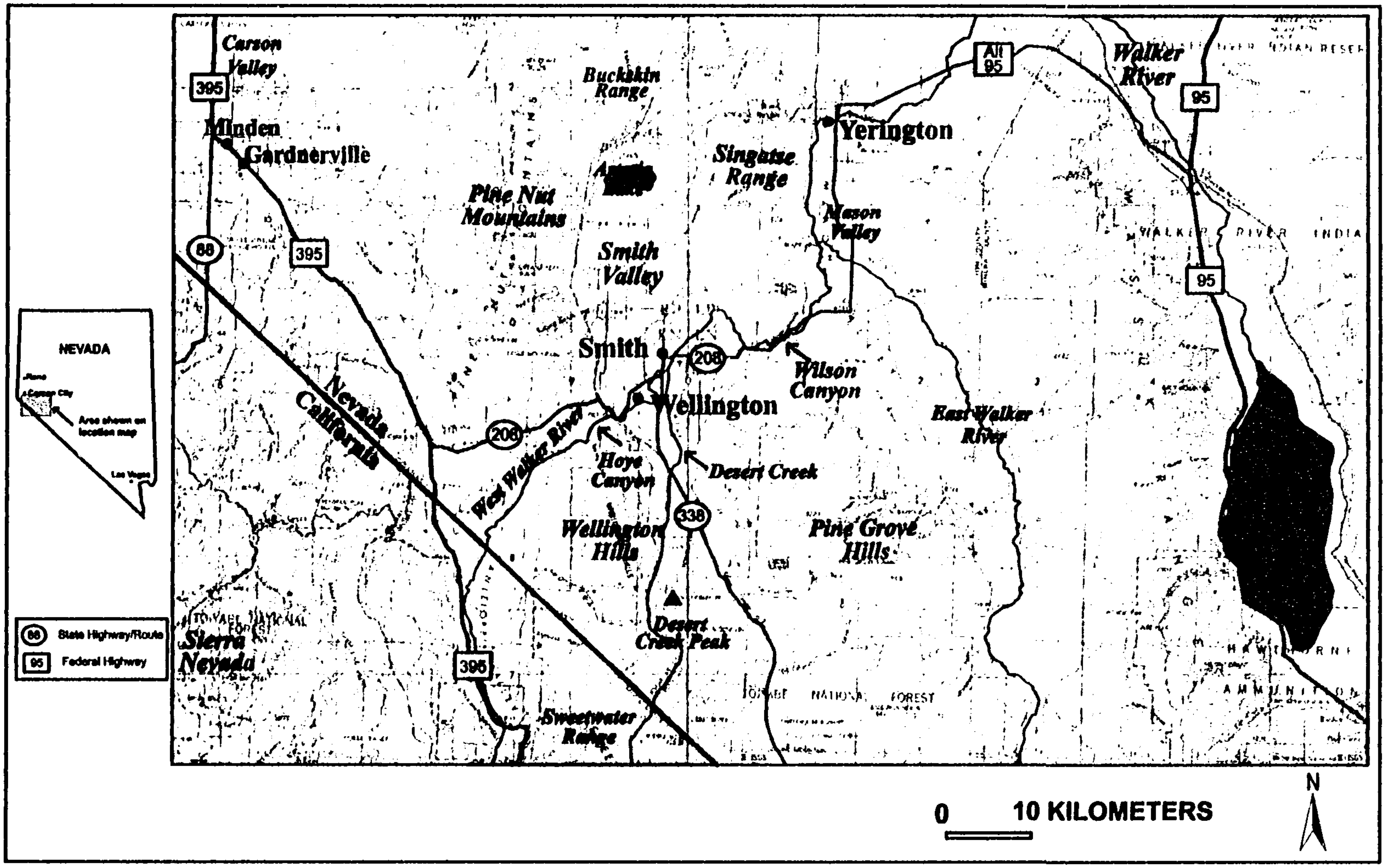


Figure 1. Location of Smith Valley and localities in the region. USGS topographic map (original scale 1:25,000) used as base map downloaded from Microsoft TerraServer USA at http://terraserver-usa.com/.

ArcView 3.2 Geographic Information Systems (GIS) software to model the lake at its last highstand.

Pluvial lakes form in internally drained desert basins during times when precipitation exceeds evapotranspiration, and their formation has been approximately correlated with the end of glacial periods (Morrison, 1991). The internally draining basins within western North America, including those in western Nevada, such as Smith Valley, were filled with approximately 120 moderately deep to deep lakes during Pleistocene time (Morrison, 1991).

Since the early 20th century, pluvial lakes have been regarded as important evidence of terrestrial responses to global climate shifts (Mifflin and Wheat, 1979). Important issues concerning pluvial lakes include: 1) age and location of lakes, 2) lake volumes, and 3) factors controlling development and extent. Studies of pluvial lakes can increase the understanding of how local geologic records document past climate change and provide insight into future climate change. At present, the relationships between pluvial lake evidence of climate change and other climate indicators, such as marine isotope records and glacial histories, are not well established (Reheis, 2003, written communication).

Most research on pluvial lakes in western North America to date has focused on lakes Bonneville and Lahontan. Establishment of chronologies for smaller, contemporaneous lakes, such as Lake Wellington, will add detail to the Quaternary history of the region. Such chronologies could clarify the relationship between the cycles of smaller lakes and those of the larger lakes Bonneville and Lahontan. Furthermore, because some of these smaller lakes were apparently never connected to the two larger paleolake systems, their histories allow for independent comparisons to other climate-related records, and can further the understanding of the controls on isolated lake basins.

Study Area Setting

Smith Valley is a 40-km-long north-trending valley in western Nevada. The bottom of the valley floor lies at an elevation of approximately 1,385 m. The west side of the valley is flanked by the Pine Nut Mountains, a north-south trending range that rises to about 2,740 m, and by the lower Wellington Hills, south of the West Walker River (Fig. 1). On the east side of Smith Valley, the Singatse Range rises to an altitude of almost 2,150 m to the north of the West Walker River; south of the river, the Pine Grove Hills are higher than 2,460 m. In the southern part of Smith Valley, Desert Creek Peak (Fig. 1) is the northernmost part of the Sweetwater Range, rising to an elevation of over 2,730 m (Moore, 1969).

The West Walker River flows approximately east-northeast across Smith Valley, entering the valley at Hoye Canyon, at the town of Wellington (Sec. 2, T11N, R23E), and exiting through Wilson Canyon in the east (Sec. 17, T11N, R24E), where it flows into Mason Valley and joins the East Walker River. Wilson Canyon is thought to be the outflow channel for the final overflow of Lake Wellington into Mason Valley (Mifflin and Wheat, 1979). The Walker River continues north, makes a large meander, and finally flows south into Walker Lake (Fig. 1).

Desert Creek (Fig. 1) flows north from the Sweetwater Mountains into the West Walker River in Smith Valley. Desert Creek has deposited a large fan that has elevated the southern part of Smith Valley above the level of Lake Wellington shorelines. Thought to be a remnant of Lake Wellington, modern Artesia Lake (Fig. 1), located in the northwestern part of the valley, has been pumped for agricultural and residential purposes and is at low levels most of the year.

The major population centers in Smith Valley are the towns of Wellington and Smith, both located in the southern part of the valley along the West Walker River, as is a majority of the agriculture. Currently, the total population of the valley is approximately 3,300. Several paved roads provide access in the valley, the largest and most traveled being Nevada State Highway 208. Because of the mining and agricultural activities of the 19th and 20th centuries, numerous unpaved roads also cross the valley; many of these lie at a distance from the current population centers, north of the West Walker River (Fig. 1).

GEOLOGY

Bedrock Geology

The bedrock in Smith Valley comprises mostly Mesozoic metamorphic and igneous rocks, which are exposed in many of the mountain ranges and elsewhere along the valley margins. In addition, Tertiary sedimentary and volcanic rocks are exposed in the southern part of the valley, in deep gullies, and in the area west of Wilson Canyon (Fig. 1; Stewart and Dohrenwend, 1984).

The Pine Nut Mountains are composed primarily of Mesozoic granitic rocks, which are likely related to the Sierran Batholith about 35 km to the west, and Triassic and Jurassic metavolcanic and metasedimentary rocks. The Wellington Hills, located south of the Pine Nut Mountains, are underlain by Tertiary volcanic rocks, as well as undifferentiated Tertiary sedimentary rocks (Moore, 1969). Desert Creek Peak is located south of the valley and is a part of the Sweetwater Range. The Sweetwater Range consists of west-tilted fault blocks, extending north to the Wellington Hills. The range is composed mostly of Cretaceous granitic rocks (Moore, 1969).

The northern end of the valley is dominated by the Buckskin Range. The Buckskin Range is composed of Tertiary volcanic rocks, Triassic and Jurassic metavolcanic and metasedimentary rocks, Cretaceous granitic rocks, and some areas of Tertiary and older Quaternary alluvium, predominantly fanglomerate and pediment gravel (Hudson and Oriel, 1979). The Singatse Range is primarily Cretaceous granitic rocks, Tertiary volcanic rocks, local outcrops of Tertiary sedimentary rocks, and Triassic and Jurassic metasedimentary and metavolcanic rocks. The Pine Grove Hills to the south are mostly Tertiary volcanic and sedimentary rocks (Moore, 1969).

A sequence of Upper Tertiary deposits known as the Wilson Canyon Formation is exposed west of the range front at Wilson Canyon, to the north and south of the canyon, and along the West Walker River north of the town of Smith. The Wilson Canyon Formation is mostly gravel, fine to medium sand, and laminated silt and clay (Stewart and Dohrenwend, 1984).

Quaternary Geology

The Quaternary deposits in Smith Valley consist mostly of lacustrine and deltaic gravel, sand, silt, and clay, alluvial deposits from the West Walker River and smaller fan systems, and colluvium (Stewart and Dohrenwend, 1984). These deposits are generally exposed on the valley floor and along the margins of the valley, and are described in detail by Stewart and Dohrenwend (1984) on pages 2 and 3 of the text accompanying their map.

Faults

Smith Valley is located within the Walker Lane Seismic Belt, a broad zone of predominantly normal faults in western Nevada (Fig. 2; Stewart, 1988). Many of the faults mapped in Smith Valley and the surrounding mountain ranges offset primarily pre-Quaternary formations, making it difficult to determine whether any Quaternary motion has occurred on these faults. Those faults with evidence of Quaternary slip show primarily normal offset, characteristic of faults in the Basin and Range (Stewart, 1988).

At least three faults mapped in Smith Valley appear to offset Quaternary lacustrine units as mapped by Stewart and Dohrenwend (1984). The Smith Valley fault zone (Fig. 2) is located at the base of the Pine Nut Mountains, a west-tilted fault block (Moore, 1969; dePolo et al. 1997). The

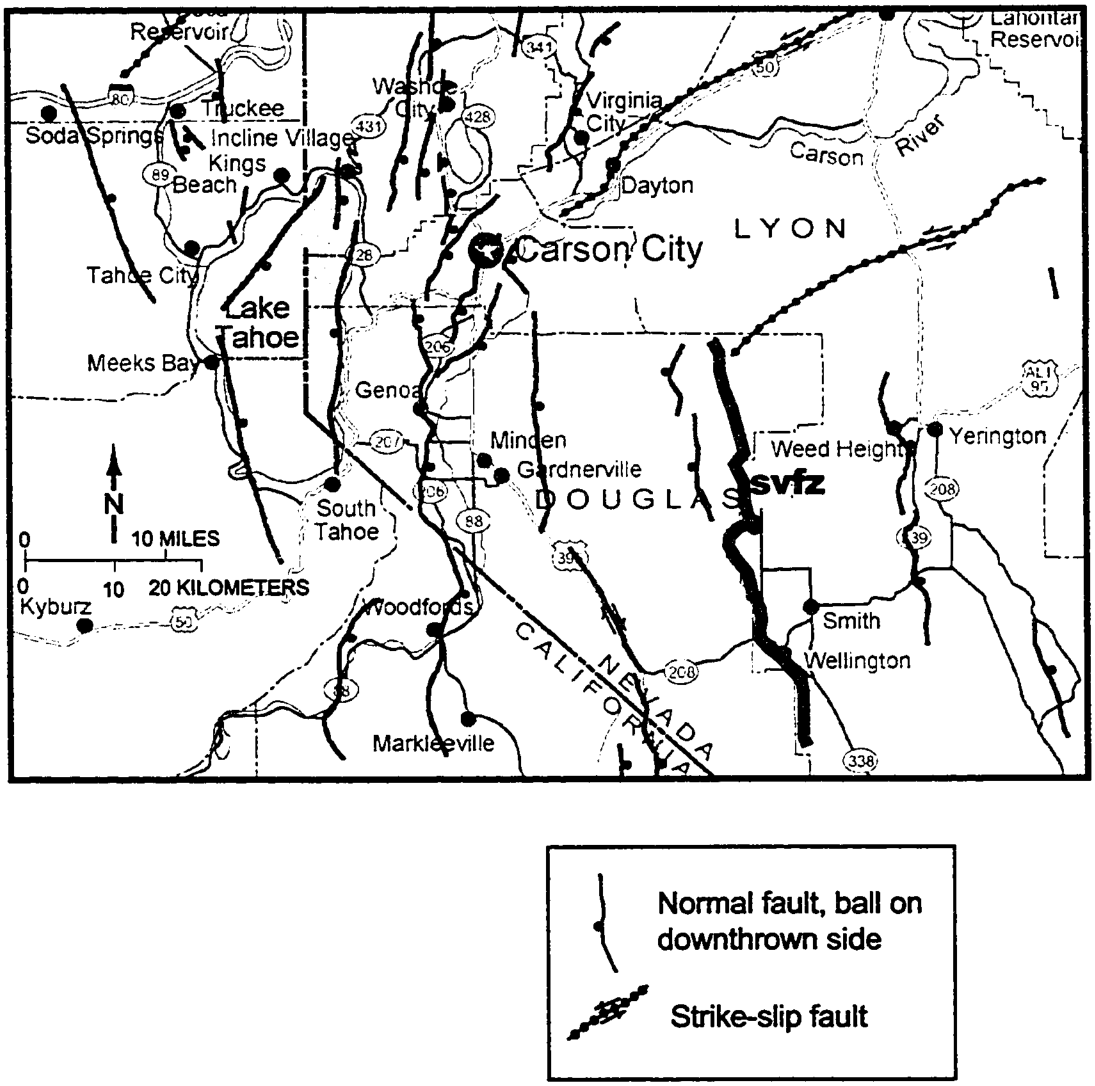


Figure 2. Map showing faults in the Reno-Carson City urban corridor, including those in the vicinity of Smith Valley. svfz = Smith Valley fault zone (dePolo et al., 1997).

Smith Valley fault zone is the longest of the faults in Smith Valley and offsets alluvium and bedrock within the study area along the base of the Pine Nut Mountains and into the Wellington Hills in the southwest part of the valley. The Smith Valley fault zone exhibits primarily normal motion and has an estimated slip rate of 0.21 to 0.81 mm/yr (Figs. 2, 3, 4, 5; dePolo et al., 1997; see Fig. 3 for location of photos).

Along the eastern edge of the Buckskin Range (Fig. 1), a much smaller normal fault appears to offset primarily bedrock and, at a few localities, Quaternary alluvium (Hudson and Oriel, 1979). On the eastern margin of Smith Valley, the Singatse Range is also considered a west-tilted fault block, with the bounding fault located on the eastern flank of the range, in neighboring Mason Valley (Moore, 1969).

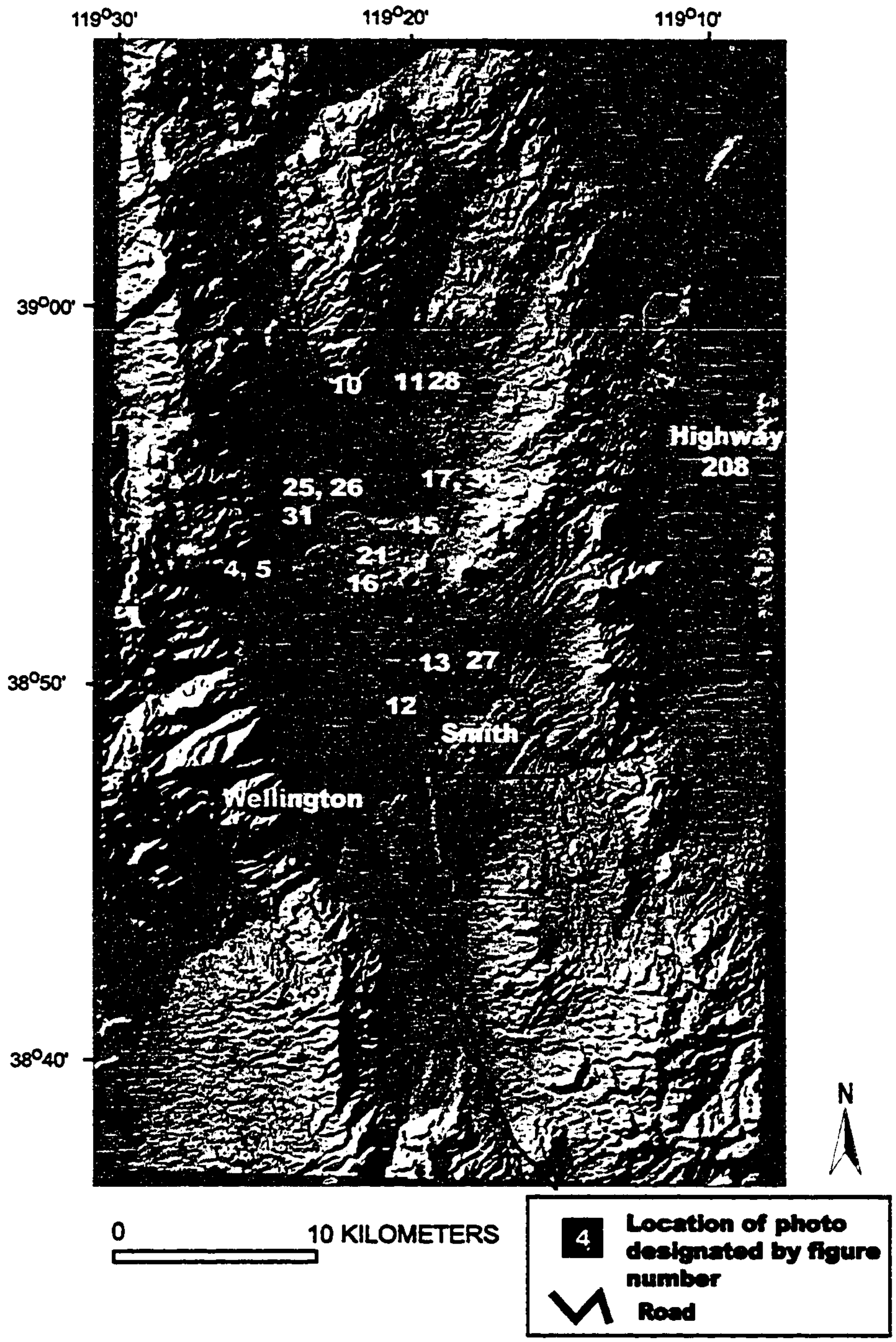


Figure 3. Digital Elevation Model (DEM) shaded relief map showing locations of photos used for illustration in this thesis. The photos are identified by their figure numbers.

Figure 4. View looking west to the rangefront fault (arrows), part of the Smith Valley fault zone, at the base of the Pine Nut Mountains (see Fig. 3 for location of photo).

Figure 5. View looking southwest at fault scarps (arrows) in alluvium at the base of the Pine Nut Mountains (see Fig. 3 for location).

PREVIOUS STUDIES

Lake History of the Lahontan Basin

Lake Lahontan was one of two large pluvial lakes that occupied what is now Nevada and western Utah during Pleistocene time (Fig. 6; Morrison 1991). Shoreline features and lacustrine deposits are found throughout the Lahontan Basin, and most of them are related to two periods of highstands. Numerous smaller lakes occupied smaller valleys in western Nevada, one of which was Smith Valley's Lake Wellington.

Early Studies in the Lahontan Basin

Most pluvial lake research in western North America has focused on lakes Bonneville and Lahontan. Early research concentrated on the physical expression of these paleo-lakes and was conducted independently of climate studies. The earliest significant study of the Lahontan Basin was carried out by geologists of the 40th Parallel Survey and later published by Clarence King (1878). King (1878) was the first to formally name Lake Lahontan. In addition to describing the tufa in the basin, he also developed a history for the lake, including inferring an

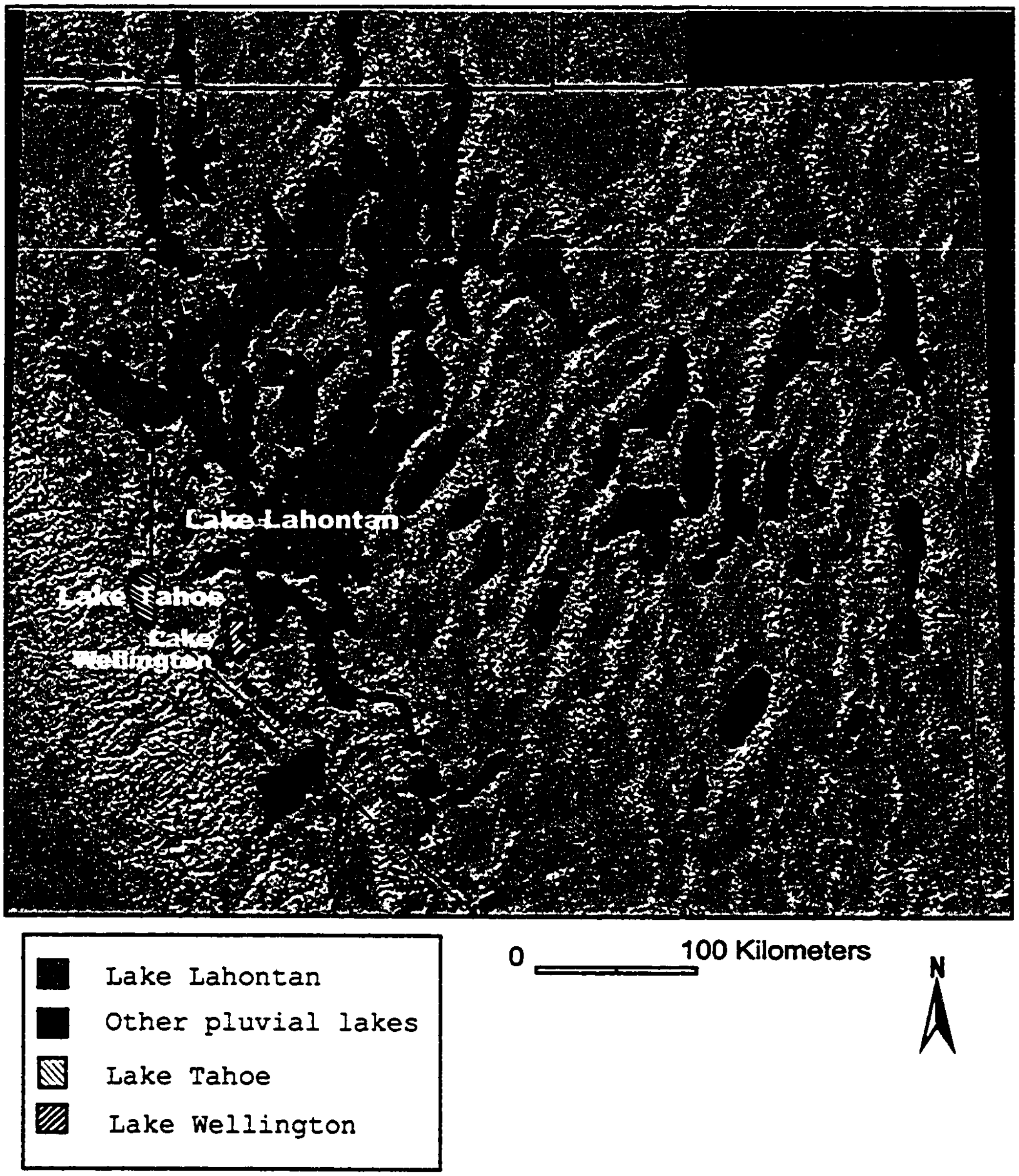


Figure 6. Map showing extent of pluvial lakes in Nevada, including the period from the Pliocene through the late Pleistocene. Base map and ArcView shapefiles of lake extent from Reheis (1999a).

overflow event, based on his geomorphic observations (Jones, 1925).

Several years later, Russell (1885) performed a comprehensive study of the Lahontan Basin. Russell (1885) was the first to recognize more than one period of high water for Lake Lahontan. His careful observations also yielded the recognition of three different types of tufa, based on morphology and a hypothesis requiring that Lake Lahontan had desiccated at least twice to account for the observed varieties of tufa. In addition, Russell (1885) estimated the age of Lake Lahontan using the salinities of remnant water bodies and the assumed salinity of the larger Lake Lahontan. He found no evidence for the overflow of Lake Lahontan postulated by King in 1878 (Jones, 1925).

In a study of Lake Lahontan, Jones (1925) detailed past and present tufa formation and noted the presence of oolitic sand. Jones (1925) estimated the age of Lake Lahontan by calculating the length of time necessary for the remnant lake salinities and chlorine concentrations to reach their recorded levels, based on known stream chemistry and flow rates and incorporating approximate evaporation rates of bodies of water in the Nevada. On the basis of the results of these evaluations, Jones concluded that Lake Lahontan was between 4,300 and 2,400 years old (Jones, 1925).

Research in the Lahontan Basin through the 1990s

By the mid-20th century, workers researching the Lahontan Basin had begun to examine connections between the lake levels and other records of climate, such as glacial deposits and global indicators of ocean temperature. The work of King (1878), Russell (1885), and Jones (1925) formed the basis for detailed research of Lahontan stratigraphy, sedimentology, soils, geomorphology, and age studies using tufa and tephrochronology, including the work of Morrison (1959, 1964), Morrison and Frye (1965), Broecker and Kaufman (1965), and Davis (1978). Morrison (1964) and Morrison and Frye (1965) conducted systematic examinations of Lahontan stratigraphy, sedimentology, and soils, and from those studies compiled the first complete chronology for Lake Lahontan. Morrison and Frye (1965) described two periods of lake highstands separated by an extended interval when the basin was either dry or occupied by shallow lakes (Fig. 7). Later studies have primarily refined and adjusted that chronology.

Marine Isotope Stages[1]	Approximate Age[1]	Sierra Nevada Glaciations[2*]	Possible Lake Lahontan stratigraphy[3*]
1	present time to ~10,000 years ago	Interglacial with minor (regional?) glacial advances	Fallon Alloformation Toyeh Soil Turupah Alloformation to ~8,000 years ago[3]
2	between ~10,000 and ~25,000 years ago	Recess Peak between ~13,000 and ~14,000 Tioga between ~14,000and ~25,000 years ago	Sehoo Alloformation between ~12,000 and ~35,000 years ago[4]
3	between ~25,000 and ~ 56,000 years ago	Interstadial with minor (regional?) glacial advances (Tenaya: ~30,000 years ago; Tahoe II between ~42,000 and ~50,000 years ago)	Churchill Soil Wyemaha Alloformation between ~35,000 and ~130,000 years ago[3] (alternating wet and dry periods, evidence of moderately deep lakes)[5]
4	between ~56,000 and ~75,000 years ago	Mono Basin between ~60,000 and ~80,000 years ago	
5	between ~75,000 and ~128,000 years ago	Interglacial	
6	between ~128,000 and ~190,000 years ago	Tahoe I between ~140,000 and ~200,000 years ago	Eetza Alloformation (multiple lake cycles) between ~140,000 and ~280,000 years ago[6]
7	between ~190,000 and ~240,000 years ago	Interglacial	

[1] Imbrie et al., 1984
[2] Clark et al., 2003
[3] Morrison, 1991
[4] Benson et al., 1990
[5] Reheis et al., 2003
[6] Adams and Wesnousky, 1999
*Note: Timing of the Sierra Nevada glaciations and the ages of Lahontan units may be revised due to recent and ongoing studies

Figure 7. Diagram showing Marine Isotope Stages, correlations with Sierra Nevada glacial advances, and poss correlations with Lahontan Basin pluvial lake cycles.

Lacustrine deposits of Eetza age (Morrison, 1964) date to between approximately 280,000 and 140,000 years B.P. (Fig. 7; Morrison, 1991; Adams and Wesnousky, 1999) and correspond approximately to marine isotope stages (MIS) 6 and 7. They include both progradational and recessional deposits that record lake-level fluctuations and the highest stand reached by Lake Lahontan, at approximately 1,348 m (Morrison and Frye, 1965).

Deposits of the Eetza Alloformation are widespread in the greater Lahontan Basin and contain the coarsest gravels of all deposits related to Lake Lahontan (Morrison, 1964). Morrison (1991) assigned the term alloformation to the Lahontan units he had previously mapped, and subsequent workers have continued to use this terminology. An alloformation is defined as "a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities" (North American Stratigraphic Code, North American Commission on Stratigraphic Nomenclature (NACSN), 1983). The term alloformation in this study is used to refer to the Lake Lahontan pluvial stratigraphic units originally described by Morrison (1959), and to Lake Bonneville pluvial stratigraphic units, for which the term is also used (Oviatt et al., 1987; McCoy, 1987; Kaufman et al., 2001).

Approximately 125 km north of Smith Valley near the Lahontan Mountains (Fig. 8), Morrison and Frye (1965) noted that the Eetza Alloformation is exposed only in the highlands. At this location, the Eetza Alloformation consists primarily of boulder to pebble gravel, with rare sand, silt, clay, and tufa. In contrast, exposures of the Eetza Alloformation in the badlands of the Truckee River near Wadsworth (Fig. 8), are mostly clay, silt, and sand, with small amounts of gravel (Morrison and Frye, 1965). Subaerial deposits associated with the lacustrine deposits of the Eetza Alloformation are rare, and tufa deposits occur less commonly and with smaller areal extent than in deposits from the later Sehoo highstand (Morrison, 1964). During early stages of Lake Lahontan, lake levels fluctuated, sometimes to near-desiccation (Morrison, 1964, 1991).

The Wyemaha Alloformation, as described by Morrison and Frye (1965) near the Lahontan Mountains (Fig. 8), consists of eolian sand, alluvium, and local colluvium. Below about 1,225 m, these deposits interfinger with lacustrine deposits of sand, silt, and clay (Morrison and

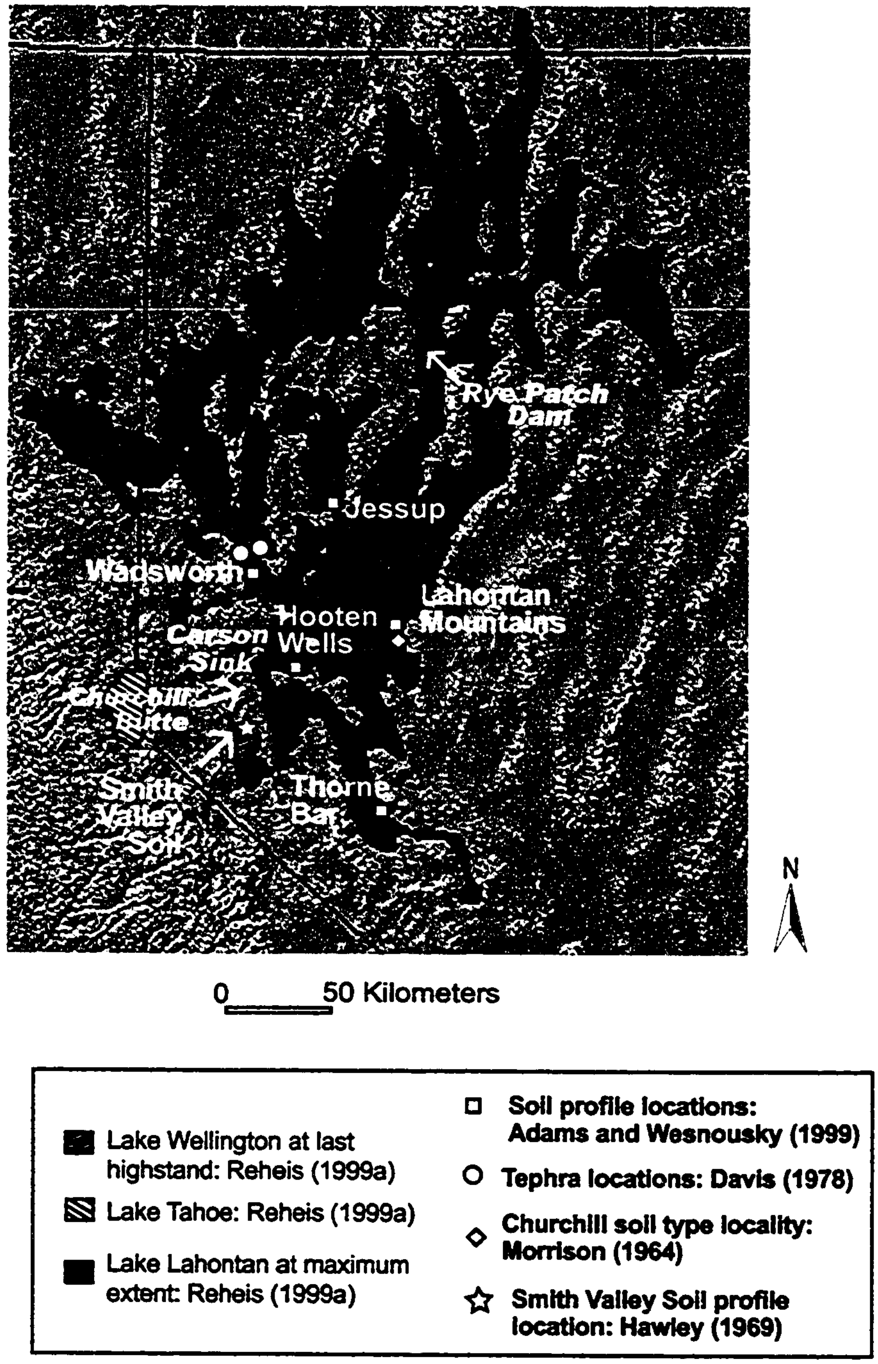


Figure 8. Map showing locations of previous studies discussed in text. Base map and shapefiles of lakes from Reheis (1999a).

Frye, 1965). In areas such as the Truckee River badlands near Wadsworth, the Wyemaha Alloformation appears to be primarily subaerial alluvium, consisting of sand and alluvial gravel (Morrison and Frye, 1965). During the deposition of the Wyemaha Alloformation, between 130,000 and 35,000 years B.P., the Lahontan basin experienced extended periods of drying out, corresponding roughly to interglacial and interstadial periods during MIS 5 and 3 (Fig. 7; Morrison, 1964, 1991).

The age of the Sehoo Alloformation (Morrison, 1964) corresponds approximately to MIS 2 (between approximately 25,000 and 10,000 years B.P.; Fig. 7; Benson et al., 1990; Morrison, 1991). At least six deep-lake cycles are recorded in the Lahontan Basin by Sehoo deposits resembling those of the Eetza Alloformation (Morrison and Frye, 1965). As described near the Lahontan Mountains, the Sehoo Alloformation is composed of gravel, sand, silt, and clay of lacustrine origin (Morrison, 1964; Morrison and Frye, 1965). In addition, abundant tufa formations of different ages are distinguishable by their occurrence at specific stratigraphic horizons and by their morphologic characteristics.

Paleohydrologic studies also have been conducted in Nevada, including those correlating the varying geometries of pluvial lakes with changes in local and regional hydrologic and climatic conditions (Benson and Paillet, 1989). Historically, variations of lake level and lake volume have also been used to determine basin response to climate changes (e.g. Russell, 1885). The most reliable indicator of changes in climatic and hydrologic regimes is the total surface area of all lakes in a basin, because lake levels, in particular, can vary for reasons other than climate changes (Benson and Paillet, 1989).

Recent Studies in the Lahontan Basin

Recent stratigraphic and sedimentologic studies of Lahontan deposits (Adams and Wesnousky, 1998, 1999; Blair, 1999; Reheis et al., 2003) have further refined and revised the stratigraphy of Lake Lahontan. Blair (1999) studied the sedimentology and facies relationships of a Sehoo-aged Lake Lahontan gravel shore deposit at Churchill Butte (Fig. 8). The history of the Lahontan Basin before the existence of Lake Lahontan is less well defined, but recent studies of high shorelines and discontinuous older deposits indicate that pluvial lakes existed in western Nevada at least as far back as Pliocene time (Reheis et al., 1993; Reheis, 1999b; Reheis et al., 2002, 2003).

Current reexamination of pluvial evidence in the Lahontan Basin also indicates that moderately deep lakes existed between 75,000 and 56,000 years ago (Fig. 7; Reheis, 2003, written communication; Reheis et al., 2003), corresponding approximately to MIS 4, which had been previously thought to be a period of drying out in the basin.

Sierra Nevada Glaciations

Studies of glaciation of the eastern Sierra Nevada have been conducted by various researchers over the last 150 years. Blackwelder (1931) published the first comprehensive examination of alpine glaciation in the American West and laid the foundation for subsequent western glacial research. His work has been largely supported by later research (Gillespie et al., 1999; Clark et al., 2003). Blackwelder (1931) focused his study of glaciation in the Sierra Nevada's eastern slope, where he developed methods for distinguishing between deposits of different glacial stages. Among Blackwelder's important contributions to modern understanding of Sierra Nevada glacial history was his determination of a fourth glacial stage in addition to the three previously known. Blackwelder (1931) classified all four as stages and used local geographic names to differentiate them, rather than attempting to establish correlations with the stages recognized in the central United States. In addition, Blackwelder anticipated that evidence for a fifth stage would be discovered preserved near Mono Lake. That evidence was subsequently located and described by Sharp and Birman (1963).

Many researchers have refined the glacial history of the Sierra Nevada, but many aspects, especially the precise timing of glacial advances, remain unresolved. Recent results from new dating methods, including cosmogenic and surface-exposure dating, have led to revisions of the chronology (Fig. 7; Phillips et al., 1996; Clark et al., 2003). A persistent controversy involves the age of glacial deposits historically classified as Tahoe. The Tahoe glaciation, one of the four major glaciations in the Sierra Nevada, has generally been designated as occurring during MIS 6. In light of more precise dating methods and reassessment of stratigraphic correlations, some glacial deposits previously classified as relating to the Tahoe glaciation are now considered to be from a younger glacial advance, during MIS 3. Thus, the Tahoe glaciation during MIS 6 is referred to as the Tahoe I, and the later glaciation, occurring between approximately 50,000 and 42,000 years B.P., during MIS 3, is referred to as the Tahoe II (Fig. 7; Clark et al., 2003).

Dating Studies

Tephra Analyses

In the Lahontan Basin, tephra layers have proven to be valuable stratigraphic markers for mapping and correlating Quaternary lacustrine deposits. Analyses and correlations of these layers in recent decades have also been essential in terms of refining the chronologies of pluvial lake deposits (Morrison, 1991).

Davis (1978) devised a tephrochronology for the Lake Lahontan Basin and consequently revised the chronology and stratigraphy of Morrison (1964) and Morrison and Frye (1965). All but six of the tephra layers identified by Davis (1978) were erupted after 35,000 years ago, during the Late Pleistocene Sehoo highstand of Lake Lahontan and continuing into Holocene time. Of the tephra layers studied by Davis, seven were from Mt. Mazama, three from the Mono Basin, one from Mt. St. Helens, and two from different local vents northwest of Fallon, Nevada (Davis, 1978).

One tephra layer older than 35,000 years, the Wadsworth bed, was erupted during the Eetza highstand of Lake Lahontan (Davis, 1978). Recent studies on the Wadsworth tephra have determined the age to be between 200,000 and 150,000 years old (Berger, 1991). The type section of the Wadsworth bed in the Eetza Alloformation is at Wadsworth (Fig. 8), along the Truckee River just south of Pyramid Lake. According to Davis (1978), no source has been suggested for this layer and the only known occurrences of this tephra are at the type locality in Wadsworth (Fig. 8) and in Nixon, along the Truckee River approximately 20 km north of Wadsworth.

Davis' research changed the date of the oldest part of the Sehoo Alloformation to 35,000 years ago, almost 10,000 years earlier than the dates on samples of tufa obtained by Broecker and Kaufman (1965) and used by Morrison and Frye (1965). The revision moved the end of the Wyemaha to before 35,000 (Fig. 7; Davis, 1978). More recent revisions to the Lake Lahontan chronology indicate that evidence of

Sehoo lake cycles may be as old as 39,000 years (Reheis, 2003, written communication, Reheis et al., 2003).

The Rockland Ash, used by Morrison (1959) to define the base of the Eetza Alloformation, was not analyzed by Davis (1978). Distal deposits of this tephra, whose source is near the present Lassen Peak in northeastern California, have been found in much of California as far south as Bridgeport and Ventura and as far east as western Nevada and southern Idaho (Lanphere et al., 1999). New Ar-Ar dates and stratigraphic evidence from ocean cores indicate that the Rockland Ash is between 620,000 and 570,000 years old (Lanphere et al., 1999; Sarna-Wojcicki, 2000).

Soil Development

Researchers in the Lahontan Basin also have conducted several studies of the soils developed on Lake Lahontan sediments and older deposits. The Churchill Soil (Morrison, 1964) is developed on eolian sediment of the Wyemaha Alloformation, which overlies the Eetza Alloformation. The type locality for the Churchill Soil is in Churchill Valley, about 55 km northeast of Smith Valley. At that locality (Sec. 15, T18N, R30E), the soil and the underlying sand of the Wyemaha Alloformation occur below lacustrine sediments of the Sehoo Alloformation (Morrison, 1964). The soil also occurs at elevations between 1,194 m and 1,539 m in areas near the Lahontan Mountains (Morrison, 1964).

The type Churchill Soil has an oxidized B horizon up to approximately 46 cm thick, and an underlying calcic (B_k) horizon, typically between approximately 61 cm and 125 cm thick (Morrison, 1964). Morrison (1964) did not measure the pedogenic calcium carbonate content of the soil, but he noted the presence of calcium carbonate as mottles, streaks, and weak cement throughout the calcareous horizon (Morrison, 1964). Where preserved, the oxidized B horizon contains between 7 and 16 percent pedogenic clay; in general, less clay is present in the Churchill Soil than in an older underlying soil (Morrison, 1964).

The older, more strongly developed Cocoon Soil formed on the youngest gravels of the Paiute Alloformation and on older deposits, directly underlying the Eetza Alloformation (Morrison, 1964). First described near the Cocoon Mountains, approximately 20 km south of the Lahontan Mountains, the Cocoon Soil is also exposed along the Truckee and Humboldt rivers, and at Rye Patch Dam (Fig. 8). Morrison (1964) described the Cocoon Soil as having a prominent calcium carbonate or K horizon, up to almost 4 m thick, with alternating layers of higher and lower carbonate concentrations.

More recently, Adams and Wesnousky (1999) studied 36 soils formed on lacustrine beach barriers in the Lahontan Basin and seven soils older than latest Pleistocene age. The purpose of their study was to differentiate soils formed following the last Sehoo highstand, approximately 13,000 years ago, from those formed following the Eetza highstand, between 280,000 and 140,000 years ago (Adams and Wesnousky, 1999). These studies did not include any soils in Smith Valley.

Adams and Wesnousky compared soils formed on the Sehoo beach barriers at Jessup (Fig. 8) with soils at other locations (Adams and Wesnousky, 1999). Fifteen soil profiles were described in the Jessup area, thirteen at the Lahontan Mountains site, eight at the Hooten Wells site, and seven at pre-late Pleistocene deposits located at various sites within the Lahontan Basin (Fig. 8). In all basins except the Walker Lake subbasin, Adams and Wesnousky (1999) determined that both the prominent shoreline at 1,348 m and the soils formed in deposits associated with those shore features correspond to the most recent Sehoo highstand, approximately 12,000 years B.P., near the end of MIS 2).

In the Walker Lake subbasin, which does not include Smith Valley, the best preserved lacustrine landform is the Thorne Bar complex, located on the southeastern shore of Walker Lake (Fig. 8). This landform consists of preserved morphological features below 1,360 m, but above the shorelines at other sites, and interpreted as beach barriers by Reheis (1996). Soils formed on the deposits associated with the beach barriers display pedogenic carbonate accumulation characterized as Stage II, and are interpreted as being older than the Sehoo Alloformation (Adams and Wesnousky, 1999). In addition to the Walker Lake subbasin, the Hooten Wells site (Fig. 8) is the only other site studied by Adams and Wesnousky (1999) that is close to Smith Valley. At that location, Adams and Wesnousky (1999) interpreted the deposits to be latest Pleistocene, based on soil development correlative with that of the Sehoo Alloformation.

Previous Studies of Smith Valley

In the 1960s, John Hawley and others of the U.S. Soil Conservation Service made several field excursions to western Nevada, including to Smith Valley, on a reconnaissance investigation of argillic soil development (Hawley, 1969; Hawley, 2001, written communication). They conducted field reconnaissance of soil sites in Smith Valley and described soil profiles mainly of Holocene and Late Pleistocene age. Hawley and others described the soil formed on a gravel bar later identified by Mifflin and Wheat (1979) at Sec. 17, T13N, R24E (Fig. 8), which they estimated to be Pleistocene in age (Hawley, 1969). Hawley (1969) also noted well-rounded pebbles, horizontal stratification of clasts, and the presence of well stratified fine- to medium-grained sediment at the gravel bar.

Studies of the shorelines, deposits, and soils in Smith Valley by Mifflin and Wheat (1979) and Stewart and Dohrenwend (1984) indicated that a lake unconnected to contemporaneous Lake Lahontan occupied the valley during Pleistocene time. They suggested that shorelines and deposits of two highstands were preserved in Smith Valley. Mifflin and Wheat (1979) also suggested that this lake overflowed into neighboring Mason Valley before 35,000 years ago. The approximate timing of overflow was based on the estimated age of the soil profile formed on beach deposits (Mifflin and Wheat, 1979) and on post-lake stabilized dunes east of Artesia Lake (Hawley, 1969).

Stewart and Dohrenwend (1984) produced a geologic map of the Wellington 15-minute quadrangle, including Quaternary deposits and geomorphic features. Their accompanying descriptions of Quaternary deposits are general, concluding that the deposits consist of lacustrine-related gravel, silt, clay, and sand.

The Quaternary history of the Walker River, especially the West Walker River, is not well documented, and it is unclear exactly where the river was while Smith Valley was occupied by Lake Wellington. Although small terraces occur at elevations above the river's present entrance into Smith Valley, at Hoye Canyon, and at the base of the Wellington Hills, no fan exists at this locality or in neighboring Mason Valley. Mifflin and Wheat (1979) speculated that an earlier, higher stand of Lake Wellington, at approximately 1,539 m, resulted from an inferred stream capture of the East Walker River by the West Walker River due to the presence of an ice dam in the Eastern Sierra Nevada (Mifflin and Wheat, 1979). However, no conclusive evidence was documented for this earlier highstand.

METHODS

Field Methods

The field work for this study consisted of 1) description of sediment and measurement of stratigraphic sections, 2) collection of GPS data for shorelines, faults, and section localities, and 3) assessment of soil development at two localities and of pedogenic carbonate morphology at one additional location. In addition, a map of shorelines and faults was made using 1938 U.S. Department of Agriculture, Soil Conservation Service aerial photographs at a scale of 1:20,000 at the Aerial Photograph Library at the Nevada Bureau of Mines and Geology in Reno, Nevada, and was compiled onto a 1:62,500 topographic base map.

Stratigraphic sections were measured at the three localities selected based on elevation and geographic location, proximity to the 1,477-m strandlines and degree of exposure of the stratigraphy. Two sections were described using a 30-m measuring tape, and the third was measured using a Jacob's Staff. Sediment colors were determined using a Munsell Soil Color Chart (Munsell Color, 1992). Sections were excavated in some places until near-vertical faces were exposed, and where not excavated, the angle of the slope was measured to correctly derive the thickness of the units. All dips of units were determined with a Silva Ranger compass or a Brunton compass.

The third section was measured using a Jacob's Staff, primarily because the exposure is an almost vertical road cut. Because of colluvial deposition and erosion, the road cut does not expose sufficient portions of stratigraphy to describe the complete section. Where possible, a single unit was traced out along the road cut until a more complete exposure of that unit was located.

GPS and GIS Methods

The computer work for this project was done with ArcView GIS v.3.1 and v.3.2 and Spatial Analyst v.1.1 to model terrain in Smith Valley using 30-m Digital Elevation Models (DEMs), obtained from the GIS DataDepot (ThinkBurst Media, Inc., 2003). In addition, Global Positioning System (GPS) data were collected for this study using a Trimble Pro-XRS Differential GPS (DGPS) receiver and were converted to ArcView "shapefile" format using Trimble Pathfinder Office software. GPS data were collected from shorelines as well as coarse- and fine-grained lacustrine deposits identified from aerial photographs and field work as correlating to the 1,477-m highstand. These data were post-processed using the two closest base stations for which data were available: Mammoth Lakes, California, about 160 km south of Smith Valley, and Tonopah, Nevada, about 200 km southeast of Smith Valley.

Within ArcView, these data were projected to match the projection of the DEMs, as were shorelines mapped from aerial photographs, which were correlated across the valley. Where no GPS data were collected and where no shorelines were observed on air photos, shorelines were inferred from modern valley topography and elevations using the Artesia Lake, Smith, and Pine Nut Valley 7.5-minute quadrangle topographic maps. Although field examination of shorelines showed no obvious warping by Quaternary faulting, the possibility of deformation cannot be disregarded. The DEM data are defined by 30-m grid cells, each cell containing a single elevation representing the mean elevation within that 900 m^2 area. Slight warping would not be detectable due to the coarse nature of the data.

DEMs and ArcView shapefiles, including regional road and political boundary data, were also obtained from the

GIS DataDepot and from the University of Nevada, Reno, geospatial data web site (University of Nevada, Reno, 2003). Along with the GPS data obtained in the field for this project, these data were analyzed using ArcView GIS software to study the terrain as well as to reconstruct the lake at its last highstand.

The GPS data were collected from several locations where prominent shorelines of the 1,477-m highstand exist: the northwest corner of the valley, the gravel bar in the northeast corner of the valley, and the Nordyke Pass area. Additional GPS data were obtained for other features, including unconformities, locations of stratigraphic sections, and various geographic features, such as road intersections, which would assist in locating mapped features during analysis in ArcView GIS.

A Triangulated Irregular Network (TIN) was generated in ArcView from DEM data and used in conjuction with the Wellington 15-minute topograhic map as a base map for digitizing of shorelines from air photos because the topography appeared more realistic on the TIN than on the DEM. A TIN is an image representing surface features generated from irregularly spaced points (each with x and y coordinates and a z value) and breakline features (GIS

Lounge, 2003). A hillshade was then constructed using original DEM data and was used as the base map to better display the final geometric data for the lake. On the hillshade, the digitized shoreline data were combined with the shoreline polyline shapefiles. Using an ArcView script, these shorelines were interpolated between actual mapped segments to create one continuous polyline approximation of the highest water level at 1,477 m. Using another ArcView script, this approximated polyline, designated "Higherstand," was converted to a polygon representing surface area of the lake. The "Lowerstand" for the lake was constructed by reducing the maximum depth by 12 m and creating a highstand at 1,465 m. This change drops the lake level below the elevation of a broad topographic high and significantly reduces the surface area. This "Lowerstand" was not used as the model for the lake at the final highstand, but calculations for volume were made using the smaller surface area.

Using an ArcView script, the polygon was "clipped" onto the underlying DEM grid file, creating a new grid file. The surface elevation of Artesia Lake was used as the bottom elevation of Lake Wellington as no depth information is available for Artesia Lake. The surface elevation of Artesia Lake from the DEM data was adjusted to match the topographic map elevation of 1,385 m. The 1,477-m Lake Wellington shoreline elevation was not adjusted because those data were mapped using 7.5-minute topographic maps as base maps. The resulting grid file represents the difference in elevation between the surface of the modeled lake and the elevations of the surface of Artesia Lake and modern valley floor, creating an approximate bathymetry of the lake. The resolution of the grid file showing lake bathymetry is the same as the original DEM file: 30 m by 30 m. Values for maximum elevation, area, and perimeter of this lake level were obtained directly from ArcView tables of the new bathymetric grid file. These ArcView tables of the bathymetry data were exported to Excel, where calculations for average depth and approximate volumes were made. The average elevation of the lake bottom was determined and this value was subtracted from the maximum elevation of the lake surface to approximate an average depth for the lake. Surface area was calculated using both an ArcView script and a planimeter. The average overall depth of the highstand was multiplied by the surface area to approximate a minimum value for the maximum volume of the lake. The accuracy of the estimates for volume and accuracy of the estimates for volume and surface area is influenced by inherent errors in the DEM data sets.

Laboratory and Analytical Methods

Tephra samples were prepared for Electron Microprobe analysis and described petrographically in the Tephrochronology Laboratory at the U.S. Geological Survey in Menlo Park. The samples were wet sieved in plastic sieves with nylon screens of 100, 200, and 325 mesh, corresponding to approximately 140, 80, and 30 μm, and then treated with HCL and HF to remove authigenic carbonates and surficial coatings. The samples were placed in an ultrasonic vibrator and then sieved again in water. After the samples were dried under a heat lamp, glass and phenocrysts were separated using a methylene iodide-acetone solution and a magnetic separator (Sarna-Wojcicki et al., 1987).

Each glass sample was analyzed by James Walker at the USGS using a JEOL 8900 Electron Microprobe. The microprobe analyzes each glass sample for the following nine elements: silicon, aluminum, iron, magnesium, manganese, calcium, titanium, sodium, and potassium, determined from previous studies to be useful in characterization and correlation of tephra layers (Sarna-Wojcicki et al., 1987). Elements used to correlate tephra are those for which: 1) the concentration can be measured accurately; 2) concentrations differ in tephra of demonstratively different ages; and 3) distribution is fairly even within the glass from a single tephra layer (Sarna-Wojcicki et al., 1984). In addition, Sarna-Wojcicki et al. (1984) used those elements for which analytical error is very low. From the electron microprobe analysis results, concentrations of calcium and sodium are most useful because, unlike other elements, they are less affected by diagenetic processes, their concentrations tend to be more sensitive to differing volcanic chemistry, and concentrations can vary in different tephra layers erupted from the same volcanic source more than those of the other elements (Sarna-Wojcicki et al., 1984).

From the electron microprobe results, Andrei Sarna-Wojcicki used SIMANAL (Sarna-Wojcicki et al., 1987) and RATIONAL (standard deviation of ratios of element concentrations; Sarna-Wojcicki et al., 1987) to determine chemical composition matches. SIMANAL is given by the following equation:

$d(A,B) = \Sigma R_i \;/n$

where $d(A,B)$ = similarity coefficient for comparison between sample **A** and sample **B**

i = element number

n = number of elements

R_i = X_iA/X_iB if $X_iB > X_iA$; otherwise X_iB/X_iA

X_iA = concentration of element **i** in sample **A**

X_iB = concentration of element **i** in sample **B**

RATIONAL is given by the following equation:

$\Sigma(A,B)$ = standard deviation of $r(A,B)$

where

$r(A,B)$ = $\Sigma R_i/n$

and

$r(A,B)$ = average ratio for comparison between sample **A** and sample **B**

i = element number

n = number of elements

R_i = X_iA/X_iB, regardless of which X_i is greater

X_iA = concentration of element **i** in sample **A**

X_iB = concentration of element **i** in sample **B**

EVIDENCE FOR LAKE WELLINGTON

Study of aerial photographs and field mapping of geomorphic features in Smith Valley for this project revealed prominent shorelines, cut into alluvium and bedrock, approximately correlated to a high lake-stand at 1,477 m. The map of features constructed on the USGS Wellington 15-minute quadrangle (Plate 1) was used for field work, both to locate exposures of lacustrine deposits that could be correlated to the shorelines and as a reference for GPS mapping of the shoreline features.

Shorelines

Four areas at or below 1,477 m with particularly prominent erosional shore features are Localities A and C, in the northern part of Smith Valley, along the eastern margin of the valley (Locality F) and in the area around Nordyke Pass (Locality B), about 10 km north-northeast of the town of Smith (Fig. 9; Plate 1). Shorelines were not observed south of the West Walker River, because deposits from Desert Creek bury evidence of Lake Wellington. On the western margin of the valley, scarps related to the Smith Valley fault zone are abundant, and shorelines there were

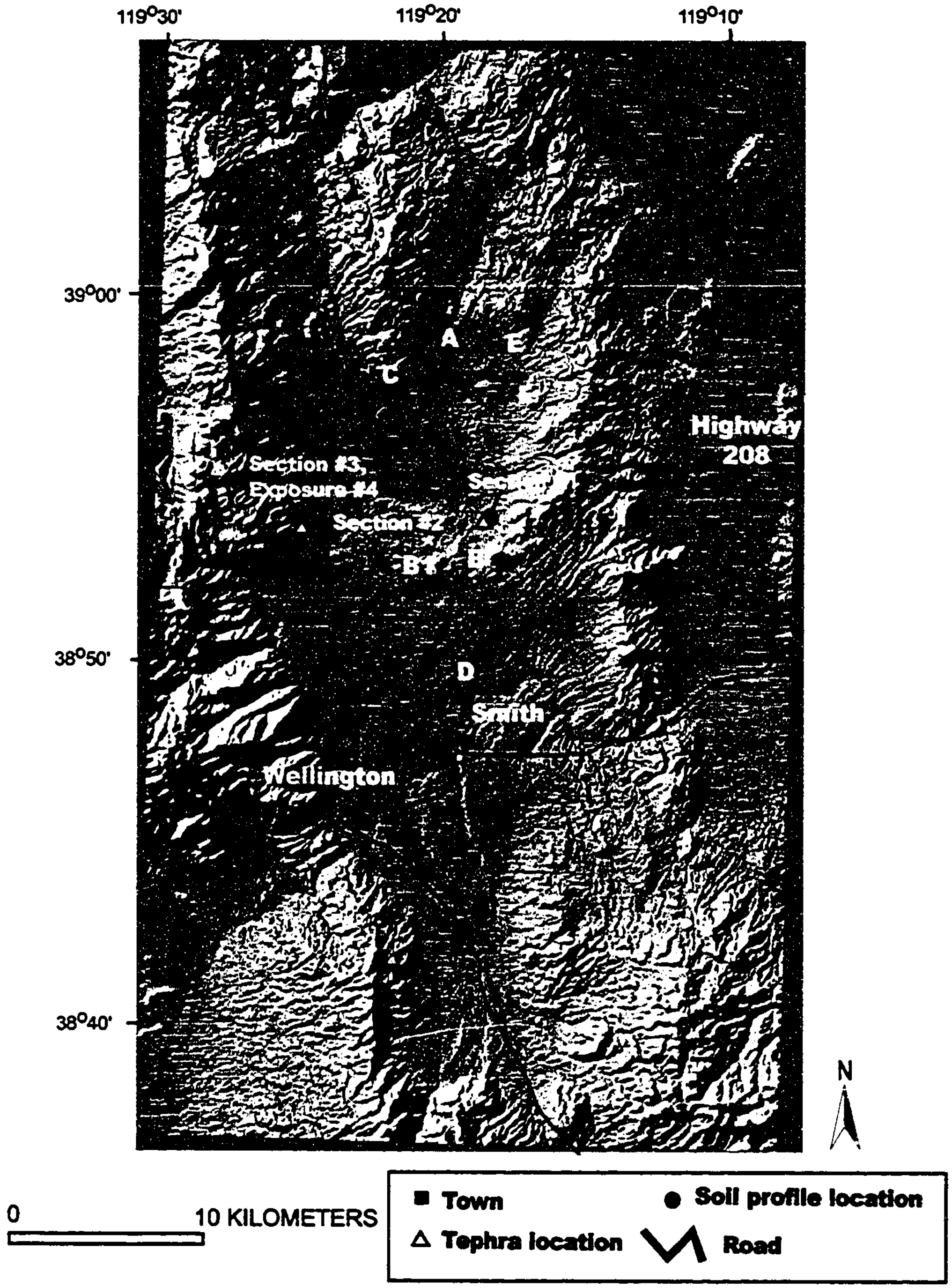
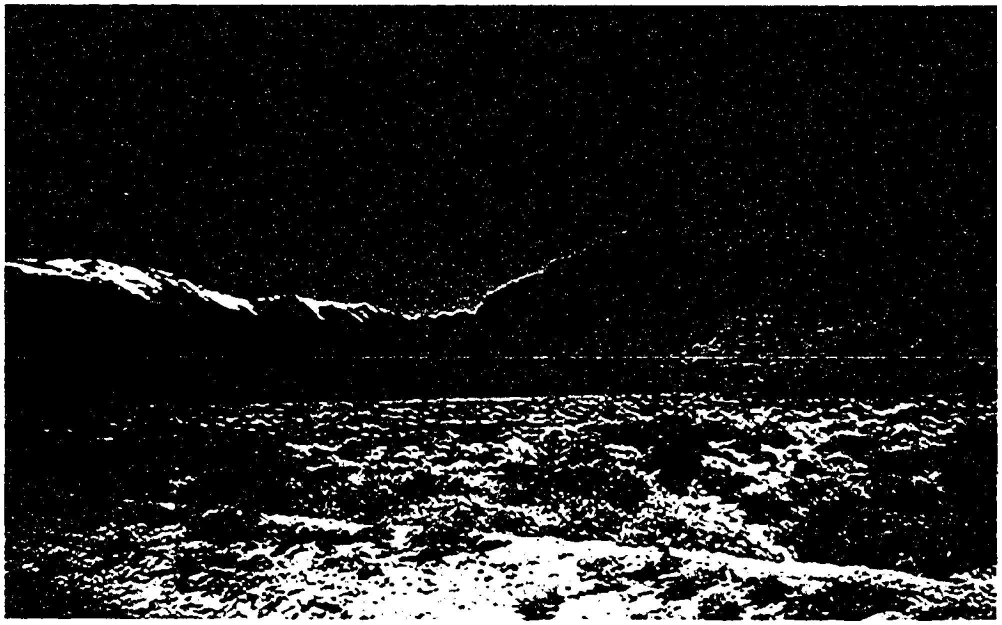


Figure 9. DEM shaded relief map showing localities studied in the course of this project.

difficult to confirm in the field. Along most of the length of the West Walker River in Smith Valley, shorelines and lake sediment are generally absent. The origins of small terraces present at Hoye Canyon and at the base of the Wellington Hills are ambiguous, and they were not included in this study.

The northern valley margin, along the south end of the Buckskin Range, features a conspicuous wave-cut cliff in bedrock, as well as an adjacent bedrock knob showing at least one obvious strandline, previously noted by Mifflin and Wheat (1979) and Stewart and Dohrenwend (1984) and shown here in Fig. 10 and Plate 1. To the east of the wave-cut cliff, at 1,477 m, lies a gravel bar, inferred by Mifflin and Wheat (1979) to be the best preserved constructional lacustrine feature in the valley (Fig. 11; Plate 1). Another constructional feature related to the lake is an alluvium-capped gravel deposit at Locality D (Figs. 9, 12, 13; Plate 1). The deposit is interpreted as a beach and located at approximately 1,477 m along Hudson Way, less than 1 km northeast of the town of Smith. There is no clear deposit produced by a Lake Wellington outflow event in Mason Valley. However, elevated gravel deposits



A

B

Figure 10. Two views of wave-cut cliff (arrows) at the southern end of the Buckskin Range in the northern part of Smith Valley (Locality C, Fig 9; see Fig. 3 for location of photos). **A**, View looking northwest; and **B**, View looking northeast. Cliff is about 95 m high.

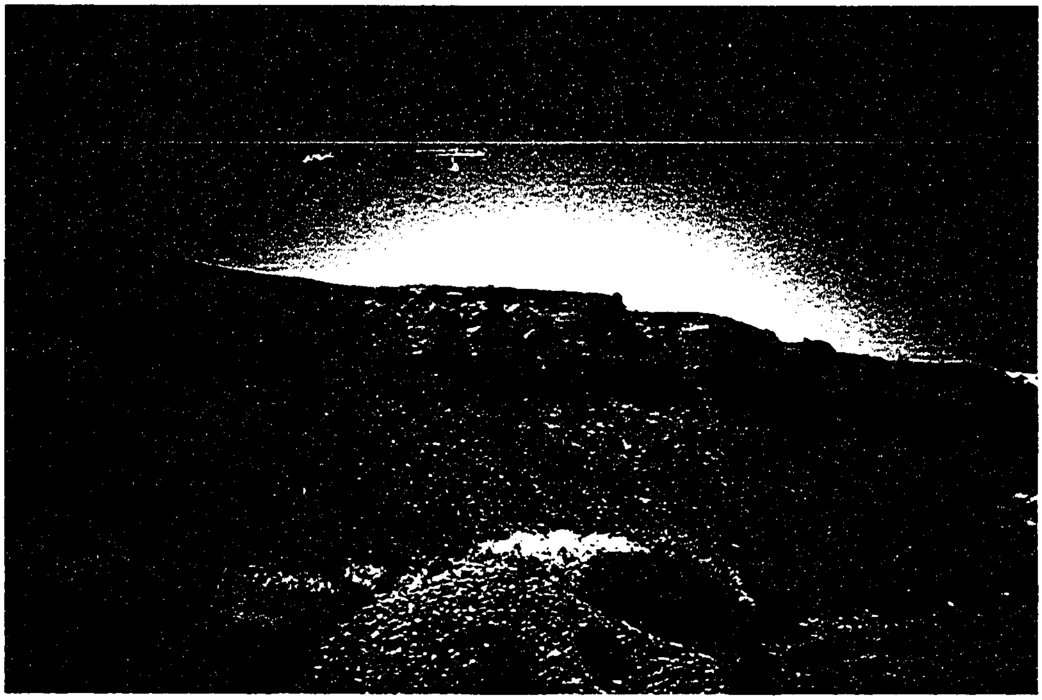


Figure 11. View southwest of gravel layers exposed at Locality A (Fig. 9; see Fig. 3 for location of photo), the gravel bar in the northeast part of Smith Valley. Exposure is about 10 m high.

Figure 12. View east toward Locality D (Fig. 9; Plate 1; see Fig. 3 for location of photo), along Hudson Way, just north of the West Walker River. Fine-grained Tertiary deposits are capped by Quaternary sediment (arrows), related to Lake Wellington and located at about 1477 m. Location of Figure 13 is behind the hill at the right edge of the photo.

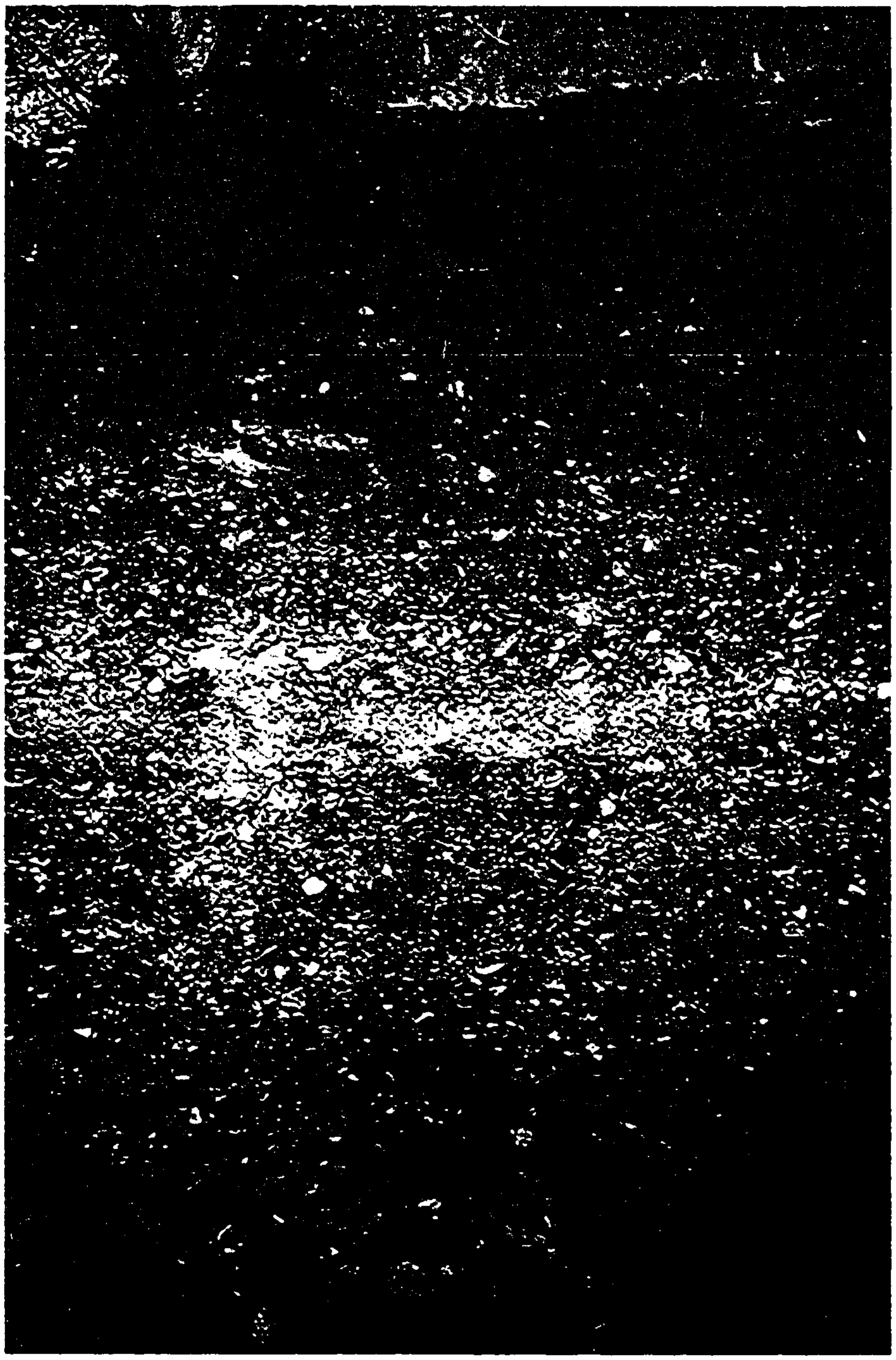


Figure 13. Quaternary gravel deposit capped by finer grained alluvium at Locality D (Fig.9; Plate 1; see Fig. 3 for location of photo) along Hudson Way at about 1,477 m. Strongly developed carbonate horizon is visible in the center of the photograph. Hammer head is 18 cm long.

less than 6 m above the level of the modern West Walker River are present north and south of the river where it enters Mason Valley from Wilson Canyon.

The area around Nordyke Pass (Figs. 14, 15) includes a group of bedrock hills that project westward into the center of Smith Valley. These hills probably formed a peninsula, creating a partially sheltered bay or lagoon to the north when the lake was at its highstand. In addition, a prominent fault scarp in bedrock above 1,477 m at Locality B1 (Fig. 16) west of Nordyke Pass appears to have been modified by wave action (Fig. 16).

In the northeast corner of the valley, at Locality E (Fig. 9; Plate 1), prominent benches are cut into the bedrock above 1,477 m, at approximately 1,539 m, the level of Mifflin and Wheat's (1979) postulated higher stand of Lake Wellington. Field reconnaissance of the area for this project corroborated the existence of these benches, but they can not be confirmed to be shorelines, because no lacustrine deposits are present beneath the benches. No other evidence of the postulated 1,538-m highstand (Mifflin and Wheat, 1979) was observed during the course of this study.

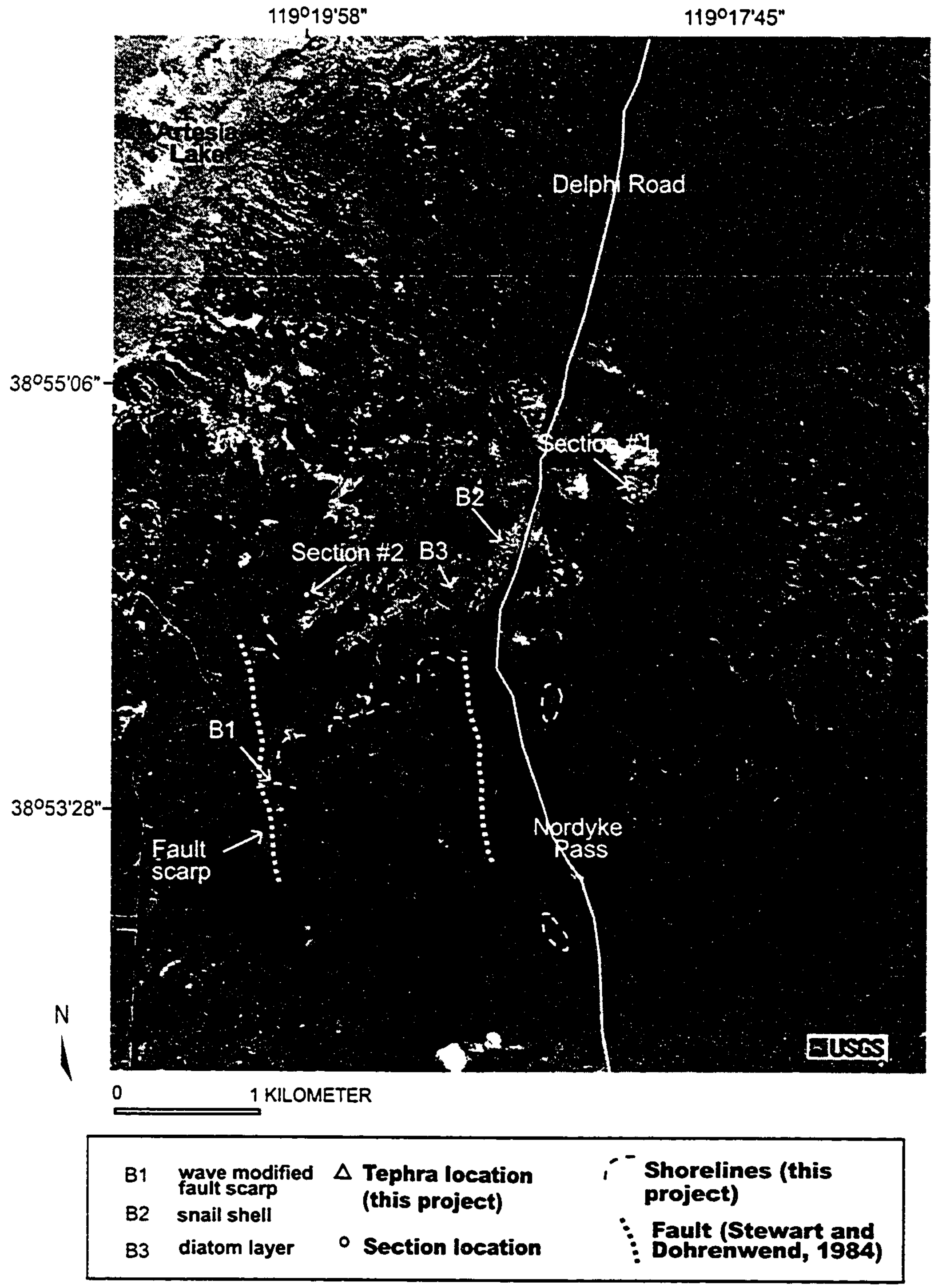
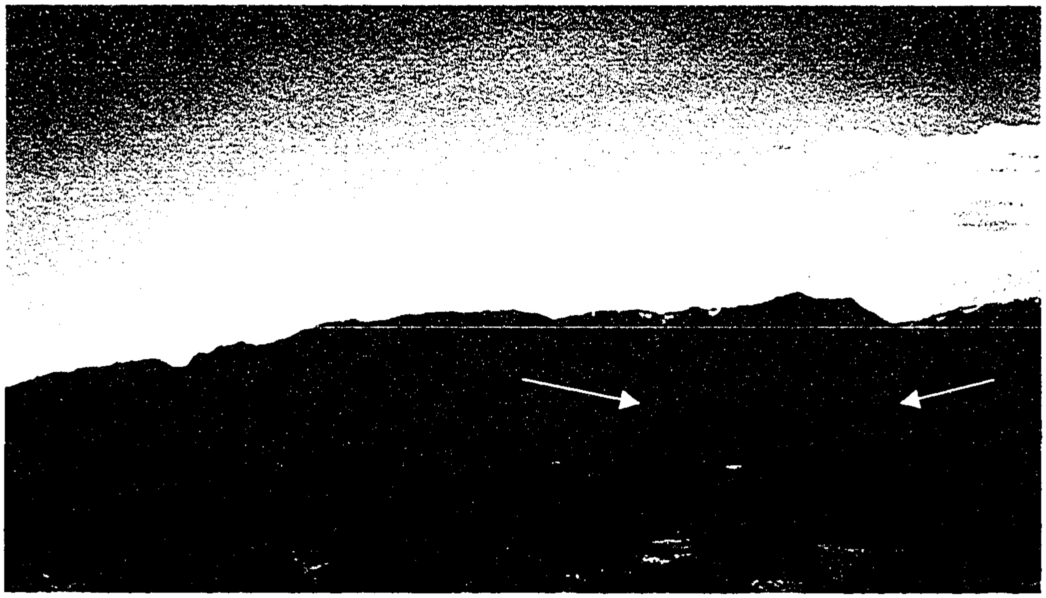


Figure 14. USGS Digital Orthophotoquad showing the Nordyke Pass area, downloaded from Microsoft TerraServer-USA, at http://www.terraserverusa.com/. Photo taken in 1994.



A

B

Figure 15. Views of shorelines at Locality B (Fig. 9; see Fig. 3 for location of photos), the area at Nordyke Pass. **A**, view to southwest toward shorelines (arrows); and **B**, view to south.

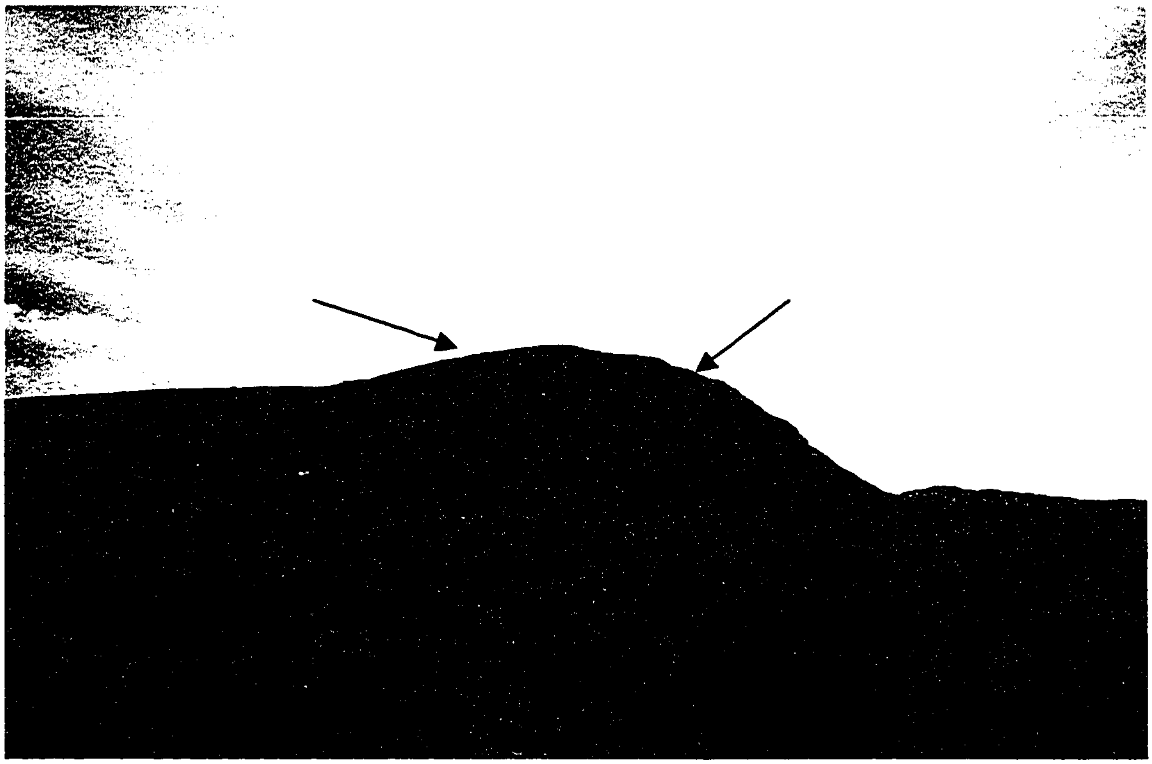


Figure 16. View looking south to wave-cut bench (left arrow) inset into existing fault scarp (right arrow) at Locality B1 (Figs. 9, 14). The wave-cut bench lies above 1477 m. The fault scarp is about 73 m high.

Lake Sediment

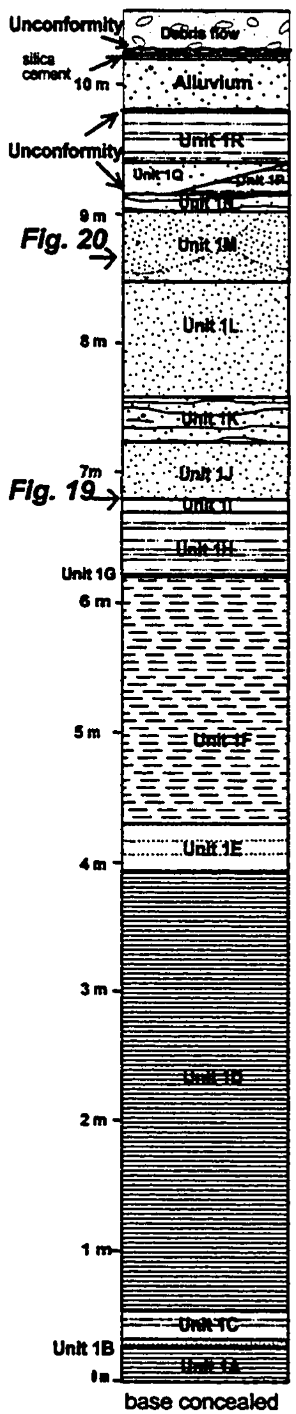
North of about 38° 50′ N and south of about 39° 00′ N (Plate 1), areas of Smith Valley below 1,477 m are covered primarily with deposits of massive and laminated silt and clay, and by minor fine to medium sand (Stewart and Dohrenwend, 1984). Some exposures of fine to medium sand were also observed at or less than a few meters below 1,477 m, and a majority of these deposits show either crossbedding or indistinct horizontal lamination.

In general, exposures associated with the 1,477-m-highstand are located along the valley margins. The deposits range in thickness from less than 1 m to more than 6 m. The three measured sections (Fig. 9; Plate 1) are well exposed, fairly thick, contain discernible stratigraphy, and are associated with the 1,477 m-highstand by their elevations and proximity to mapped shorelines. Sections #1, #2, and #3 are fine-grained exposures and appear to be typical of the deposits of Lake Wellington in grain size and the presence of interbeds of fine to medium sand. Layers with indistinct lamination about 1 mm thick in the clay, and cross-lamination at a scale of a few millimeters in the silt and sand are the only stratification in these exposures. Exposure #4 is located near the topmost unit of Section #3, and is probably stratigraphically out of place because of faulting along the adjacent Smith Valley fault zone. Therefore, it was considered separately from Section #3.

Section #1 (Figs. 14, 17, 18, 19, 20), measured east of Nordyke Pass, is mostly clay and silt with interbeds of fine to medium sand. The section appears to coarsen upward. Section #1 contains a 1.5-cm-thick tephra layer (Unit 1G; Fig. 18) located between layers of clay and silt. The tephra layer is about 220 cm below cross-bedded sand of Unit 1M and approximately 250 cm below the poorly sorted pebbly sand of units that overlie Unit 1N (Fig. 18). This section also contains at least one distinct layer of fossilized plants within a sequence of silt and clay (Unit 1I; Fig. 18). No similar layer was noted in any of the other three sections.

Section #1 is much thicker than the other sections and likely contains a more complete record of deposition (Fig. 18). The section is capped by about 0.25 m of poorly sorted gravel containing boulders up to almost 1 m along their long axes. This deposit is part of the alluvial deposit at the top of the section and is interpreted as a debris flow. Its relative resistance to erosion accounts

Figure 17. View looking east to Section #1 (Fig. 9; See Fig. 3 for location of photo), northeast of Nordyke Pass (Fig. 14).



Debris flow yellowish brown to brownish yellow (10YR,5/8 near top; 10YR, 6/8, 6/6 rest of unit), poorly-sorted, ~25% gravel, boulders up to 1 m, base of unit is pinkish white/pinkish gray (7.5YR,8/2, 7/2), silica cement, less than 10% gravel

Alluvium coarse sand and silt, brownish yellow/yellow (10YR,6/6, 7/6), poorly-sorted, < 10% gravel, decreasing upsection, indurated,

Unit 1R silt and clay, pale yellow (2.5Y,7/3), <<5 % gravel, pedogenic carbonate nodules and veins

Unit 1Q sand, pale yellow/light yellowish brown, (2.5Y,7/4, 6/4), moderately sorted, pebble layer, less carbonate than Unit 1R

Unit 1P silt and sand, olive yellow, (2.5Y,6/6), poorly sorted

Unit 1N silt and fine sand, pale yellow, (2.5Y,7/4) moderately sorted, unlaminated, carbonized plants at base of unit, pedogenic carbonate

Unit 1M fine sand, pale yellow (2.5Y,8/3, 7/3) well-sorted, weakly cemented, 2 to 4 cm cross-lamination dipping towards lake center, lithics, quartz, mica, carbonized plants, top 10 cm coarser

Unit 1L silt with more fine sand than unit 1K, pale yellow (2.5Y,8/3, 7/3), possible burrows, carbonized and modern plant roots

Unit 1K silt with some fine sand, pale yellow (2.5Y,8/3,7/3)

Unit 1J fine sand, well-sorted, light gray (2.5Y 7/2), more fines upsection, modern and possible older plant roots and debris

Unit 1I silt and fine sand, light gray/pale yellow (2.5Y7/2, 7/3), subhorizontal lamination, carbonized plants

Unit 1H silt with possible reworked ash, pale yellow (2.5Y,7/3), fairly well consolidated, coarsens above 7.5 cm

Unit 1G tephra, wispy, thin, but continuous, white to gray, 1.5 cm thick

Unit 1F clay, tightly packed, horizontal lamination

Unit 1E sand, light yellowish brown (2.5Y,6/3, 6/4 (dry)), possible very faint cross-lamination,loose to moderately compacted

Unit 1D clayey silt, pale yellow, (2.5Y, 7/3 (dry)) no visible lamination, tightly compacted

Unit 1C silt, pale yellow (2.5Y,7/3 (dry)), faint thin, horizontal lamination, moderately sorted, loosely to moderately compacted

Unit 1B1 and Unit 1B2 two distinct layers of sand; fining upsection from lower layer 1B1(1.75 cm thick) medium to fine sand light gray (2.5Y,7/2 (dry)) to upper layer 1B2 (2.75 cm thick) fine sand, pale yellow (2.5Y, 7/4 (dry)), moderately to well-sorted, subrounded to rounded grains

Unit 1A silt and clay, light yellowish brown (2.5Y,6/4),faint lamination, well-sorted, moderately to tightly compacted, iron stained, mica, quartz, pyrite

Figure 18. Stratigraphy at Section #1 (Fig. 9). All colors from Munsell Color (1992) for moist sediment, unless otherwise specified.

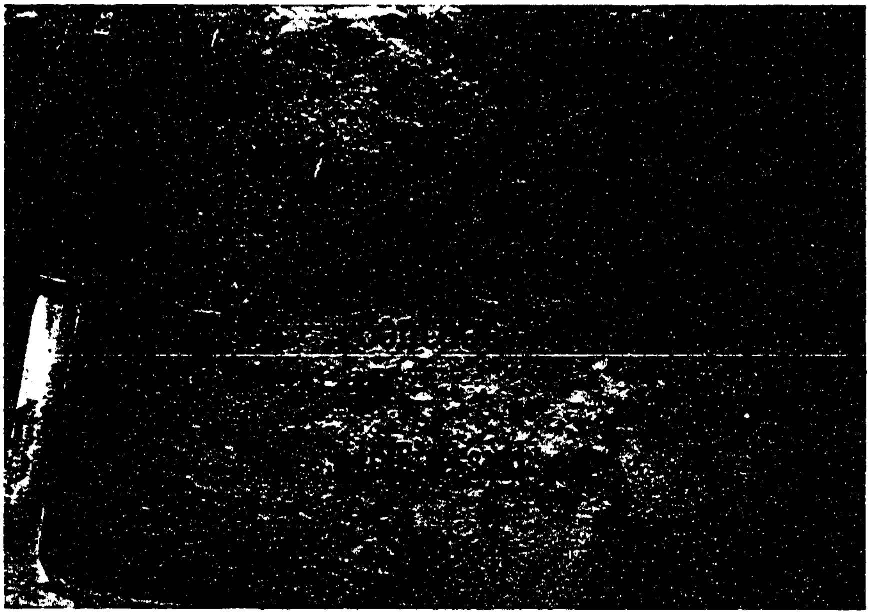


Figure 19. Contact between fine sand of Unit 1J (above) and silt and fine sand of Unit 1I (below) in Section #1, east of Locality B (Fig. 9). See Fig. 18 for location of photograph within section. Metal part of rock hammer shaft is 10.5 cm long.

Figure 20. Faint cross-bedding in fine sand of Unit 1M in Section #1 (Figs. 3, 9). See Fig. 18 for location of photograph within section. Length of mirror part of Silva compass is 7.5 cm.

for the preservation of the sedimentary deposits beneath it. The debris flow also appears to have eroded the topmost portion of the post-lacustrine subaerial deposit above Unit 1R (Fig. 18) as well as upper soil horizons.

Section #2 (Figs.9, 21, 22) is generally fine-grained sediment, ranging from silt at the base to fine sand and silt, silty clay, and silt at the top. The silt and clay layers are generally massive, with faint lamination at a scale of about 1 mm. The silt and fine sand also lack bedding, except for faint cross-lamination at the scale of a few millimeters. The exposure is capped by very well sorted fine-grained sand, mapped as eolian sand by Stewart and Dohrenwend (1984), modern alluvium derived from the bedrock highs to the south, and a thin veneer of subrounded fine gravel and coarse sand. Like Section #1, Section #2 contains layers of fine sand, some showing cross-lamination at a scale of a few millimeters, near or at the top of the lacustrine sequence (Fig. 22).

Section #3 and Exposure #4 (Figs. 9, 23, 24, 25, 26) were originally observed by Marith Reheis of the U.S. Geological Survey (USGS), who noted that lacustrine sediment appeared to be offset by a fault (Fig. 23) and

Figure 21. View looking southwest to Section #2 (arrow; Figs. 9, 14; see Fig. 3 for location of photo), northeast of Nordyke Pass (Locality B; Figs. 9, 14; Plate 1). Shoreline at 1477 m located almost at center of photo (horizontal arrow) and the Pine Nut Mountains (Fig. 1; Plate 1) are in the distance.

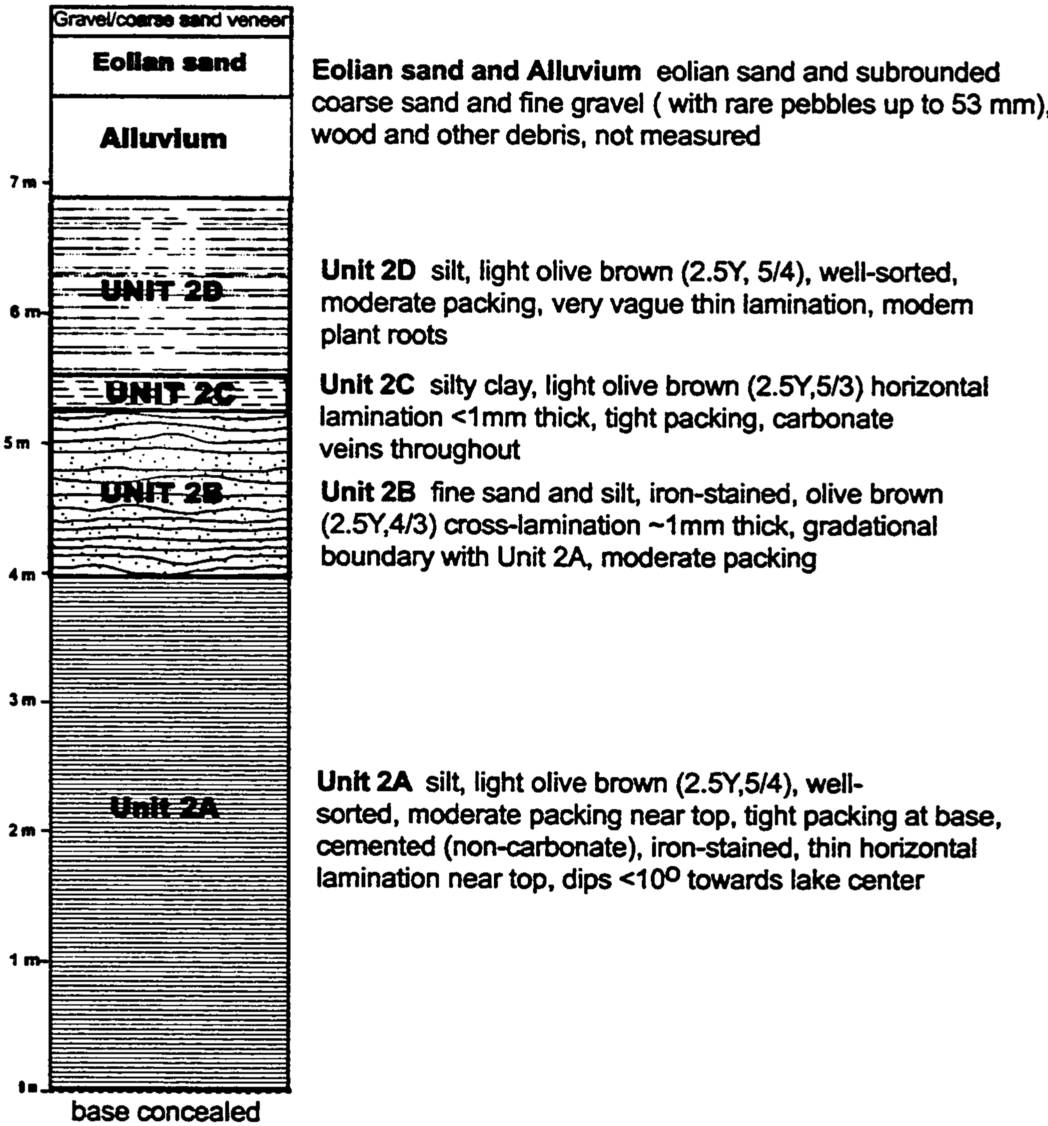


Figure 22. Stratigraphy at Section #2 (see Fig. 9 for location). All colors for moist sediment, unless otherwise specified.

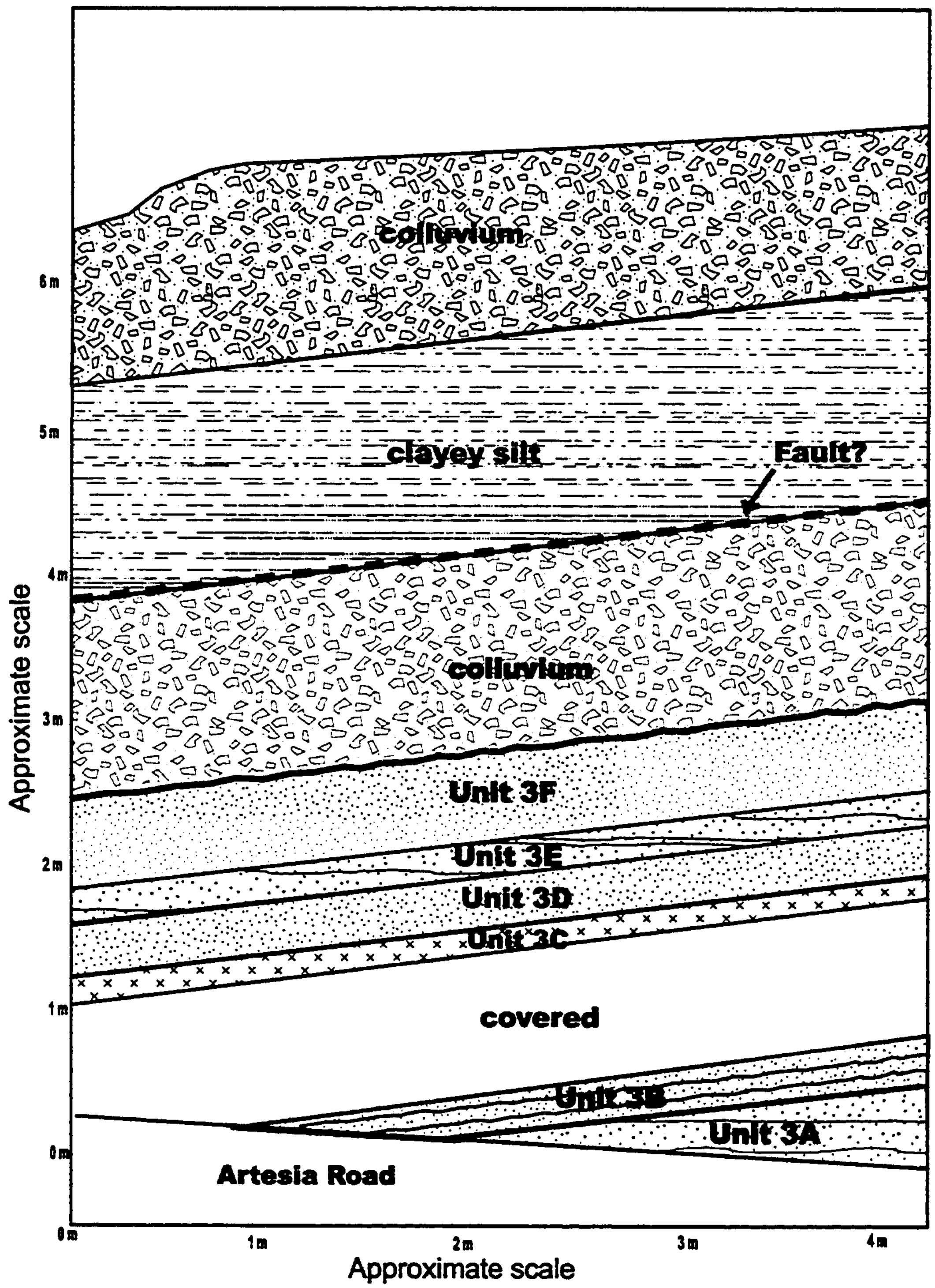
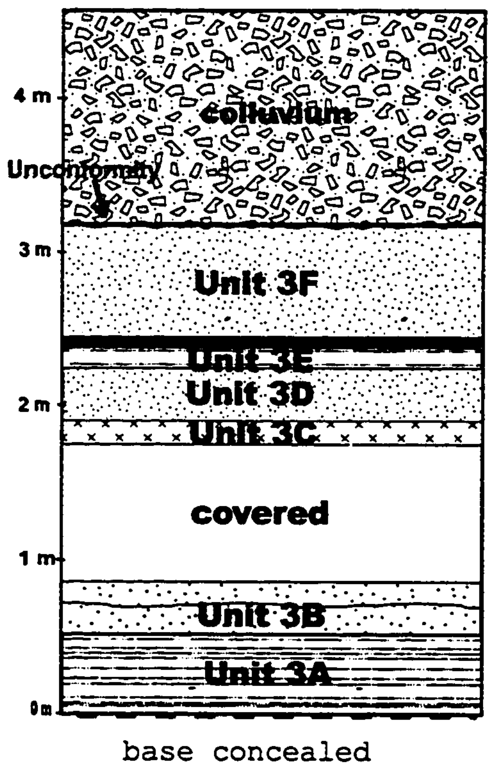


Figure 23. Schematic diagram of east-facing roadcut exposure at Section #3 (Fig. 9) along Artesia Road. Roadcut is a little more than 6 m high.



Colluvium fine sand and silt matrix, clasts up to 30 cm, poorly sorted, primarily granitic, meta-granitic, gneissic clasts

Unit 3F fine to very fine sand, lamination, iron stained along lamination, dark layer with roots and limonite at base and 23 cm from top of unit

Unit 3E silt and very fine sand, pale yellow, 2.5Y 7/3, lamination from <1mm to 3mm, gradational over 4 to 5 cm with Unit 3D, possible organic matter (black layer) 37 mm from base

Unit 3D very fine sand,olive yellow, 5Y 6/6, no apparent sedimentary structures, mica, bitotie, quartz, maybe some reworked ash?

Unit 3C volcanic ash, reworked, light gray fine sand, exposed a little above the covered area

Unit 3B interbedded silt and sand, with some clay, lamination at <3 mm, sand shows cross-lamination,plant roots, iron-stained

Unit 3A silt and fine sand, pale yellow, 2.5Y 7/4, at bottom:laminated with heavy iron staining approximately parallel to lamination, lamination becomes less distinct upsection, moderately indurated

Figure 24. Stratigraphy at Section #3 (see Fig. 9 for location). All colors for moist sediment, unless otherwise specified.

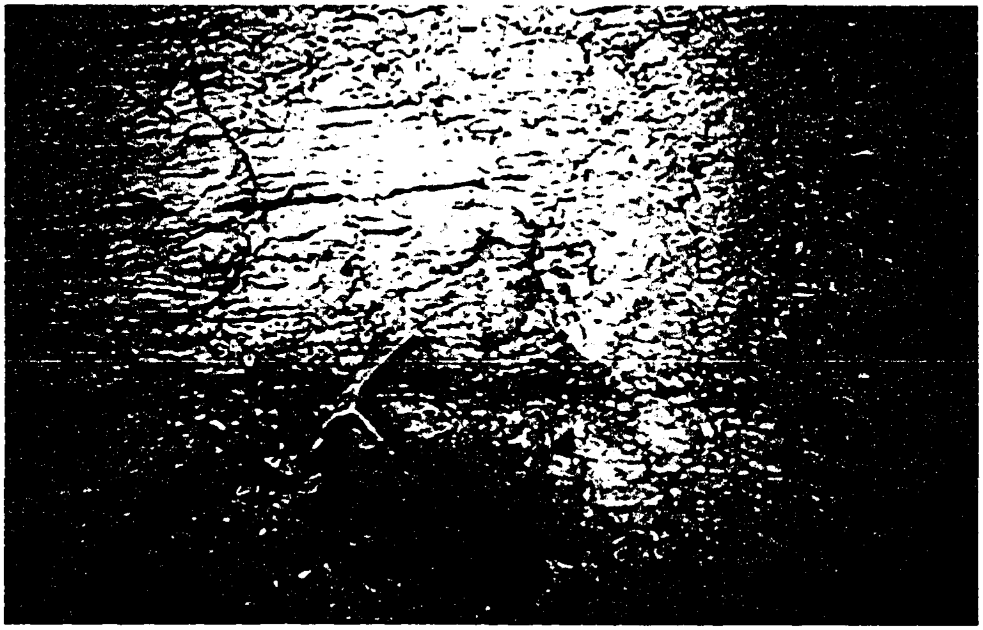


Figure 25. Section #3 (Fig. 9) showing iron-stained laminated silt and fine sand of Unit 3A (Fig. 24). Hammer head is 18 cm long.

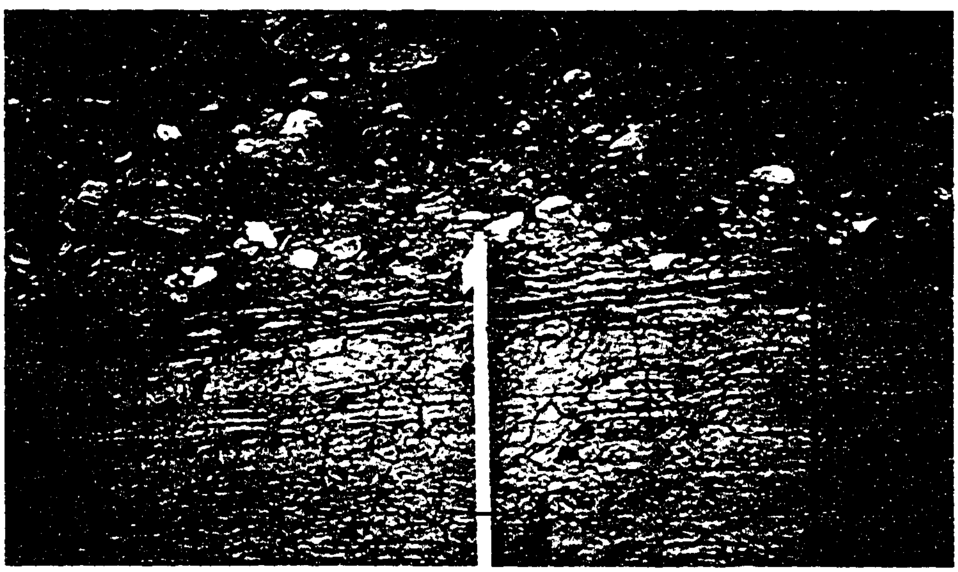


Figure 26. Section #3 (Fig. 9) showing coarse-grained, poorly sorted colluvium unconformably overlying the fine-grained, well-sorted lacustrine sediment of Unit 3F (Fig.24).

that a tephra layer is located below the faulted section (Reheis, M., USGS, 1998, oral communication).

The trace of the Smith Valley fault zone as mapped by dePolo et al. (1997), is located between the road cut and the range front of the Pine Nut Mountains, and fault scarps can be seen adjacent to Section #3. Although no offset was evident within Section #3, a deposit of clayey silt is exposed less than two meters upslope from Unit 3F (Fig. 23), and colluvium is present between Unit 3F and the clayey silt upslope (Fig. 23). Because of the uncertainty of the relationship between the clayey silt and Unit 3F, the colluvium and clayey silt were not included in Section #3. Also in Section #3, a 13-cm-thick tephra layer (Unit 3C, Fig. 24) lies 150 cm below the top of Unit 3F (Fig. 24).

Two additional exposures (Localities A and D, Figs. 9, 27, 28; Plate 1) were not measured but were described. Both contain moderately well to well sorted gravel and sand, showing both imbrication (Figs. 27, 28) and cross bedding, and are interpreted as beach deposits. The clasts in both deposits are metamorphic, granitic, and volcanic rocks locally derived from the surrounding mountain ranges.

Figure 27. Imbricated gravel layers at Locality A (Fig. 9; see Fig. 3 for location of photo). Hammer head is 18 cm long.

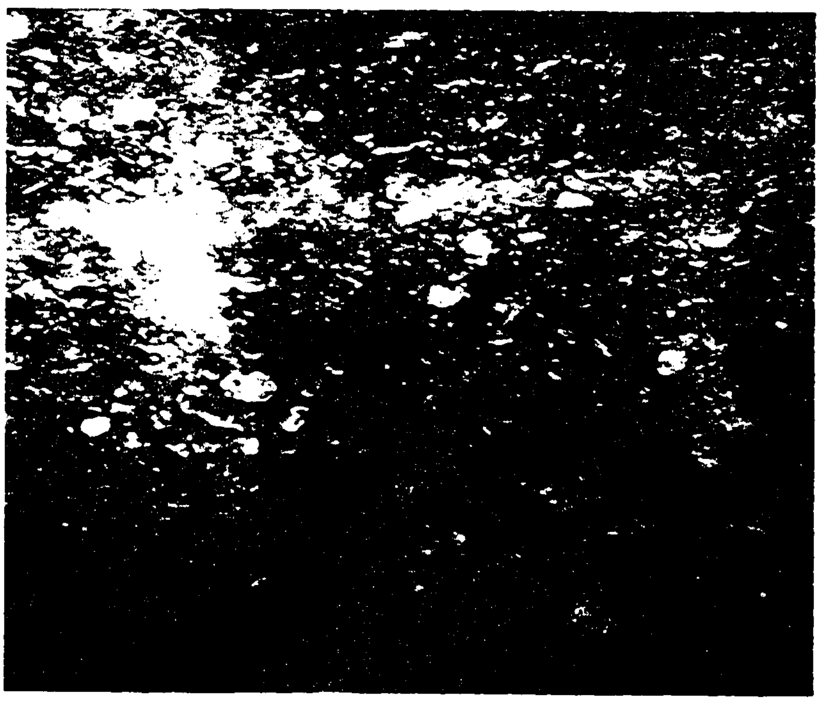


Figure 28. Exposure of horizontally layered medium pebble gravel at Locality D (Fig. 9; see Fig. 3 for location of photo). Hammer head is 18 cm long.

Though most clasts are around 5 cm in size (Figs. 27, 28), some at Locality D are as large as 20 cm, and individual layers are well sorted in both deposits, with little fine matrix.

The clasts in all layers at Localities A and D show imbrication, and cross-bedding of a few millimeters is common in layers primarily of coarse sand. Possible trough cross-bedding of a few centimeters can be seen in layers of coarse to medium sand in the deposits at Locality A. Although the localities do not contain any interbedded fine-grained lacustrine sediment and cannot be correlated to the measured sections, they do provide evidence of deposition at or near the lake shore. Deposits at Locality D are located less than 1 km north of the West Walker River and about 26 m above the West Walker River. Because horizontal layering suggests imbrication, the gravel at Locality D is interpreted as lacustrine, related to Lake Wellington, rather than to the West Walker River.

Lacustrine Fossils

Snails

In the Nordyke Pass area, at the center of sec. 17, T12N, R23E (Figs. 9, 14; Locality B2), one complete snail shell and three shell fragments were discovered in float. These shells were located on fine-grained lacustrine units located topographically below Sections #1 and #2 at approximately 1,445 m, 60 m above Artesia Lake.

The shells were tentatively identified as freshwater snails belonging to the Family Planorbidae and Genus *Helisoma* using Boardman et al. (1987). This particular lacustrine snail family is widespread in lakes and large streams throughout the North American continent, and the Genus *Helisoma* is currently extant in Nevada, with fossils dating back to the Pliocene (Call, 1884; Taylor, 1966). Because no shells were found in situ and no dating techniques were applied to the shells to determine an age, the presence of such shells serves only to support the former existence of a lake at the level where they were found.

Diatoms

Three sediment samples originally collected in the process of looking for tephra were determined to contain rare diatoms (Fig. 29) along with mineral grains. The first sediment sample, AL9811-43, was collected at Locality B3 (Fig. 14), in a gully west of Nordyke Pass (Figs. 9,

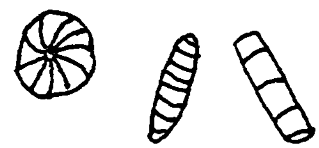
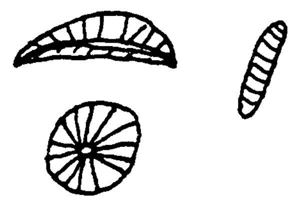
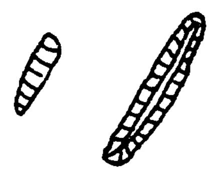
Sample Number	Location	Unit Number	Diatoms
AL9811-43	Locality B3, gully west of Nordyke Pass	Not in measured section	
99PNV728-162	Section #3	Unit 3B	
99AL615-134	Section #2	Unit 2B	

Figure 29. Sketches of diatoms in three lacustrine sediment samples. Magnification is 10X.

14), from a layer of grayish sediment. This sample contained at least three different types of diatoms (Fig. 29), differentiated by morphology, in addition to mineral grains of mostly quartz. This layer was not correlated to any layers either in Section #2 farther to the west or in Section #1, to the east of Locality B3 (Fig. 14).

The second sample, 99PNV728-162, was collected from Section #3, in Unit 3B, a layer with interbeds of silt and fine sand. Like sample AL9811-43, this sample also contained at least three different types of diatoms (Fig. 29) as well as mineral grains of quartz, biotite, and feldspar. The third sample, 99AL615-134, was collected from Section #2, in Unit 2B (Fig. 22). This sample contained fewer diatoms and less diversity than the other two samples (Fig. 29). Although these samples were examined and described using a binocular microscope, identification of the types of diatoms was beyond the scope of this project.

AGE OF DEPOSITS

Tephra Analyses

Two tephra layers located in lake sediment associated with the final highstand of Lake Wellington were chemically analyzed and correlated to tephra of known age. The tephra ages better refine the timing of the final highstand, which was estimated by Mifflin and Wheat (1979) from soil development to be before 35,000 years ago. Microscope study and chemical analyses were conducted on samples from the tephra layers found in Section #1 and in Section #3 (Fig. 9). Microprobe analyses were done at the U.S. Geological Survey by James Walker, and the results were compared to chemical analyses of other tephra of known ages and origins by Andrei Sarna-Wojcicki.

Sample 99AL617-154 was collected from the tephra layer located in Section #1 about 430 cm from the top of the section (Figs. 18, 30). The petrographic study for this sample revealed a majority of glass shards, 5 to 10% non-glass particles, including some twinned feldspars, biotite, quartz, and various volcanic and metamorphic minerals. Sample AL98-51A (PN9811-51A) was collected from a tephra

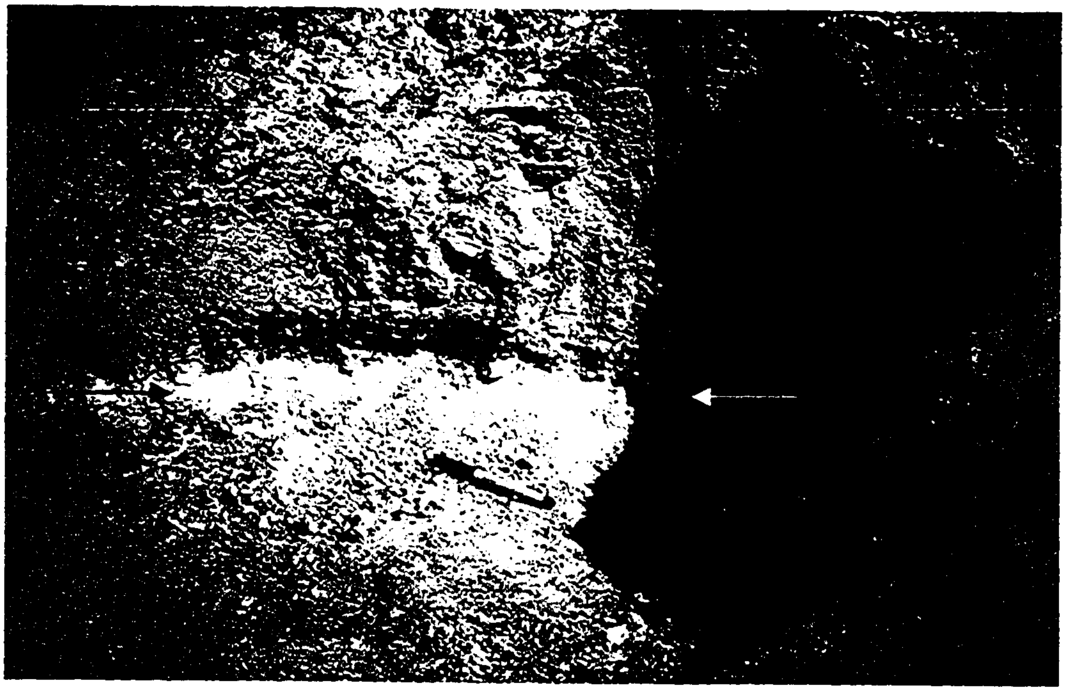


Figure 30. Tephra layer, Unit 1G (arrows) in Section #1 (Figs. 9, 18; see Fig. 3 for location of photo). Pen is 13.5 cm long.

layer located in Section #3 (Figs. 24, 31), 150 cm stratigraphically below the top of Unit 3F (Fig. 24). The petrographic analysis for this sample yielded a majority of glass shards, and 10-20% non-glass constituents, including biotite, quartz, volcanic minerals, feldspars, and various metamorphic minerals.

Sarna-Wojcicki (2003, written communication) examined the chemical results from the microprobe analyses and concluded that sample 99AL617-154 matches well with several samples from cores in Walker Lake (Appendix A, p. 109), with a similarity coefficient (SC) between 0.95 and 0.97. It is likely derived from a proto-Mono Craters source. In the Walker Lake cores, this tephra layer occurs in the interval between 60 and 80 m below the top of the cores, and corresponds to age estimates between approximately 80,000 and 60,000 years, based on the dating of these cores and sedimentation-rate estimates for Walker Lake (Sarna-Wojcicki, 2003, written communication). In the Mono Basin area, this proto-Mono Craters tephra layer is exposed on the north shore of Mono Lake and on Negit Island, where the layer is interbedded with tephra from a Mammoth Mountain source dated between 100,000 and 50,000 years (Sarna-Wojcicki, 2003, written communication).

Figure 31. Tephra layer, Unit 3C (arrows) in fine-grained lacustrine sediment in Section #3 (Figs. 9, 24; see Fig. 3 for location of photo). Tephra layer is approximately 13 cm thick.

Sample AL98-51A (PN9811-51A) does not appear to match well with other known tephra, and comparisons indicate that the closest match with a borderline SC of 0.95 is to a tephra unit with no independent age control in southern Nevada. Of the tephra units with independent age control, the closest match, with a SC of about 0.92, is with a sample from an Owens Lake core (Appendix A, p. 114) where the layer is estimated to be approximately 75,000 years old (Sarna-Wojcicki, 2003, written communication).

Soil Development

Examination of soil profile development was made at Sectin #1 and at two exposures of gravelly shore deposits (Locality A, also examined by Mifflin and Wheat, 1979, and Locality D) correlated with the 1,477-m shoreline. All soils were described according to the techniques and terminology outlined in Birkeland et al. (1991) and Birkeland (1999). Both the soil profile at Locality A and the soil at Section #1 have well-developed argillic horizons and significant pedogenic carbonate development (Appendix B).

Examination of the soil development on the sediment in Section #1 (Appendix B, p. 120) revealed the presence of two soils, indicated by two calcic horizons. At the top of the section, a debris flow truncates an alluvial deposit above Unit 1R (Figs. 18, 32) with a zone of pedogenic silica (B_{qm} horizon). The silica horizon directly overlies the upper B_k carbonate horizon between 7 and about 20 cm below the top of the soil (Fig. 32). The older, buried carbonate horizon ($2B_{kb}$) is developed within the lake sediment of Unit 1R beneath the alluvium (Fig. 32).

As is true in many desert soil profiles, the morphology of pedogenic carbonate is an indicator of profile development (Birkeland, 1999). Sediment in Section #1 was observed to have significant carbonate development on alluvial deposits and on the underlying lacustrine deposits (Figs. 32, 33). The $2B_{kb}$ was determined to be 36 cm thick and the carbonate morphology was inferred be at least Stage II, using the criteria in Birkeland et al. (1991).

Soil development was also examined at Locality A (Fig. 34; Appendix B, p. 121). The exposed portion of the section was studied for soil characteristics, including pedogenic carbonate development. The K or carbonate

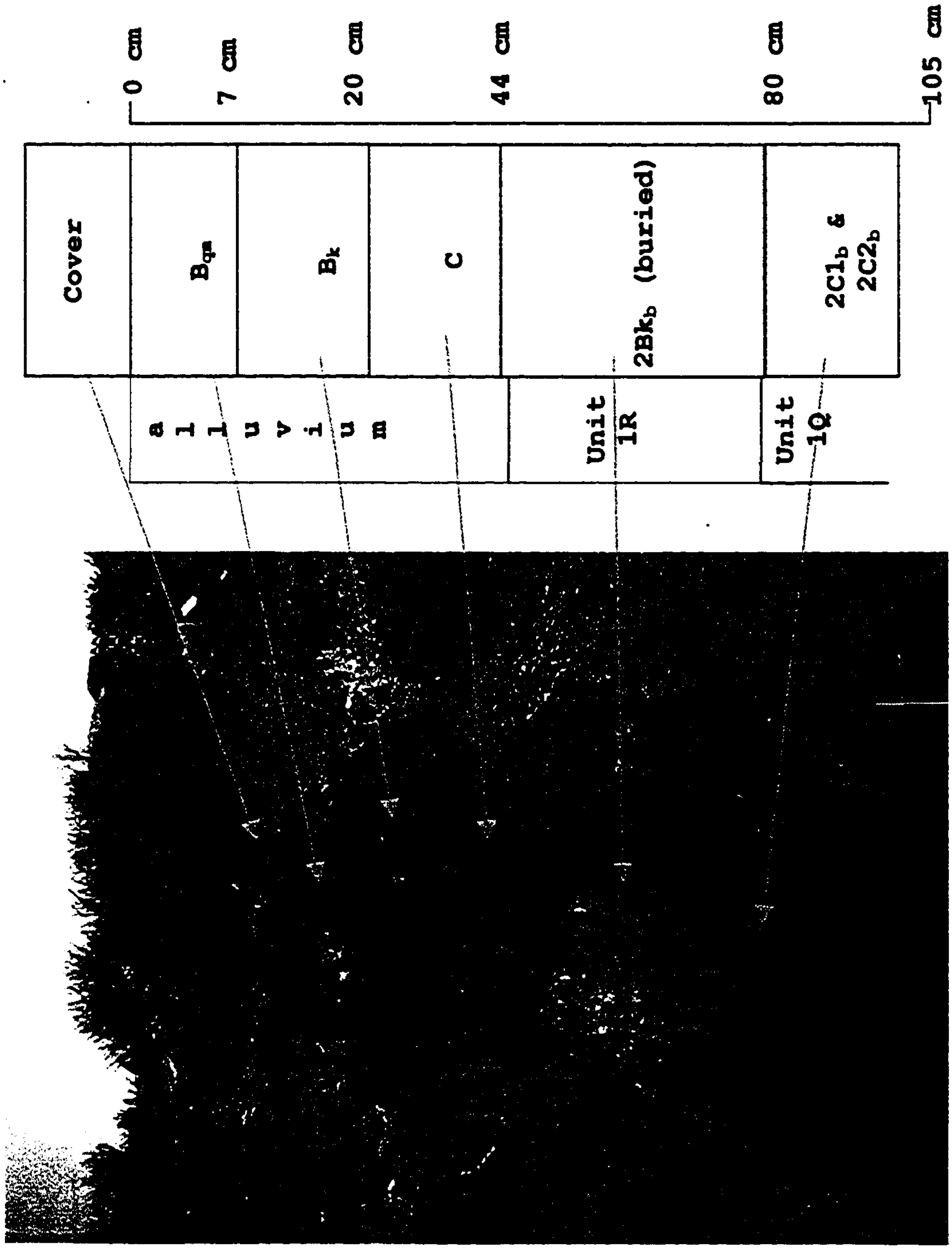


Figure 32. Photograph and soil profile of soil in Section #1 (Figs. 9, 14). Hammer head is 18 cm long. Soil horizon terminology from Birkeland et al., 1991.

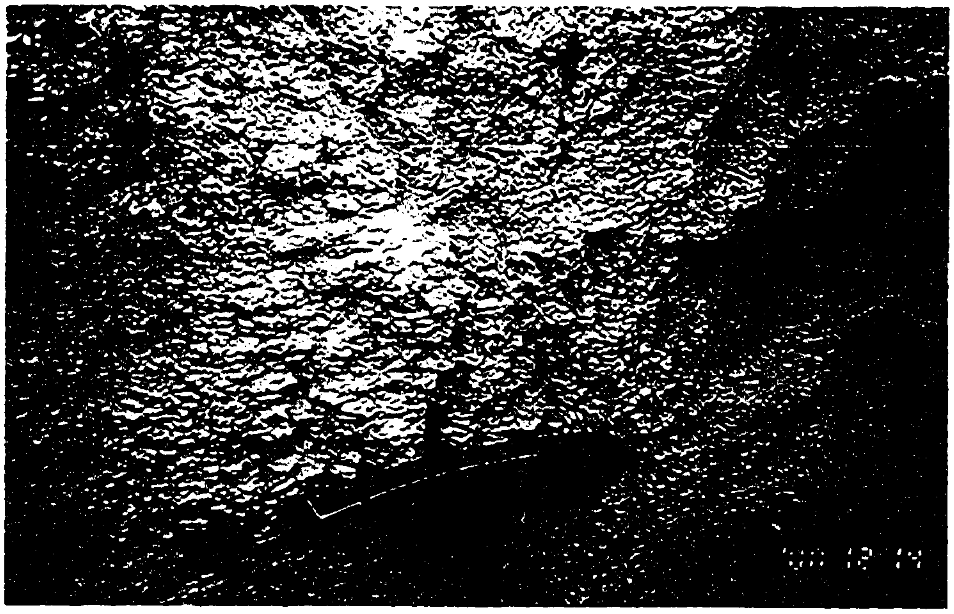


Figure 33. Stage II pedogenic carbonate on fine sediment of Unit 1R in Section #1 (Fig. 9), in Soil exposure #1 (Fig. 9). Hammer head is 18 cm long. (See Fig. 32 for location within section).

Figure 34. Weak Stage III pedogenic carbonate on gravels at Locality A (Fig. 9). Hammer head is 18 cm long.

horizon appears to be at least 40 cm thick, but an exact measurement was not obtained because debris from quarrying activities conceals the lower portion of the section. At this locality, the pedogenic carbonate is developed primarily on gravel and coarse sand, and the morphology represents a weak Stage III, based on the field criteria in Birkeland et al. (1991).

No profile was described for the soil at Locality D, but the carbonate morphology at that location is interpreted to be a Stage II (Fig. 13). This similar to the carbonate morphology at Section #1 (Fig. 33).

RECONSTRUCTION OF LAKE WELLINGTON

GIS Reconstruction

Using the modeled lake and DEMs of the valley, a model of estimated lake bathymetry was constructed in ArcView. From these data the perimeter, area, average depth, and volume of water of the lake were calculated for the 1,477-m highstand, referred to as "Higherstand", and also for the highstand at 1,465 m, referred to as "Lowerstand" (Table 1). The average and maximum depths as well as a minimum estimate for the maximum lake volume were based on modern valley geometry, the only data available in digital format. Based on the restored extent of the lake, a digital planimeter was then used to make a preliminary estimate of lake perimeter and area at that highstand.

Using GPS shoreline data imported as shapefiles and hand-digitized shorelines from the map constructed from air photo study, the lake level was modeled for the 1,477-m highstand (Fig. 35). At 1,477 m, Lake Wellington evidently had a perimeter of 80 km and a corresponding surface area of 217 km^2 or 84 mi^2. The maximum depth was estimated to be 92 m, using an estimate of the present elevation of Artesia Lake at 1,385 m, and bathymetry of the lake was modeled

Table 1. Paleogeometry for Lake Wellington

Highstand (m)		Perimeter (km)	Surface Area (km^2)	Maximum Depth (m)	Average Depth (m)	Volume (m^3)	Volume (acre-feet)
1465	"Lowerstand"	47	115	90	45	5.87×10^{12}	4.76×10^{9}
1477	"Higherstand"	80	217	102	51	11.1×10^{12}	9.00×10^{9}

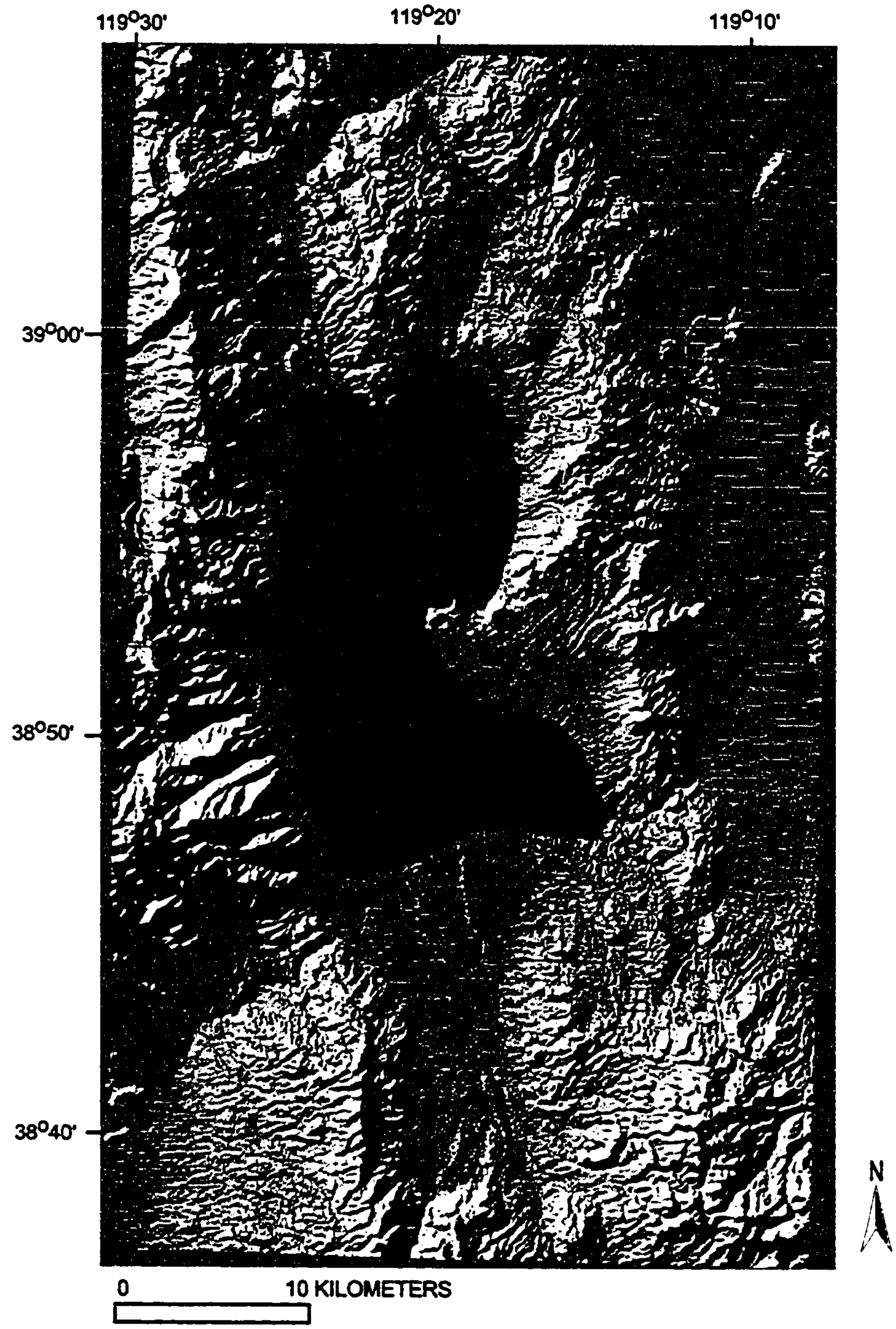


Figure 35. DEM shaded relief map showing reconstructed areal extent of Lake Wellington at its final highstand, 1,477 m.

(Fig. 36). Using the surface area and an average depth of 46 m, the volume of water contained in the lake basin was estimated to be 9.98 x 10^9 m^3 (8.09 x 10^6 acre-feet; Table 1).

Less than 2 km north of the West Walker River, a broad, elevated, relatively flat-topped area spans a distance of about 8 km, trending roughly northeast-southwest at an elevation of approximately 1,477 m. This nearly flat surface could have caused significant changes in surface area with slight changes in lake elevation, which either submerge the bench or drop the lake below it. This area was referred to as the "Beaman-Nordyke Bench" by Hawley (1969). A reduction in the maximum depth by 12 m to 80 m reduces the average depth to 40 m and the lake surface area to 115 km^2 (44 mi^2), 53% of the larger surface area. During a particular highstand, lake levels can fluctuate at or near the highstand elevation before dropping and remaining at a lower level. These fluctuations can give rise to several strandlines at slightly different elevations. To assess the effect of the Beaman-Nordyke Bench on the lake parameters while taking into account these fluctuations, an additional lake was modeled using a

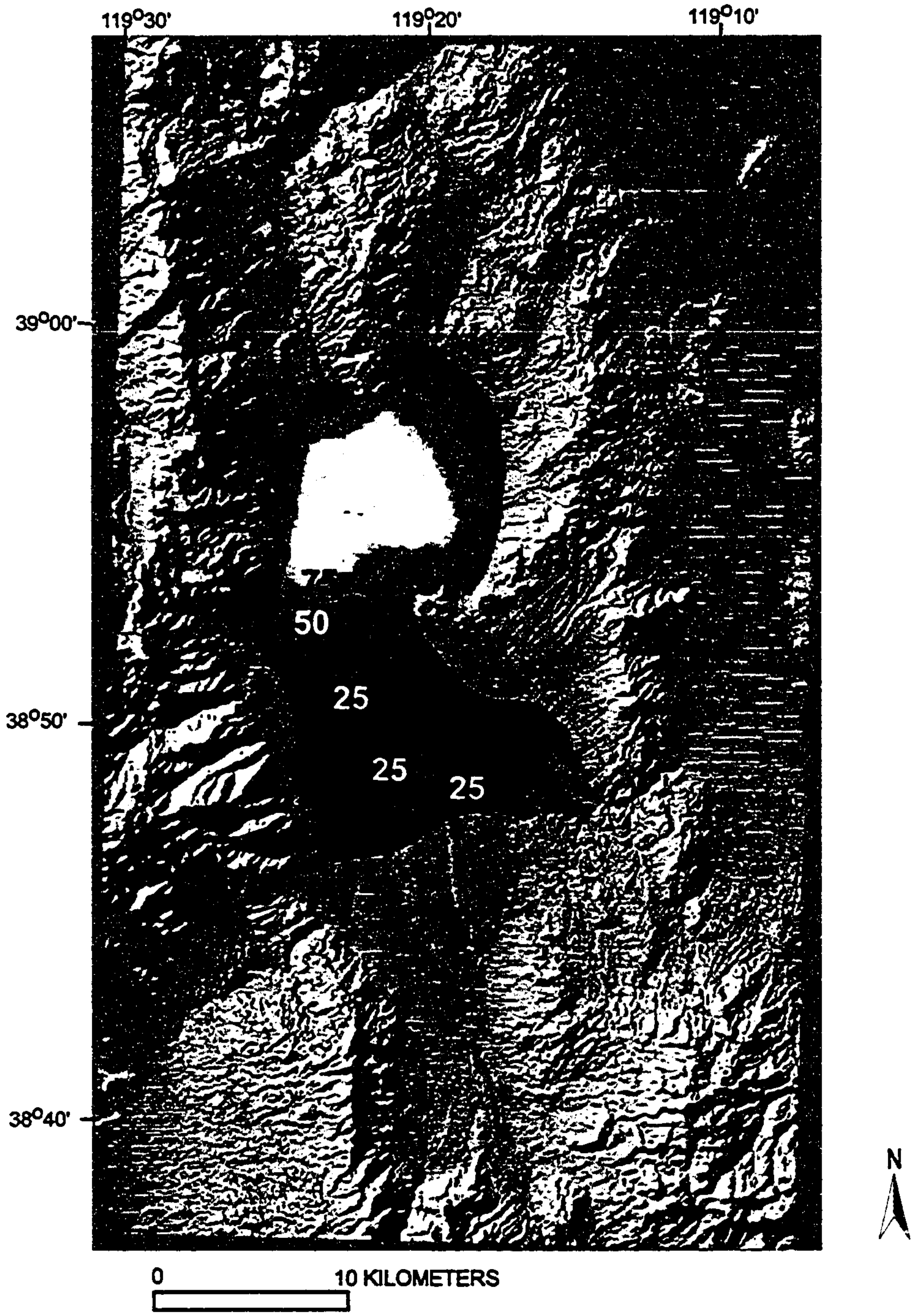


Figure 36. DEM shaded relief map showing bathymetry of Lake Wellington, using geometry of modern Smith Valley. Contour interval is 25 m.

lower set of shorelines found in the basin at an approximate elevation of 1,465 m.

This lower level of Lake Wellington, termed the "Lowerstand" on Table 1, evidently had a perimeter of 47 km, 59% of the perimeter of the highest lake stand. The estimated volume corresponding to the "Lowerstand" is 4.60 x 10^9 m^3 (3.73 x 10^6 acre-feet), 46% of the volume of the higher stand.

Hydrologic Indices

Estimations of paleogeometry for Lake Wellington, as well as calculations of the Hydrological Index (**HI**), allow for comparisons with other pluvial lakes in the region. Calculations of the Pluvial Hydrologic Index (**HI**) for Lake Wellington were made using the following equation from Reheis (1999b):

HI=AL/AT,

where **AL** is the maximum lake area as indicated by the highest shore and **AT** is the total tributary basin area or the total basin area minus the maximum lake area

The equation for **HI**, originally used by Mifflin and Wheat (1979), involves the terms for only basin and lake areas, both parameters that can be directly measured. For the purposes of this investigation, the pluvial hydrologic index (**HI**) for Smith Valley was calculated using the basin area value for Smith Valley from Mifflin and Wheat (1979) and the lake area values obtained for this study (Table 2).

Reheis (1999b) used Mifflin and Wheat's (1979) pluvial hydrological index (**HI**) to estimate the moisture conditions necessary to produce lakes that would have created shorelines in Nevada higher than the highest level of Lake Lahontan (Reheis, 1999b). Of the paleogeometric elements for Lake Wellington, the most useful parameter is the total lake-surface area, which Benson and Paillet (1989) have shown can accurately measure changes in hydrologic regime. Although total lake surface area values for **HI** for Lake Wellington are useful for comparative purposes, **HI** does not use any of measures of regional climatic conditions and extrapolation of regional climatic parameters from the **HI** values of Lake Wellington would not be appropriate.

Table 2. Calculated values of Pluvial Hydrological Index for the Lake Wellington highstands and the most recent Lake Lahontan highstand

Lake Name	**Highstand level (m)**	**A_L=Lake Area (km^2)**	**Basin Area (km^2)**	**A_T= Total tributary area (km^2)**	**Pluvial Hydrological Index (HI)[1]**	**Reference**
Wellington	1477	217	3,082.1[2]	2,779.1[2]	0.078	this project
Wellington[2]	1539 (estimated)	303	3,082.1	2,779.1	0.11	Mifflin and Wheat, 1979
Lahontan[2]	1318 to 1343 [3]	21,000	115,000	n/a[4]	0.24	Mifflin and Wheat, 1979

[1]calculated using the following equation for a single basin from Reheis (1999b):

HI = A_L/A_T, where A_L = lake area and A_T = basin area minus lake area

[2]from Mifflin and Wheat, 1979

[3]variable due to post-lake tectonic deformation (Mifflin and Wheat, 1979)

[4]total tributary area was not used for the entire Lahontan basin because the Mifflin and Wheat estimation of Pluvial Hydrological Index for Lake Lahontan is based on calculations for multiple subbasins

INTERPRETATIONS

Timing of Lake Highstand

The carbonate morphology in the paleosols, Stage II and Stage II+ in Section #1 and at Locality D, and weak Stage III at Locality A, indicates that the soils present at both of these locations are too well developed to have formed after MIS 2, a time when neighboring Lake Lahontan experienced its final highstand (Birkeland, 1999; Birkeland et al., 1991). In conjuction with other dating techniques, stages of carbonate development in soil profiles in the western United States, including Nevada, can help to estimate the age of the soil and the deposit upon which it formed (Birkeland et al., 1991; Birkeland, 1999). For soils in arid regions of the western United States, carbonate morphology of Stage III indicates that the soil formed between approximately 100,000 and 20,000 years ago (Birkeland, 1999). A carbonate morphology of Stage II indicates a younger age range for the soil, between approximately 20,000 years and 10,000 years (Birkeland, 1999).

Therefore, these soils must have formed on lacustrine sediment deposited before MIS 2. In addition, as noted by Mifflin and Wheat (1979), the morphology of the gravel bar (Locality A) appears too well preserved to be from the older period of major glacial advances, MIS 6. These constraints effectively bracket the age of the 1,477-m highstand as younger than MIS 6, but older than MIS 2.

The identification of the tephra layer in Section #1 indicates that the age of the 1,477-m highstand is likely between 80,000 and 60,000 years, approximately corresponding to a period during MIS 4 (Fig. 7). Because the tephra layer is interbedded with lacustrine sediment near 1,477 m, it is unlikely that the tephra was deposited on a dry lake bed at an earlier time and then submerged during the last Lake Wellington highstand.

The tephra layer in Section #3, Sample AL98-51A (PN9811-51A), does not have a close match to other tephra layers of known age, but it does chemically resemble a tephra layer estimated at 75,000 years of age from Owens lake (Sarna-Wojcicki, 2003, written communication). Although the chemistry is not similar enough for a direct correlation, analytical results of the tephra sample from Section #3 do not contradict the results from the tephra sampled in Section #1.

Both the assessment of pedogenic carbonate development and the analysis of the tephra in Lake Wellington deposits confirm that the exposed lacustrine deposits and the prominent shorelines in the valley most likely formed between 80,000 and 60,000 years ago, during MIS 4. Because pluvial lakes formed because of regional climate changes, it would be reasonable to hypothesize that Nevada did indeed have areas of moderately deep lakes correlating to MIS 4. However, the magnitude of the MIS 4 glaciation and filling of pluvial lakes was significantly smaller than the later MIS 2 glaciation in most places (Clark et al., 2003). Thus, much of the lacustrine evidence from MIS 4 probably was obliterated by later erosion and deposition in other lake basins. Consequently, moderate to deep lakes in Nevada during MIS 4 (between 80,000 and 60,000 years ago), appear to have left only a few records. Many stratigraphic records from both Lake Lahontan and Lake Bonneville have been interpreted to show periods of drying out and soil development during MIS 4 (Morrison, 1991).

The only confirmed evidence for a moderately deep lake during MIS 4 in the Lahontan Basin exists in the Walker Lake Basin in the form of high shorelines and isolated high deposits (Reheis et al., 2003). Adams and Wesnousky's

(1999) studies of soils formed on shorelines also imply that evidence for the presence of a moderately deep lake prior to the MIS 2 glaciation exists in the Walker Lake Basin. Surface exposure dating using cosmogenic ^{36}Cl on four levels of shorelines in the Walker Lake Basin, and results from samples taken from the lowest shoreline, previously correlated with the Sehoo highstand at approximately 15,000 years B.P., indicate that the age of the shoreline is between 95,000 and 62,000 years B.P. (Kurth, G., New Mexico Tech, 2001, written communication; Kurth et al., 2002; Reheis et al., 2003). Two areas in the Lake Bonneville Basin also show evidence of moderately deep to deep lakes during MIS 4, based on amino acid studies of freshwater gastropod shells, radiocarbon dating of organic material, and optically stimulated luminescence dating of lacustrine sediment (Oviatt et al., 1987; Oviatt and McCoy, 1992; Kaufman et al., 2001).

To date, the evidence for a lake highstand during MIS 4 in Smith Valley, along with the cosmogenic evidence from the Walker Lake Basin, appears the most definitive among basins in the region. Preservation of the evidence was apparently the result of the subsequent draining of Lake Wellington (Mifflin and Wheat, 1979). After throughflowing drainage was established, the lake never reached levels close to that of 1,477-m highstand. As a result, lake features from MIS 4 are preserved in Smith Valley, in contrast to much of the rest of the region.

The 1,477-m highstand in Smith Valley also occurred at a time when many other pluvial lakes in the region were at lower levels or absent entirely (Morrison, 1991), suggesting that controls on Lake Wellington could have differed from the controls on neighboring basins. Unlike the greater Lahontan Basin, the hydrologic regime of Smith Valley may have been dominated, as it is today, by the West Walker River. During MIS 4, the West Walker River's headwaters in the Eastern Sierra Nevada probably were partially glaciated (Clark et al., 2003). Therefore, unlike larger Lake Lahontan, at least at the time of its final highstand, Lake Wellington was probably strongly influenced by the West Walker River's responses to Sierran glaciations.

Depositional Environments

Changing depositional environments in pluvial Lake Wellington can be interpreted from sedimentary sequences, especially those in Sections #1 and #2. The character of the deposits in Sections #1 and #2, including grain size, sorting, and rare sedimentary structures, indicates that the depositional environment changed from the deeper, quieter water represented by the clayey silt and silt, to the shallower water, relatively higher energy environments of the sand and laminated silt. The deposits of clay and silt are interpreted as having formed in a low-energy lacustrine environment, either a sheltered cove or deeper water farther away from shore. The deposits of sand, especially the layers with cross-lamination, indicate a higher-energy environment, closer to shore. Section #1 generally coarsens upsection, and above about 1.5 m from the top of the section, the deposits appear to be subaerial above Unit 1R (Fig. 18). This stratigraphy reflects a prograding shoreline or a gradually receding lake.

In Section #1, a layer of fossilized plants, including well-preserved leaves within silt and fine sand (Unit 1N; Fig. 18), also supports the interpretation of a lower-energy depositional environment. The fact that the plant material is preserved indicates that the energy at the site of Section #1 was low and, because of the proximity to a shoreline and elevation of the deposit, about 1472 m, the water could not have been deeper than 5 m. The silt and fine-grained sand showing cross-bedding and ripple-scale cross-lamination (Unit 1M; Unit 2B) probably represent deposition during periods of higher wave energy, such as during storms. Another possibility is that the sand and silt layers were deposited during lake-level fluctuations at times when the lake receded somewhat and wave action became more effective. No bioturbation was observed in the sections.

Section #3 coarsens upward from silt to fine-grained sand, implying a changing depositional environment from one of relatively low energy, represented by the silt, to one of relatively higher energy, represented by the sand. The clayey silt of Exposure #4 may be separated from Section #3 by a near-vertical fault, dipping approximately parallel to the face of the road cut. If this is the case, the fault would be located between the lower colluvium unit and the clayey silt unit, as shown in the diagram in Fig. 23. The units in the measured Section #3 have been faulted downward relative to the deposits appearing above them in the exposure. Because there is no evidence a recent lake in Smith Valley near the level of the prominent shorelines at 1,477 m, it is unlikely that the clayey silt was deposited by a younger lake at the level where the deposit is located. However, the clayey silt deposit may be older than or approximately the same age as the similar sediment described in Unit 3A (Fig. 24). If the clayey silt is older than Unit 3A, the whole sequence would indicate upward shallowing similar to the sequence represented in Section #1.

The gravel deposits at Locations A and D (Figs. 9, 27, 28) are interpreted to have been deposited in a high-energy, shallow-water environment, based on the coarse average grain size, the roundness of the clasts, and imbrication of the larger clasts. The gravel deposits imply that the shore of Lake Wellington, at least at Locations A and D, experienced high-energy wave action, probably brought about by winds blowing across the surface of the lake. This is interpreted as a transition from lacustrine to lake-margin environments as the lake level dropped or as sediment filled part of the lake. Deposits with similar characteristics are found along the margins of basins occupied by Lake Lahontan, including the Carson Sink (Adams and Wesnousky, 1998; Blair, 1999). Winds blowing across a lake surface create waves that vary in size depending on the duration and velocity of the wind and the fetch (Adams, 2003). These winds can generate waves sufficient to entrain pebbles, cobbles, and even boulders as they travel shoreward. Although the surface area of Lake Wellington was a fraction of that of Lake Lahontan, the large average grain size and imbrication of the clasts at Localities A and D imply that the fetch must have been sufficient to move coarse material.

UNANSWERED QUESTIONS AND FUTURE RESEARCH

Many questions about the pluvial history of Smith Valley remain unanswered. Among these are: 1) Where is the evidence for a lake of MIS 6 age, if any, in Smith Valley?; 2) Why did the final overflow occur at 1,477 m during MIS 4 and not at the postulated higher stand of approximately 1539 m during MIS 6?; and 3) What was the duration of the MIS 4 highstand? In addition, further exploration into the Pleistocene history of the West Walker River may help to clarify the relationships between the river and Lake Wellington.

Supplementary Quaternary research in Smith Valley could include more detailed study of the stratigraphy of lacustrine and non-lacustrine deposits, specifically from a core or cores from Artesia Lake and from additional surface stratigraphic sections. Better age control on deposits and shorelines would provide better understanding of the timing of climate changes in the basin. Furthermore, extended study of the Quaternary faulting in Smith Valley using the lake stratigraphy and tephra would lead to better understanding of recent tectonic history of the region.

CONCLUSIONS

On the basis of correlation of a single tephra layer in Section #1 and on soil development studies, the Lake Wellington highstand responsible for the prominent shorelines at 1,477 m and associated lacustrine deposits in Smith Valley occurred between 80,000 and 60,000 years ago, during MIS 4. Using modern topographic information from DEMs, Lake Wellington, at its highest level during the 1,477-m highstand, is inferred to have had a surface area of approximately 217 km^2, about 44% the surface area of modern Lake Tahoe. Using the calculated Lake Wellington surface area, the volume of water required to create the highstand features of Lake Wellington is estimated to be approximately 9.98×10^9 m^3.

Based on the examination of Sections #1 and #2 and Localities A and D, lacustrine deposits at these localities exhibit coarsening upward sequences. This is interpreted as a transition from lacustrine to lake-margin environments as the shoreline prograded or the lake level dropped. In addition, the lacustrine deposits appear to record a combination of water level decline and lake stillstand. Although it is apparent that Smith Valley was occupied by a moderately deep lake during MIS 4, evidence for a larger, older lake during MIS 6 is much more ambiguous. It is important to note that this investigation revealed no evidence for a lake of significant size in Smith Valley during MIS 2.

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APPENDIX A

RESULTS OF MICROPROBE ANALYSES (performed by Walker, J., 2000) AND CLOSEST MATCHES (Sarna-Wojcicki, 2003, written communication) FOR TEPHRA SAMPLES

Summary of Results from tephra sample 99AL617-154

Tephra sample 99AL617-154 was collected for this project from Unit 1G (Fig. 18) in Section #1 (Figs. 9, 14; Plate 1). Tephra sample WLC-85-2 is the closest match and is one of several samples taken from Walker Lake cores. This tephra originated from a Proto-Mono Craters Source and is estimated to be between 80,000 and 60,000 years old.

Sample 99AL617-154, T440-2

Listing of 40 closest matches for COMP. NO. 4620 for elements: Mg, Al, Si, K , Ca, Ti, Fe Date of Update: 08/20/03

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4620	99AL617-154 T440-2	6-29-00	76.45	13.46	0.80	0.06	0.05	0.82	0.10	3.42	4.83	99.99	1.0000
2	1571	WLC-85-2 (13.65M) T128-2	8/18/86	76.71	13.06	0.84	0.06	0.06	0.81	0.09	3.43	4.94	100.00	0.9693
3	1985	WL-5-16 (73.62m) T164-14	5/22/88	76.34	13.31	0.83	0.06	0.03	0.73	0.10	3.47	5.13	100.00	0.9690
4	2590	FLV-176-TC T229-8	6/14/91	76.53	13.22	0.85	0.07	0.06	0.82	0.10	3.44	4.91	100.00	0.9662
5	1983	WL-5-16 (73.40m) T164-12	5/22/88	76.37	13.29	0.81	0.05	0.04	0.75	0.10	3.70	4.89	100.00	0.9585
6	1037	WL 3-7-2.66	08/18/84	76.74	13.00	0.82	0.06	0.03	0.83	0.08	3.51	4.92	99.99	0.9582
7	3735	FLV-231-CuC T346-4	11/96	75.79	13.81	0.79	0.06	0.06	0.80	0.08	3.60	5.00	99.99	0.9564
8	1137	WL-5-19-0.27M T84-13	12/3/84	76.42	13.19	0.85	0.07	0.05	0.82	0.09	3.67	4.84	100.00	0.9537
9	2595	EL-1-M T230-5	7/2/91	76.61	13.14	0.85	0.06	0.04	0.79	0.08	3.64	4.79	100.00	0.9529
10	1262	*WL 5-19 78.91m	5/29/85	77.29	12.54	0.79	0.06	0.05	0.84	0.08	3.62	4.73	100.00	0.9520
11	2684	LOVW-3 T242-7	11/13/91	75.50	13.70	0.71	0.06	0.07	0.84	0.10	3.02	6.00	100.00	0.9484
12	2697	LOVW-20 T244-5	11/27/91	76.01	13.26	0.70	0.06	0.06	0.80	0.10	2.84	6.17	100.00	0.9447
13	909	DR-14		76.37	13.21	0.87	0.08	0.06	0.80	0.10	3.60	4.90	99.99	0.9445
14	1040	WL 4-30-28M, T78-13	07/18/84	76.80	12.82	0.92	0.07	0.03	0.85	0.10	3.44	4.97	100.00	0.9444
15	1894	YJC-2-87 T150-12	11/9/87	76.45	13.39	0.68	0.06	0.08	0.65	0.10	3.56	5.02	99.99	0.9428
16	2571	RA-WC-1 T227-5	6/13/91	76.17	13.41	0.64	0.06	0.08	0.82	0.09	3.34	5.39	100.00	0.9412
17	2918	OL92-1001 T270-5	12/16/92	77.42	12.67	0.78	0.06	0.05	0.77	0.08	3.61	4.56	100.00	0.9410
18	1480	6VI84-1-5.5M T117-13	3/6/86	76.73	13.08	0.87	0.06	0.05	0.74	0.08	3.55	4.85	100.01	0.9409
19	4874	AJ-01-D1_POP2 T476-1	4-2-02	76.29	13.32	0.78	0.05	0.06	0.80	0.08	3.81	4.81	100.00	0.9382
20	3398	KDA94CS-35M T316-3	1/6/95	76.30	13.23	0.90	0.07	0.04	0.84	0.11	3.42	5.09	100.00	0.9373
21	1951	WL-4-8B (21.275M) T162-5	5/14/88	76.67	13.13	0.82	0.06	0.07	0.65	0.12	3.47	5.01	100.00	0.9340
22	2695	LOVW-17 T244-2	11/27/91	75.82	13.50	0.65	0.06	0.08	0.75	0.10	3.09	5.95	100.00	0.9325
23	1962	WL-4-25 (62.76M) T164-6	5/15/88	76.91	12.91	0.79	0.05	0.05	0.70	0.09	3.62	4.87	99.99	0.9313
24	546	KRL71082(CII), T56-3	07/01/83	76.09	13.39	0.90	0.08	0.03	0.83	0.09	3.74	4.85	100.00	0.9304
25	5037	JRK-DV-223 T496-1	3-17-03	76.10	13.34	0.83	0.06	0.06	0.57	0.10	3.31	5.63	100,00	0.9291
26	3399	KDA94CS-35U T316-4	1/6/95	76.15	13.27	0.96	0.07	0.05	0.85	0.11	3.47	5.06	99.99	0.9287
27	4409	RKLR-9A T405-1	03/29/99	75.77	13.68	0.87	0.07	0.04	0.86	0.08	3.74	4.89	100.00	0.9276
28	113	GV-76-1, T16-10		77.03	12.98	0.66	0.06	0.03	0.73	0.10	2.50	5.91	100.00	0.9270
29	301	PRU, T25-6		77.07	12.78	0.77	0.06	0.06	0.57	0.10	3.15	5.44	100.00	0.9267
30	1595	MOD-10 T130-6	9/19/86	78.20	11.69	0.78	0.06	0.05	0.60	0.10	3.34	5.18	100.00	0.9265
31	3397	KDA94CS-35L T316-2	1/6/95	76.03	13.39	0.92	0.06	0.04	0.92	0.13	3.42	5.09	100.00	0.9240
32	1510	BE-262 (?) T119-10	4/28/86	77.16	12.94	0.60	0.07	0.06	0.77	0.10	3.63	4.67	100.00	0.9236
33	3764	TV-1800-A MAJOR T349-3	11/96	76.69	13.68	0.84	0.08	0.06	0.79	0.09	2.46	5.30	99.99	0.9226
34	1239	WL 3-7 17.51m T93-8	5/2/85	76.22	13.30	0.89	0.10	0.03	0.83	0.10	3.61	4.92	100.00	0.9219
35	3961	JEO 3/10/97-1 OBS. T361-1	4/97	76.93	12.99	0.72	0.07	0.03	0.61	0.10	3.66	4.87	99.98	0.9217
36	3188	F8-90-G21 (39-41cm) Major T304	3/24/93	76.89	13.00	0.96	0.07	0.05	0.69	0.10	3.63	4.62	100.01	0.9212
37	1954	WL-4-11 (26.20M) T162-8	5/15/88	77.03	12.78	0.77	0.07	0.04	0.62	0.10	3.39	5.20	100.00	0.9209
38	849	LM-2		77.99	12.51	0.74	0.06	0.03	0.56	0.10	2.80	5.21	100.00	0.9207
39	1261	*WL 4-30 78.77m t95-10	5/29/85	77.12	12.57	0.89	0.08	0.04	0.86	0.11	3.50	4.83	100.00	0.9195
40	1476	3(31) KESI T117-9	3/6/86	77.61	12.73	1.00	0.08	0.03	0.84	0.10	2.63	4.96	99.98	0.9187

(this project)
← Sample 99AL617-154
← Sample WLC-85-2 (closest match

Sample 99AL617-154, T440-2

Listing of 50 closest matches for COMP. NO. 4620 for elements: Na, Al, Si, K , Ca, Fe Date of Update: 08/02/00

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4620	99AL617-154 T440-2	6-29-00	76.45	13.46	0.80	0.06	0.05	0.82	0.10	3.42	4.83	99.99	1.0000
2	2590	FLV-176-TC T229-8	6/14/91	76.53	13.22	0.85	0.07	0.06	0.82	0.10	3.44	4.91	100.00	0.9834
3	1571	WLC-85-2 (13.65M) T128-2	8/18/86	76.71	13.06	0.84	0.06	0.06	0.81	0.09	3.43	4.94	100.00	0.9803
4	1037	WL 3-7-2.66	08/18/84	76.74	13.00	0.82	0.06	0.03	0.83	0.08	3.51	4.92	99.99	0.9803
5	1137	WL-5-19-0.27M T84-13	12/3/84	76.42	13.19	0.85	0.07	0.05	0.82	0.09	3.67	4.84	100.00	0.9751
6	3735	FLV-231-CuC T346-4	11/96	75.79	13.81	0.79	0.06	0.06	0.80	0.08	3.60	5.00	99.99	0.9742
7	907	DR-12		76.27	13.53	0.73	0.09	0.03	0.81	0.12	3.61	4.81	100.00	0.9727
8	1965	WL-4-27 (69.77M) T163-9	5/15/88	76.69	13.07	0.87	0.09	0.05	0.80	0.11	3.38	4.94	100.00	0.9715
9	860	LM-15		77.08	13.23	0.80	0.13	0.06	0.78	0.10	3.21	4.61	100.00	0.9698
10	909	DR-14		76.37	13.21	0.87	0.08	0.06	0.80	0.10	3.60	4.90	99.99	0.9685
11	2595	EL-1-M T230-5	7/2/91	76.61	13.14	0.85	0.06	0.04	0.79	0.08	3.64	4.79	100.00	0.9683
12	1262	*WL 5-19 78.91m	5/29/85	77.29	12.54	0.79	0.06	0.05	0.84	0.08	3.62	4.73	100.00	0.9681
13	2822	JB-BS-3 T226-8	6/24/92	76.16	13.29	0.85	0.08	0.04	0.81	0.08	3.65	5.04	100.00	0.9680
14	3262	FLV 3.13 (9.89m) T310-9	8/1/94	76.04	13.48	0.88	0.08	0.04	0.81	0.08	3.66	4.92	99.99	0.9677
15	1239	WL 3-7 17.51m T93-8	5/2/85	76.22	13.30	0.89	0.10	0.03	0.83	0.10	3.61	4.92	100.00	0.9668
16	1983	WL-5-16 (73.40m) T164-12	5/22/88	76.37	13.29	0.81	0.05	0.04	0.75	0.10	3.70	4.89	100.00	0.9668
17	3398	KDA94CS-35M T316-3	1/6/95	76.30	13.23	0.90	0.07	0.04	0.84	0.11	3.42	5.09	100.00	0.9658
18	1966	WL-4-30 (78.72M) T163-10	5/15/88	76.62	13.09	0.89	0.09	0.05	0.87	0.09	3.49	4.82	100.01	0.9649
19	1570	WLC-85-2 (11.34M) T128-1	8/18/86	76.89	12.97	0.84	0.04	0.05	0.75	0.08	3.54	4.85	100.01	0.9645
20	1326	BE-58 T105-4	8/29/85	76.74	13.31	0.71	0.08	0.05	0.88	0.09	3.42	4.71	99.99	0.9633
21	546	KRL71082(CII), T56-3	07/01/83	76.09	13.39	0.90	0.08	0.03	0.83	0.09	3.74	4.85	100.00	0.9629
22	3523	CCLS-14 T327-4	8/30/95	75.92	13.43	0.84	0.10	0.04	0.77	0.14	3.39	5.37	100.00	0.9622
24	696	RSCS2		77.33	12.80	0.89	0.01	0.00	0.81	0.05	3.50	4.60	99.99	0.9593
23	1985	WL-5-16 (73.62m) T164-14	5/22/88	76.34	13.31	0.83	0.06	0.03	0.73	0.10	3.47	5.13	100.00	0.9614
25	1261	*WL 4-30 78.77m t95-10	5/29/85	77.12	12.57	0.89	0.08	0.04	0.86	0.11	3.50	4.83	100.00	0.9591
26	4409	RKLR-9A T405-1	03/29/99	75.77	13.68	0.87	0.07	0.04	0.86	0.08	3.74	4.89	100.00	0.9584
27	1480	6VI84-1-5.5M T117-13	3/6/86	76.73	13.08	0.87	0.06	0.05	0.74	0.08	3.55	4.85	100.01	0.9582
28	1040	WL 4-30-28M, T78-13	07/18/84	76.80	12.82	0.92	0.07	0.03	0.85	0.10	3.44	4.97	100.00	0.9580
29	2405	89B475 T206-8	5/15/90	77.11	12.97	0.89	0.17	0.04	0.84	0.15	3.35	4.49	100.01	0.9565
30	2918	OL92-1001 T270-5	12/16/92	77.42	12.67	0.78	0.06	0.05	0.77	0.08	3.61	4.56	100.00	0.9557
31	3799	OL92-1 DR-18 SL-C T351-1	12/96	76.59	13.15	0.83	0.03	0.05	0.72	0.06	3.69	4.88	100.00	0.9556
32	1964	WL-4-27 (68.59M) T163-8	5/15/88	76.85	13.06	0.85	0.04	0.06	0.75	0.06	3.64	4.69	100.00	0.9552
33	334	RS-2(2), T34-6		77.51	12.82	0.81	0.16	0.02	0.74	0.15	3.39	4.40	100.00	0.9552
34	1963	WL-4-26 (66.50M) T163-7	5/15/88	76.67	13.24	0.84	0.04	0.04	0.73	0.07	3.66	4.70	99.99	0.9552
35	1962	WL-4-25 (62.76M) T164-6	5/15/88	76.91	12.91	0.79	0.05	0.05	0.70	0.09	3.62	4.87	99.99	0.9551
36	549	KRL71082F, T55-5	11/25/83	76.59	13.26	0.86	0.05	0.05	0.71	0.07	3.59	4.82	100.00	0.9550
37	1569	WLC-85-2 (10.65M) T127-14	8/18/86	76.61	13.40	0.87	0.03	0.06	0.70	0.05	3.52	4.76	100.00	0.9540
38	1047	DSDP 36-10-2 SSA3, T78-5	07/18/84	77.04	13.17	0.81	0.02	0.06	0.67	0.03	3.50	4.69	99.99	0.9539
39	3399	KDA94CS-35U T316-4	1/6/95	76.15	13.27	0.96	0.07	0.05	0.85	0.11	3.47	5.06	99.99	0.9534
40	1258	*WL 4-26 66.79m t95-5	5/29/85	76.94	12.84	0.81	0.05	0.04	0.73	0.07	3.77	4.75	100.00	0.9527
41	1243	WL 4-26 66.40m T93-12	5/2/85	76.71	13.12	0.83	0.05	0.04	0.71	0.06	3.70	4.78	100.00	0.9525

Sample 99AL617-154, T440-2

Listing of 50 closest matches for COMP. NO. 4620 for elements: Na, Al, Si, K , Ca, Ti, Fe Date of Update: 08/02/00

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4620	99AL617-154 T440-2	6-29-00	76.45	13.46	0.80	0.06	0.05	0.82	0.10	3.42	4.83	99.99	1.0000
2	2590	FLV-176-TC T229-8	6/14/91	76.53	13.22	0.85	0.07	0.06	0.82	0.10	3.44	4.91	100.00	0.9857
3	860	LM-15		77.08	13.23	0.80	0.13	0.06	0.78	0.10	3.21	4.61	100.00	0.9741
4	909	DR-14		76.37	13.21	0.87	0.08	0.06	0.80	0.10	3.60	4.90	99.99	0.9730
5	1239	WL 3-7 17.51m T93-8	5/2/85	76.22	13.30	0.89	0.10	0.03	0.83	0.10	3.61	4.92	100.00	0.9716
6	1983	WL-5-16 (73.40m) T164-12	5/22/88	76.37	13.29	0.81	0.05	0.04	0.75	0.10	3.70	4.89	100.00	0.9715
7	1571	WLC-85-2 (13.65M) T128-2	8/18/86	76.71	13.06	0.84	0.06	0.06	0.81	0.09	3.43	4.94	100.00	0.9688
8	1985	WL-5-16 (73.62m) T164-14	5/22/88	76.34	13.31	0.83	0.06	0.03	0.73	0.10	3.47	5.13	100.00	0.9669
9	1137	WL-5-19-0.27M T84-13	12/3/84	76.42	13.19	0.85	0.07	0.05	0.82	0.09	3.67	4.84	100.00	0.9644
10	1040	WL 4-30-28M, T78-13	07/18/84	76.80	12.82	0.92	0.07	0.03	0.85	0.10	3.44	4.97	100.00	0.9640
11	1965	WL-4-27 (69.77M) T163-9	5/15/88	76.69	13.07	0.87	0.09	0.05	0.80	0.11	3.38	4.94	100.00	0.9626
12	3398	KDA94CS-35M T316-3	1/6/95	76.30	13.23	0.90	0.07	0.04	0.84	0.11	3.42	5.09	100.00	0.9577
13	1966	WL-4-30 (78.72M) T163-10	5/15/88	76.62	13.09	0.89	0.09	0.05	0.87	0.09	3.49	4.82	100.01	0.9557
14	1037	WL 3-7-2.66	08/18/84	76.74	13.00	0.82	0.06	0.03	0.83	0.08	3.51	4.92	99.99	0.9545
15	1326	BE-58 T105-4	8/29/85	76.74	13.31	0.71	0.08	0.05	0.88	0.09	3.42	4.71	99.99	0.9542
16	546	KRL71082(CII), T56-3	07/01/83	76.09	13.39	0.90	0.08	0.03	0.83	0.09	3.74	4.85	100.00	0.9539
17	907	DR-12		76.27	13.53	0.73	0.09	0.03	0.81	0.12	3.61	4.81	100.00	0.9528
18	1261	*WL 4-30 78.77m t95-10	5/29/85	77.12	12.57	0.89	0.08	0.04	0.86	0.11	3.50	4.83	100.00	0.9520
19	3735	FLV-231-CUC T346-4	11/96	75.79	13.81	0.79	0.06	0.06	0.80	0.08	3.60	5.00	99.99	0.9493
20	1962	WL-4-25 (62.76M) T164-6	5/15/88	76.91	12.91	0.79	0.05	0.05	0.70	0.09	3.62	4.87	99.99	0.9473
21	3399	KDA94CS-35U T316-4	1/6/95	76.15	13.27	0.96	0.07	0.05	0.85	0.11	3.47	5.06	99.99	0.9470
22	2595	EL-1-M T230-5	7/2/91	76.61	13.14	0.85	0.06	0.04	0.79	0.08	3.64	4.79	100.00	0.9443
23	1262	*WL 5-19 78.91m	5/29/85	77.29	12.54	0.79	0.06	0.05	0.84	0.08	3.62	4.73	100.00	0.9441
24	2822	JB-BS-3 T226-8	6/24/92	76.16	13.29	0.85	0.08	0.04	0.81	0.08	3.65	5.04	100.00	0.9440
25	3262	FLV 3.13 (9.89m) T310-9	8/1/94	76.04	13.48	0.88	0.08	0.04	0.81	0.08	3.66	4.92	99.99	0.9437
26	1570	WLC-85-2 (11.34M) T128-1	8/18/86	76.89	12.97	0.84	0.04	0.05	0.75	0.08	3.54	4.85	100.01	0.9410
27	2742	BUR-915 LoFe		76.47	13.19	0.75	0.14	0.09	0.81	0.10	2.82	5.64	100.01	0.9408
28	1584	ASW 61186-5B	8/19/86	78.17	12.54	0.81	0.10	0.04	0.69	0.10	3.28	4.28	100.01	0.9406
29	1045	DSDP 36-10-2 SSA, T78-5	07/18/84	76.90	12.80	0.85	0.04	0.04	0.72	0.09	3.73	4.83	100.00	0.9402
30	1954	WL-4-11 (26.20M) T162-8	5/15/88	77.03	12.78	0.77	0.07	0.04	0.62	0.10	3.39	5.20	100.00	0.9401
31	1587	ASW 61186-5E T129-3	8/19/86	78.60	12.11	0.79	0.08	0.04	0.71	0.10	3.33	4.24	100.00	0.9396
32	2571	RA-WC-1 T227-5	6/13/91	76.17	13.41	0.64	0.06	0.08	0.82	0.09	3.34	5.39	100.00	0.9379
33	1894	YJC-2-87 T150-12	11/9/87	76.45	13.39	0.68	0.06	0.08	0.65	0.10	3.56	5.02	99.99	0.9372
34	4109	H97Sm-53 t376	1-30-98	77.55	12.72	0.66	0.11	0.05	0.73	0.10	3.16	4.91	99.99	0.9363
35	4082	EL-73-PV LO FE T374-10	11/97	76.26	13.27	1.29	0.08	0.04	0.82	0.10	3.27	4.87	100.00	0.9359
36	2837	911005C T260-1	7/14/92	77.01	12.92	0.76	0.17	0.07	0.75	0.11	3.77	4.43	99.99	0.9358
37	4409	RKLR-9A T405-1	03/29/99	75.77	13.68	0.87	0.07	0.04	0.86	0.08	3.74	4.89	100.00	0.9357
38	1510	BE-262 (?) T119-10	4/28/86	77.16	12.94	0.60	0.07	0.06	0.77	0.10	3.63	4.67	100.00	0.9357
39	1387	ASW-61385-35B T109-5	9/24/85	78.15	12.31	0.81	0.10	0.02	0.68	0.10	3.57	4.26	100.00	0.9357
40	1480	6VI84-1-5.5M T117-13	3/6/86	76.73	13.08	0.87	0.06	0.05	0.74	0.08	3.55	4.85	100.01	0.9356
41	2918	OL92-1001 T270-5	12/16/92	77.42	12.67	0.78	0.06	0.05	0.77	0.08	3.61	4.56	100.00	0.9335

Sample 99AL617-154, T440-2

Listing of 40 closest matches for COMP. NO. 4620 for elements: Mg, Al, Si, K, Ca, Ti, Mn, Fe Date of Update: 08/20/03

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4620	99AL617-154 T440-2	6-29-00	76.45	13.46	0.80	0.06	0.05	0.82	0.10	3.42	4.83	99.99	1.0000
2	1137	WL-5-19-0.27M T84-13	12/3/84	76.42	13.19	0.85	0.07	0.05	0.82	0.09	3.67	4.84	100.00	0.9595
3	1262	*WL 5-19 78.91m	5/29/85	77.29	12.54	0.79	0.06	0.05	0.84	0.08	3.62	4.73	100.00	0.9580
4	1571	WLC-85-2 (13.65M) T128-2	8/18/86	76.71	13.06	0.84	0.06	0.06	0.81	0.09	3.43	4.94	100.00	0.9523
5	2590	FLV-176-TC T229-8	6/14/91	76.53	13.22	0.85	0.07	0.06	0.82	0.10	3.44	4.91	100.00	0.9496
6	2918	OL92-1001 T270-5	12/16/92	77.42	12.67	0.78	0.06	0.05	0.77	0.08	3.61	4.56	100.00	0.9484
7	1480	6VI84-1-5.5M T117-13	3/6/86	76.73	13.08	0.87	0.06	0.05	0.74	0.08	3.55	4.85	100.01	0.9482
8	3735	FLV-231-CuC T346-4	11/96	75.79	13.81	0.79	0.06	0.06	0.80	0.08	3.60	5.00	99.99	0.9411
9	1962	WL-4-25 (62.76M) T164-6	5/15/88	76.91	12.91	0.79	0.05	0.05	0.70	0.09	3.62	4.87	99.99	0.9399
10	1983	WL-5-16 (73.40m) T164-12	5/22/88	76.37	13.29	0.81	0.05	0.04	0.75	0.10	3.70	4.89	100.00	0.9387
11	3399	KDA94CS-35U T316-4	1/6/95	76.15	13.27	0.96	0.07	0.05	0.85	0.11	3.47	5.06	99.99	0.9376
12	1595	MOD-10 T130-6	9/19/86	78.20	11.69	0.78	0.06	0.05	0.60	0.10	3.34	5.18	100.00	0.9357
13	2595	EL-1-M T230-5	7/2/91	76.61	13.14	0.85	0.06	0.04	0.79	0.08	3.64	4.79	100.00	0.9338
14	3188	F8-90-G21 (39-41cm) Major T304	3/24/93	76.89	13.00	0.96	0.07	0.05	0.69	0.10	3.63	4.62	100.01	0.9311
15	2697	LOVW-20 T244-5	11/27/91	76.01	13.26	0.70	0.06	0.06	0.80	0.10	2.84	6.17	100.00	0.9308
16	909	DR-14		76.37	13.21	0.87	0.08	0.06	0.80	0.10	3.60	4.90	99.99	0.9306
17	1326	BE-58 T105-4	8/29/85	76.74	13.31	0.71	0.08	0.05	0.88	0.09	3.42	4.71	99.99	0.9287
18	1965	WL-4-27 (69.77M) T163-9	5/15/88	76.69	13.07	0.87	0.09	0.05	0.80	0.11	3.38	4.94	100.00	0.9271
19	4874	AJ-01-D1_POP2 T476-1	4-2-02	76.29	13.32	0.78	0.05	0.06	0.80	0.08	3.81	4.81	100.00	0.9251
20	1969	WL-4-34 (89.85M) T163-13	5/15/88	77.14	12.79	0.78	0.07	0.05	0.60	0.09	3.71	4.78	100.01	0.9243
21	126	GV-78-20, T15-14		76.86	12.96	0.85	0.07	0.05	0.70	0.10	2.24	6.16	99.99	0.9242
22	1985	WL-5-16 (73.62m) T164-14	5/22/88	76.34	13.31	0.83	0.06	0.03	0.73	0.10	3.47	5.13	100.00	0.9229
23	1960	WL-4-20 (48.02M) T162-14	5/15/88	77.19	12.80	0.76	0.05	0.05	0.63	0.09	3.65	4.78	100.00	0.9228
24	1966	WL-4-30 (78.72M) T163-10	5/15/88	76.62	13.09	0.89	0.09	0.05	0.87	0.09	3.49	4.82	100.01	0.9220
25	4611	LB-4-3-00 T439-4	5-5-00	77.28	12.97	0.95	0.06	0.05	0.96	0.08	3.22	4.43	100.00	0.9208
26	3398	KDA94CS-35M T316-3	1/6/95	76.30	13.23	0.90	0.07	0.04	0.84	0.11	3.42	5.09	100.00	0.9201
27	2684	LOVW-3 T242-7	11/13/91	75.50	13.70	0.71	0.06	0.07	0.84	0.10	3.02	6.00	100.00	0.9191
28	5037	JRK-DV-223 T496-1	3-17-03	76.10	13.34	0.83	0.06	0.06	0.57	0.10	3.31	5.63	100.00	0.9171
29	301	PRU, T25-6		77.07	12.78	0.77	0.06	0.06	0.57	0.10	3.15	5.44	100.00	0.9150
30	549	KRL71082F, T55-5	11/25/83	76.59	13.26	0.86	0.05	0.05	0.71	0.07	3.59	4.82	100.00	0.9138
31	1037	WL 3-7-2.66	08/18/84	76.74	13.00	0.82	0.06	0.03	0.83	0.08	3.51	4.92	99.99	0.9134
32	1510	BE-262 (?) T119-10	4/28/86	77.16	12.94	0.60	0.07	0.06	0.77	0.10	3.63	4.67	100.00	0.9123
33	2327	FLV-85-HT T192-4	6/1/89	76.70	13.10	0.72	0.06	0.05	0.62	0.08	3.11	5.56	100.00	0.9118
34	4409	RKLR-9A T405-1	03/29/99	75.77	13.68	0.87	0.07	0.04	0.86	0.08	3.74	4.89	100.00	0.9116
35	3764	TV-1800-A MAJOR T349-3	11/96	76.69	13.68	0.84	0.08	0.06	0.79	0.09	2.46	5.30	99.99	0.9114
36	1570	WLC-85-2 (11.34M) T128-1	8/18/86	76.89	12.97	0.84	0.04	0.05	0.75	0.08	3.54	4.85	100.01	0.9109
37	1257	*WL 4-26 66.68m	5/29/85	76.78	12.82	0.88	0.05	0.05	0.75	0.07	3.86	4.73	99.99	0.9106
38	4135	188-69 (perkins)		77.14	12.61	0.81	0.06	0.05	0.51	0.09	2.94	5.78	99.99	0.9091
39	4463	MRGB-26-TP T416-1	8-26-99	78.51	12.89	0.71	0.08	0.05	0.76	0.12	2.32	4.55	99.99	0.9089
40	1666	TPS-315 T132-8	10/21/86	76.15	14.14	0.69	0.08	0.05	0.70	0.09	3.48	4.62	100.00	0.9088

Summary of Results from tephra sample AL98-51A (PN9811-51A)

Tephra sample AL98-51A (PN9811-51A) was collected for this project from Unit 3C (Fig. 24) in Section #3 (Fig. 9; Plate 1). Tephra sample OL92-1 is the closest match with independent age control, and was collected from layer in an Owens Lake core estimated to be approximately 75,000 years old.

Sample AL98-51A (PN9811-51A), T440-1

Listing of 40 closest matches for COMP. NO. 4619 for elements: Mg, Al, Si, K , Ca, Ti, Mn, Fe Date of Update: 08/20/03

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4619	AL98-51A T440-1	6-29-00	73.18	14.90	1.41	0.13	0.09	0.62	0.19	4.38	5.10	100.00	1.0000
2	3754	CKS(WS)-1 T348-2	11/96	72.18	15.50	1.37	0.15	0.09	0.55	0.18	4.97	5.02	100.01	0.9506
3	3723	JRK-DV-80 T344-7	11/96	73.04	14.99	1.19	0.14	0.09	0.50	0.21	4.86	4.99	100.01	0.9318
4	3722	FLV-229-CuC T344-5	11/96	73.00	14.90	1.17	0.13	0.10	0.50	0.21	4.87	5.11	99.99	0.9296
5	1924	1-JWB-1-CM-2 T154-1	2/.24/88	72.82	14.97	1.30	0.12	0.11	0.50	0.20	5.06	4.92	100.00	0.9219
6	4791	SL-AS06-1ii_pop1 T468-3	8-1-01	75.98	12.96	1.36	0.13	0.08	0.74	0.18	3.99	4.57	99.99	0.9210
7	3770	OL92-1 (40.01-41.54M), T349-8	11/96	71.82	15.49	1.38	0.15	0.11	0.66	0.23	4.91	5.24	99.99	0.9182
8	1256	WL 4-26 66.44m t95-3	5/29/85	72.73	14.65	1.32	0.16	0.10	0.59	0.26	5.12	5.07	100.00	0.9128
9	1464	ZAUTIPAN 14 T115-7	1/27/86	74.30	14.00	1.40	0.13	0.06	0.66	0.15	4.15	5.17	100.02	0.9124
10	4536	DN-98-137 T421-7	11-5-99	72.56	15.05	1.43	0.19	0.09	0.61	0.29	4.75	5.03	100.00	0.9096
11	1925	1-JWB-1-CM-3 T154-2	2/24/88	72.87	14.90	1.29	0.12	0.12	0.48	0.20	5.10	4.92	100.00	0.9091
12	2719	FLV-204-PC T249-7	1/30/92	73.38	14.53	1.04	0.10	0.10	0.62	0.19	4.32	5.71	99.99	0.9091
13	2278	T190-4 FLV-82-HT	5/10/89	72.98	14.62	1.90	0.15	0.09	0.73	0.18	4.84	4.52	100.01	0.9088
14	2131	CCPC-5.36 C lo Na lsh		77.67	13.78	1.54	0.21	0.09	0.61	0.20	1.36	4.53	99.99	0.9030
15	3295	FL-KA-52A lofe fr. T307-3	8/1/94	71.27	15.33	1.32	0.13	0.08	0.64	0.26	4.10	6.88	100.01	0.9015
16	3225	ALT-12 T299-2	4/14/94	73.67	14.79	1.73	0.16	0.08	0.66	0.20	4.71	4.01	100.01	0.8973
17	2547	UCSB-FS-89-6-6BC T225-5	4/22/91	73.00	14.93	1.11	0.11	0.10	0.49	0.21	5.20	4.86	100.01	0.8971
18	4175	DN-97-42 T380-7	3/13/98	72.15	15.52	1.39	0.21	0.09	0.64	0.27	4.86	4.85	99.98	0.8968
19	3293	FL-KA-51 T307-2	8/1/94	72.21	15.38	1.30	0.17	0.09	0.66	0.24	3.32	6.64	100.01	0.8927
20	3762	OL92-1 (47.90M) POP#2 T149-1	11/96	72.27	15.70	1.06	0.11	0.10	0.49	0.20	5.21	4.86	100.00	0.8910
21	2023	KRL-82882-DPB T168-8	7/20/88	73.00	14.40	1.70	0.13	0.07	0.86	0.16	4.45	5.24	100.01	0.8884
22	3265	FLV 3.13 (9.89m) LoSi T310-9	8/1/94	72.48	15.47	1.12	0.13	0.12	0.47	0.21	5.21	4.81	100.02	0.8880
23	299	PR, T25-5		74.63	13.86	1.53	0.16	0.07	0.81	0.19	4.11	4.64	100.00	0.8872
24	4747	CTB-5-95 KHANSON GEOMATRIX		75.77	13.19	1.01	0.15	0.08	0.77	0.18	3.82	5.04	100.01	0.8830
25	4777	758-369(2)S_pop3 T465-7	7-23-01	72.59	14.13	2.17	0.09	0.08	0.62	0.19	4.41	5.72	100.00	0.8829
26	4784	758-369(2)S_pop3 T465-7	7-23-01	72.59	14.13	2.17	0.09	0.08	0.62	0.19	4.41	5.72	100.00	0.8829
27	4628	K-98-5-7c T441-2	6-29-00	74.18	13.81	1.46	0.11	0.08	0.40	0.19	3.31	6.46	100.00	0.8811
28	3320	1-36-26J T312-9	10/21/94	73.26	14.97	2.13	0.13	0.11	0.51	0.21	2.50	6.18	100.00	0.8784
29	3511	TPSS-340 MAJOR T324-10	6/3/95	73.00	14.63	1.88	0.17	0.11	0.66	0.18	5.19	4.18	100.00	0.8773
30	2807	dsdp-36-12-5-93-95cm T257-1	5/14/92	72.77	14.86	1.86	0.17	0.10	0.72	0.19	5.53	3.78	99.98	0.8771
31	5067	SL-AS9-II T498-6	4-23-03	76.50	13.01	1.17	0.13	0.04	0.61	0.19	3.62	4.72	99.99	0.8767
32	1568	WLC-85-2 (9.40M) T127-13	8/18/86	72.15	15.35	1.59	0.18	0.11	0.72	0.23	4.86	4.80	99.99	0.8765
33	3317	1-36-9J T312-7	10/21/94	73.17	14.68	2.06	0.12	0.08	0.52	0.20	2.20	6.96	99.99	0.8754
34	2407	TULELAKE SAMPLE 694 T207-3	5/15/90	75.11	13.79	1.43	0.13	0.04	0.72	0.17	3.98	4.65	100.02	0.8747
35	2632	UWB-1B T235-8	8/30/91	75.69	13.40	0.86	0.11	0.07	0.62	0.18	3.66	5.40	99.99	0.8740
36	1739	BRICE-2 T-136-7	4/22/87	77.25	13.45	1.26	0.15	0.08	0.56	0.21	3.59	3.47	100.02	0.8734
37	3104	DLS-572Ab (lo-fe) T289-6	11/4/93	74.01	14.22	1.55	0.17	0.06	0.58	0.22	4.61	4.59	100.01	0.8729
38	4804	SL-AS22-21 T469-1	8-1-01	75.15	13.53	1.41	0.12	0.06	0.67	0.14	4.62	4.29	99.99	0.8719
39	5074	DPB-9 T210-6(2)	4-23-03	77.09	14.52	1.39	0.18	0.09	0.62	0.26	2.73	3.12	100.00	0.8718
40	2277	T190-3 FLV-79-HT	5/10/89	72.97	14.48	1.91	0.16	0.06	0.75	0.19	4.60	4.87	99.99	0.8710

← Sample AL98-51A (PN9811-51A) (this project)

← Sample OL92-1 (closest match with age control)

Sample AL98-51A (PN9811-51A), T440-1

Listing of 50 closest matches for COMP. NO. 4619 for elements: Na, Mg, Al, Si, K , Ca, Ti, Fe Date of Update: 08/02/00

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4619	AL98-51A T440-1	6-29-00	73.18	14.90	1.41	0.13	0.09	0.62	0.19	4.38	5.10	100.00	1.0000
2	1464	ZAUTIPAN 14 T115-7	1/27/86	74.30	14.00	1.40	0.13	0.06	0.66	0.15	4.15	5.17	100.02	0.9475
3	3660	CKCS(WS)-1(WSU Lab.)		73.32	14.90	1.45	0.16	ND	0.57	0.18	4.54	4.88	100.00	0.9464
4	3754	CKS(WS)-1 T348-2	11/96	72.18	15.50	1.37	0.15	0.09	0.55	0.18	4.97	5.02	100.01	0.9357
5	2407	TULELAKE SAMPLE 694 T207-3	5/15/90	75.11	13.79	1.43	0.13	0.04	0.72	0.17	3.98	4.65	100.02	0.9328
6	3722	FLV-229-CuC T344-5	11/96	73.00	14.90	1.17	0.13	0.10	0.50	0.21	4.87	5.11	99.99	0.9295
7	1924	1-JWB-1-CM-2 T154-1	2/.24/88	72.82	14.97	1.30	0.12	0.11	0.50	0.20	5.06	4.92	100.00	0.9278
8	3770	OL92-1 (40.01-41.54M) T349-8	11/96	71.82	15.49	1.38	0.15	0.11	0.66	0.23	4.91	5.24	99.99	0.9274
9	1925	1-JWB-1-CM-3 T154-2	2/24/88	72.87	14.90	1.29	0.12	0.12	0.48	0.20	5.10	4.92	100.00	0.9227
10	2719	FLV-204-PC T249-7	1/30/92	73.38	14.53	1.04	0.10	0.10	0.62	0.19	4.32	5.71	99.99	0.9198
11	3723	JRK-DV-80 T344-7	11/96	73.04	14.99	1.19	0.14	0.09	0.50	0.21	4.86	4.99	100.01	0.9194
12	1209	TULELAKE 2104 LAP (52.06M) T91	3/1/85	76.41	12.90	1.20	0.13	0.04	0.64	0.17	3.77	4.73	99.99	0.9158
13	2963	FB29A58B-M T274-4	3/31/93	74.67	13.77	1.25	0.15	0.05	0.66	0.23	4.02	5.20	100.00	0.9152
14	2023	KRL-82882-DPB T168-8	7/20/88	73.00	14.40	1.70	0.13	0.07	0.86	0.16	4.45	5.24	100.01	0.9142
15	608	TULELAKE-264, T69-7	12/xx/83	76.16	13.00	1.24	0.11	0.05	0.62	0.17	3.93	4.72	100.00	0.9096
16	4303	MRM-20-97-8 T394-1	8-3-98	74.65	13.74	1.61	0.11	0.02	0.73	0.19	4.62	4.32	99.99	0.9086
17	3190	F8-90-G21 (39-41cm) Hi-Fe T304	3/24/94	74.47	14.01	1.71	0.14	0.04	0.77	0.18	4.30	4.37	99.99	0.9084
18	3104	DLS-572Ab (lo-fe) T289-6	11/4/93	74.01	14.22	1.55	0.17	0.06	0.58	0.22	4.61	4.59	100.01	0.9083
19	3295	FL-KA-52A lofe fr. T307-3	8/1/94	71.27	15.33	1.32	0.13	0.08	0.64	0.26	4.10	6.88	100.01	0.9074
20	299	PR, T25-5		74.63	13.86	1.53	0.16	0.07	0.81	0.19	4.11	4.64	100.00	0.9073
21	3834	CD2-8.525M T354-5	1/97	75.71	13.60	1.64	0.14	0.04	0.70	0.19	4.29	3.70	100.01	0.9073
22	1256	WL 4-26 66.44m t95-3	5/29/85	72.73	14.65	1.32	0.16	0.10	0.59	0.26	5.12	5.07	100.00	0.9072
23	2277	T190-3 FLV-79-HT	5/10/89	72.97	14.48	1.91	0.16	0.06	0.75	0.19	4.60	4.87	99.99	0.9067
24	4301	MRM-20-97-6 T392-9	8-3-98	74.76	13.57	1.71	0.12	0.03	0.71	0.18	4.61	4.31	100.00	0.9066
25	4300	MRM-20-97-5 T392-8	8-3-98	74.79	13.67	1.60	0.12	0.02	0.75	0.18	4.63	4.24	100.00	0.9065
26	492	758-373, T18-2		74.92	13.58	1.51	0.15	0.00	0.82	0.19	3.59	5.24	100.00	0.9047
27	3491	PB-LVBC-1 T318-10 redo	5/6/95	74.70	13.89	1.34	0.12	0.04	0.75	0.15	3.75	5.26	100.00	0.9034
28	1027	KRL-71082 (II-3) (592) T58-3	6/22/84	72.65	14.86	1.27	0.12	0.00	0.49	0.24	5.26	5.11	100.00	0.9033
29	4297	MRM-20-97-2 T392-5	8-3-98	74.65	13.75	1.70	0.13	0.04	0.80	0.18	4.60	4.16	100.01	0.9028
30	3225	ALT-12 T299-2	4/14/94	73.67	14.79	1.73	0.16	0.08	0.66	0.20	4.71	4.01	100.01	0.9024
31	853	LM-6		75.48	13.61	1.52	0.14	0.03	0.82	0.19	3.50	4.70	99.99	0.9020
32	1028	KRL-71082 (II-5) (594) T58-5	6/22/84	72.51	14.72	1.33	0.15	0.00	0.59	0.29	5.03	5.38	100.00	0.9018
33	1408	WL 8-2A 22.0-22.5 CM RECALC T9	5/1/85	73.77	14.24	1.66	0.12	0.06	0.72	0.13	4.16	5.13	99.99	0.9012
34	3003	JY-92-14 T278-9	5/3/93	74.47	14.01	1.33	0.16	0.04	0.89	0.19	3.72	5.18	99.99	0.9012
35	70	DSDP-3, T9-5		75.60	13.21	1.64	0.13	0.02	0.78	0.21	4.32	4.09	100.00	0.9003
36	4536	IN-98-137 T421-7	11-5-99	72.56	15.05	1.43	0.19	0.09	0.61	0.29	4.75	5.03	100.00	0.8999
37	3265	FLV 3.13 (9.89m) LoSi T310-9	8/1/94	72.48	15.47	1.12	0.13	0.12	0.47	0.21	5.21	4.81	100.02	0.8993
38	917	DR-22		74.35	13.65	1.98	0.14	0.05	0.61	0.19	5.02	4.01	100.00	0.8980
39	2278	T190-4 FLV-82-HT	5/10/89	72.98	14.62	1.90	0.15	0.09	0.73	0.18	4.84	4.52	100.01	0.8969
40	1135	Tulelake 1894 (resamp. 749) T8	12/3/84	74.53	13.60	1.87	0.14	0.05	0.74	0.17	4.45	4.45	100.00	0.8958
41	4555	AI-85-1A T431-10	12-5-99	74.57	13.89	1.77	0.13	0.03	0.96	0.19	4.00	4.46	100.00	0.8930

Sample AL98-51A (PN9811-51A), T440-1

Listing of 50 closest matches for COMP. NO. 4619 for elements: Mg, Al, Si, Ca, Ti, Fe Date of Update: 08/02/00

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4619	AL98-51A T440-1	6-29-00	73.18	14.90	1.41	0.13	0.09	0.62	0.19	4.38	5.10	100.00	1.0000
2	3660	CKCS(WS)-1 (WSU Lab)		73.32	14.90	1.45	0.16	ND	0.57	0.18	4.54	4.88	100.00	0.9416
3	1464	ZALTIPAN 14 T115-7	1/27/86	74.30	14.00	1.40	0.13	0.06	0.66	0.15	4.15	5.17	100.02	0.9410
4	2407	TULELAKE SAMPLE 694 T207-3	5/15/90	75.11	13.79	1.43	0.13	0.04	0.72	0.17	3.98	4.65	100.02	0.9403
5	3754	CKS(WS)-1 T348-2	11/96	72.18	15.50	1.37	0.15	0.09	0.55	0.18	4.97	5.02	100.01	0.9367
6	1924	1-JWB-1-CM-2 T154-1	2/.24/88	72.82	14.97	1.30	0.12	0.11	0.50	0.20	5.06	4.92	100.00	0.9320
7	3295	FL-KA-52A lofe fr. T307-3	8/1/94	71.27	15.33	1.32	0.13	0.08	0.64	0.26	4.10	6.88	100.01	0.9303
8	1925	1-JWB-1-CM-3 T154-2	2/24/88	72.87	14.90	1.29	0.12	0.12	0.48	0.20	5.10	4.92	100.00	0.9263
9	3770	OL92-1 (40.01-41.54M) T349-8	11/96	71.82	15.49	1.38	0.15	0.11	0.66	0.23	4.91	5.24	99.99	0.9257
10	3834	CD2-8.525M T354-5	1/97	75.71	13.60	1.64	0.14	0.04	0.70	0.19	4.29	3.70	100.01	0.9256
11	3722	FLV-229-CUC T344-5	11/96	73.00	14.90	1.17	0.13	0.10	0.50	0.21	4.87	5.11	99.99	0.9231
12	1209	TULELAKE 2104 LAP (52.06M) T91	3/1/85	76.41	12.90	1.20	0.13	0.04	0.64	0.17	3.77	4.73	99.99	0.9230
13	3125	RL-3484	12/17/93	74.81	14.01	1.51	0.12	0.05	0.68	0.16	4.99	3.68	100.01	0.9215
14	917	DR-22		74.35	13.65	1.98	0.14	0.05	0.61	0.19	5.02	4.01	100.00	0.9208
15	3225	ALT-12 T299-2	4/14/94	73.67	14.79	1.73	0.16	0.08	0.66	0.20	4.71	4.01	100,01	0.9171
16	853	LM-6		75.48	13.61	1.52	0.14	0.03	0.82	0.19	3.50	4.70	99.99	0.9159
17	2719	FLV-204-PC T249-7	1/30/92	73.38	14.53	1.04	0.10	0.10	0.62	0.19	4.32	5.71	99.99	0.9132
18	2215	CAES #1 678 T181B-3	1/23/89	76.05	13.35	1.28	0.13	0.04	0.76	0.17	2.87	5.35	100.00	0.9128
19	3723	JRK-DV-80 T344-7	11/96	73.04	14.99	1.19	0.14	0.09	0.50	0.21	4.86	4.99	100.01	0.9126
20	4300	MRM-20-97-5 T392-8	8-3-98	74.79	13.67	1.60	0.12	0.02	0.75	0.18	4.63	4.24	100.00	0.9124
21	4303	MRM-20-97-8 T394-1	8-3-98	74.65	13.74	1.61	0.11	0.02	0.73	0.19	4.62	4.32	99.99	0.9123
22	4301	MRM-20-97-6 T392-9	8-3-98	74.76	13.57	1.71	0.12	0.03	0.71	0.18	4.61	4.31	100.00	0.9096
23	4297	MRM-20-97-2 T392-5	8-3-98	74.65	13.75	1.70	0.13	0.04	0.80	0.18	4.60	4.16	100.01	0.9092
24	608	TULELAKE-264, T69-7	12/xx/83	76.16	13.00	1.24	0.11	0.05	0.62	0.17	3.93	4.72	100.00	0.9089
25	492	758-373, T18-2		74.92	13.58	1.51	0.15	0.00	0.82	0.19	3.59	5.24	100.00	0.9075
26	3190	F8-90-G21 (39-41cm) Hi-Fe T304	3/24/94	74.47	14.01	1.71	0.14	0.04	0.77	0.18	4.30	4.37	99.99	0.9048
27	968	DR-82		76.65	13.14	1.25	0.14	0.05	0.75	0.18	4.21	3.61	99.98	0.9043
28	2963	FB29A58B-M T274-4	3/31/93	74.67	13.77	1.25	0.15	0.05	0.66	0.23	4.02	5.20	100.00	0.9038
29	1739	BRICE-2 T-136-7	4/22/87	77.25	13.45	1.26	0.15	0.08	0.56	0.21	3.59	3.47	100.02	0.9030
30	3104	DLS-572Ab (lo-fe) T289-6	11/4/93	74.01	14.22	1.55	0.17	0.06	0.58	0.22	4.61	4.59	100.01	0.9028
31	4366	SK-98-33 T398-6	10-21-98	74.72	13.51	2.07	0.13	0.06	0.73	0.19	4.69	3.90	100.00	0.9028
32	70	DSDP-3, T9-5		75.60	13.21	1.64	0.13	0.02	0.78	0.21	4.32	4.09	100.00	0.9023
33	3265	FLV 3.13 (9.89m) LoSi T310-9	8/1/94	72.48	15.47	1.12	0.13	0.12	0.47	0.21	5.21	4.81	100.02	0.9018
34	299	PR, T25-5		74.63	13.86	1.53	0.16	0.07	0.81	0.19	4.11	4.64	100.00	0.9017
35	1256	WL 4-26 66.44m t95-3	5/29/85	72.73	14.65	1.32	0.16	0.10	0.59	0.26	5.12	5.07	100.00	0.9014
36	1372	850506-12A T104-13	8/26/85	76.43	13.49	1.11	0.15	0.04	0.66	0.18	3.54	4.40	100.00	0.9006
37	3491	PB-LVBC-1 T318-10 redo	5/6/95	74.70	13.89	1.34	0.12	0.04	0.75	0.15	3.75	5.26	100.00	0.9002
38	1027	KRL-71082 (II-3) (592) T58-3	6/22/84	72.65	14.86	1.27	0.12	0.00	0.49	0.24	5.26	5.11	100.00	0.8993
39	1028	KRL-71082 (II-5) (594) T58-5	6/22/84	72.51	14.72	1.33	0.15	0.00	0.59	0.29	5.03	5.38	100.00	0.8992
40	3895	CV-9-4-7		72.99	13.89	1.92	0.13	0.06	0.56	0.23	2.49	7.73	100.00	0.8989
41	918	DR-23		74.88	13.45	1.83	0.12	0.06	0.54	0.18	4.92	4.02	100.00	0.8986

Sample AL98-51A (PN9811-51A), T440-1

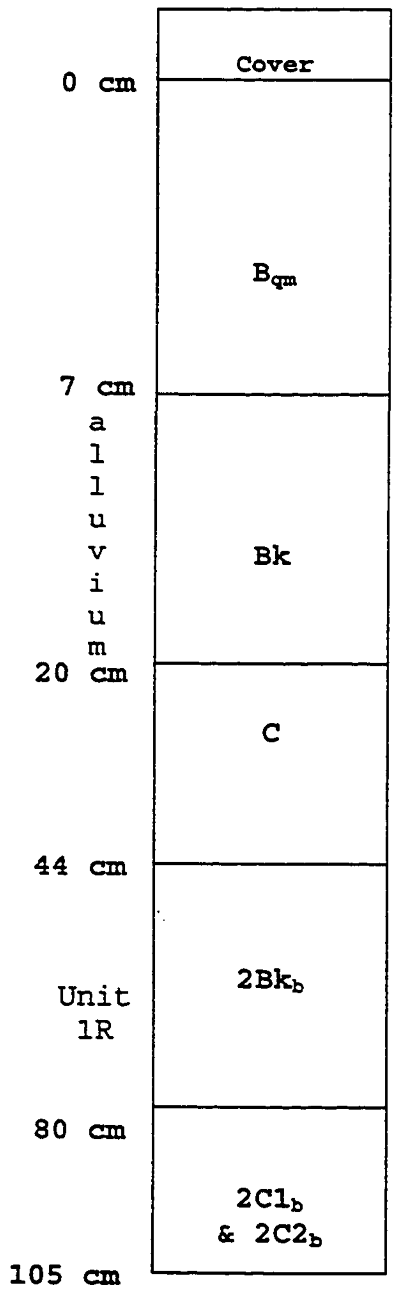
Listing of 40 closest matches for COMP. NO. 4619 for elements: Mg, Al, Si, K , Ca, Ti, Fe Date of Update: 08/20/03

	C.No	Sample Number	Date	SiO2	Al2O3	Fe2O3	MgO	MnO	CaO	TiO2	Na2O	K2O	Total,R	Sim. Co
1	4619	AL98-51A T440-1	6-29-00	73.18	14.90	1.41	0.13	0.09	0.62	0.19	4.38	5.10	100.00	1.0000
2	1464	ZAUTIPAN 14 T115-7	1/27/86	74.30	14.00	1.40	0.13	0.06	0.66	0.15	4.15	5.17	100.02	0.9475
3	3660	CKCS(WS)-1		73.32	14.90	1.45	0.16	0.00	0.57	0.18	4.54	4.88	100.00	0.9438
4	3754	CKS(WS)-1 T348-2	11/96	72.18	15.50	1.37	0,15	0.09	0.55	0.18	4.97	5.02	100.01	0.9435
5	5067	SL-AS9-II T498-6	4-23-03	76.50	13.01	1.17	0.13	0.04	0.61	0.19	3.62	4.72	99.99	0.9384
6	1924	1-JWB-1-CM-2 T154-1	2/.24/88	72.82	14.97	1.30	0.12	0.11	0.50	0.20	5.06	4.92	100.00	0.9367
7	2407	TULELAKE SAMPLE 694 T207-3	5/15/90	75.11	13.79	1.43	0.13	0.04	0.72	0.17	3.98	4.65	100.02	0.9362
8	3722	FLV-229-CuC T344-5	11/96	73.00	14.90	1.17	0.13	0.10	0.50	0.21	4.87	5.11	99.99	0.9338
9	3770	OL92-1 (40.01-41.54M) T349-8	11/96	71.82	15.49	1.38	0.15	0.11	0.66	0.23	4.91	5.24	99.99	0.9325
10	1925	1-JWB-1-CM-3 T154-2	2/24/88	72.87	14.90	1.29	0.12	0.12	0.48	0.20	5.10	4.92	100.00	0.9318
11	4791	SL-AS06-1ii_popl T468-3	8-1-01	75.98	12.96	1.36	0.13	0.08	0.74	0.18	3.99	4.57	99.99	0.9255
12	1209	TULELAKE 2104 LAP (52.06M) T91	3/1/85	76.41	12.90	1.20	0.13	0.04	0.64	0.17	3.77	4.73	99.99	0.9236
13	3723	JRK-DV-80 T344-7	11/96	73.04	14.99	1.19	0.14	0.09	0.50	0.21	4.86	4.99	100.01	0.9220
14	2215	CAES #1 678 T181B-3	1/23/89	76.05	13.35	1.28	0.13	0.04	0.76	0.17	2.87	5.35	100.00	0.9185
15	492	758-373, T18-2		74.92	13.58	1.51	0.15	0.00	0.82	0.19	3.59	5.24	100.00	0.9169
16	853	LM-6		75.48	13.61	1.52	0.14	0.03	0.82	0.19	3.50	4.70	99.99	0.9167
17	2963	FB29A58B-M T274-4	3/31/93	74.67	13.77	1.25	0.15	0.05	0.66	0.23	4.02	5.20	100.00	0.9148
18	1256	WL 4-26 66.44m t95-3	5/29/85	72.73	14.65	1.32	0.16	0.10	0.59	0.26	5.12	5.07	100.00	0.9146
19	1027	KRL-71082 (II-3) (592) T58-3	6/22/84	72.65	14.86	1.27	0.12	0.00	0.49	0.24	5.26	5.11	100.00	0.9134
20	608	TULELAKE-264, T69-7	12/xx/83	76.16	13.00	1.24	0.11	0.05	0.62	0.17	3.93	4.72	100.00	0.9113
21	2719	FLV-204-PC T249-7	1/30/92	73,38	14.53	1.04	0.10	0.10	0.62	0.19	4.32	5.71	99.99	0.9103
22	3491	PB-LVBC-1 T318-10 redo	5/6/95	74;70	13.89	1.34	0.12	0.04	0.75	0.15	3.75	5.26	100.00	0.9101
23	4767	SL-AS8-2ii T467-5	7-23-01	75;52	13.26	1.35	0.10	0.05	0.63	0.16	4.08	4.84	99.99	0.9087
24	3003	JY-92-14 T278-9	5/3/93	74.47	14.01	1.33	0.16	0.04	0.89	0.19	3.72	5.18	99.99	0.9086
25	3265	FLV 3.13 (9.89m) LoSi T310-9	8/1/94	72.48	15.47	1.12	0.13	0.12	0.47	0.21	5.21	4.81	100.02	0.9077
26	1028	KRL-71082 (II-5) (594) T58-5	6/22/84	72.51	14.72	1.33	0.15	0.00	0.59	0.29	5.03	5.38	100.00	0.9062
27	5011	WILL-CPW-AW-3 T493-9	3-17-03	74.96	13.91	1.35	0.17	0.04	0.88	0.19	3.39	5.12	100.01	0.9047
28	2023	KRL-82882-DPB T168-8	7/20/88	73.00	14.40	1.70	0.13	0.07	0.86	0.16	4.45	5.24	100.01	0.9042
29	3295	FL-KA-52A lofe fr. T307-3	8/1/94	71.27	15.33	1.32	0.13	0.08	0.64	0.26	4.10	6.88	100.01	0.9033
30	4303	MRM-20-97-8 T394-1	8-3-98	74.65	13.74	1.61	0.11	0.02	0.73	0.19	4.62	4,32	99.99	0.9030
31	299	PR, T25-5		74.63	13.86	1.53	0.16	0.07	0.81	0.19	4.11	4.64	100.00	0.9029
32	3104	DLS-572Ab (lo-fe) T289-6	11/4/93	74.01	14.22	1.55	0.17	0.06	0.58	0.22	4.61	4.59	100.01	0.9024
33	917	DR-22		74.35	13.65	1.98	0.14	0.05	0.61	0.19	5.02	4.01	100.00	0.9016
34	4804	SL-AS22-2i T469-1	8-1-01	75.15	13.53	1.41	0.12	0.06	0.67	0.14	4.62	4.29	99.99	0.9012
35	4300	MRM-20-97-5 T392-8	8-3-98	74.79	13.67	1.60	0.12	0.02	0.75	0.18	4.63	4.24	100.00	0.9008
36	4301	MRM-20-97-6 T392-9	8-3-98	74.76	13.57	1.71	0.12	0.03	0.71	0.18	4.61	4.31	100.00	0.9004
37	2277	T190-3 FLV-79-HT	5/10/89	72.97	14.48	1.91	0.16	0.06	0.75	0.19	4.60	4.87	99.99	0.9002
38	3886	GL2-26.83 (NON-MAG) T357-8	2/97	76.25	13.39	1.20	0.15	0.03	0.69	0.17	3.42	4.70	100.00	0.8987
39	4815	RK-RLC15 T470-10	10-18-01	73.96	14.03	1.33	0.16	0.06	0.77	0.20	3.48	6.02	100.01	0.8985
40	3225	ALT-12 T299-2	4/14/94	73.67	14.79	1.73	0.16	0.08	0.66	0.20	4.71	4.01	100.01	0.8985

APPENDIX B

SOIL PROFILES WITH HORIZON DESCRIPTIONS

Soil at Section #1 Horizon Descriptions



B_{qm} 7.5 Y, 7/2, 8/2, platy, fine, <10% gravel, no carbonate, very firm to extremely firm, cementation indurated, interpreted as silica (platy structure, no effervescence, harder than gypsum), abrupt smooth transition, buried desert pavement? discontinuous,indurated, prominent vertical cracks with surface material washed in, weakly coherent dry consistence, nonplastic

Bk 10 YR 6/6 peds are moderate, medium, angular, blocky, <10% gravel, no platy structure, very indurated, possible upper carbonate horizon, but very disseminated, abrupt, smooth transition to C horizon, same parent material as C horizon below, but clast size larger, coarse sand with pebbles, slightly sticky wet consistence, nonplastic

C 10 YR, 6/6, at least 10% gravel, texturally different from above horizon, abrupt, smooth transition, very gritty from 25 cm below horizon boundary, medium to coarse grain size, slightly sticky wet consistence, nonplastic

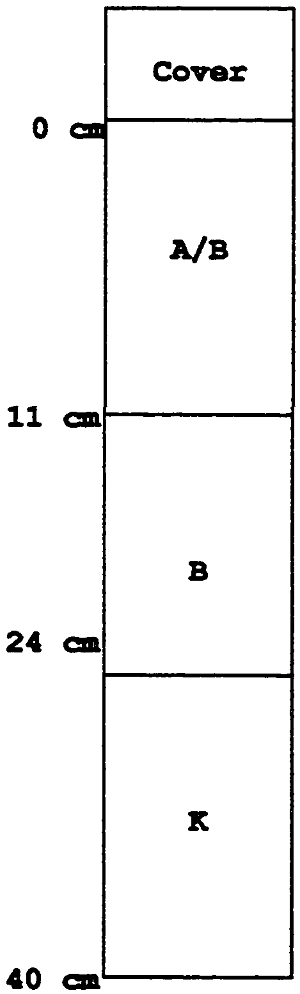
$2Bk_b$ 2.5 Y, 7/3 peds are weak, medium and angular blocky, <<5% gravel, close to 1%, carbonate occurs as nodules, veins and 50-90% of soil matrix, carbonate morphology at least stage II+, abrupt smooth transition, carbonate decreases downsection, more silty than layer above, with exception of one pebble layer, very friable, slightly sticky wet consistence, slightly plastic

$2C1_b$ silt and fine sand, possible cross-bedding lower in horizon, coarsens upsection, carbonized plants, roots, poorer sorting than horizons below, abrupt, smooth transition, indurated, but less so than sand below, no carbonate, slightly sticky nonplastic

$2C2_b$ beach sand, <10% clay, essentially unweathered

Note: Terms for texture, cementation, soil structure, and carbonate stages are from Birkeland et al. (1991). Alluvium and Unit 1R refer to the sedimentary units in Section #1 (Fig. 18).

Soil at Locality A   Horizon Descriptions



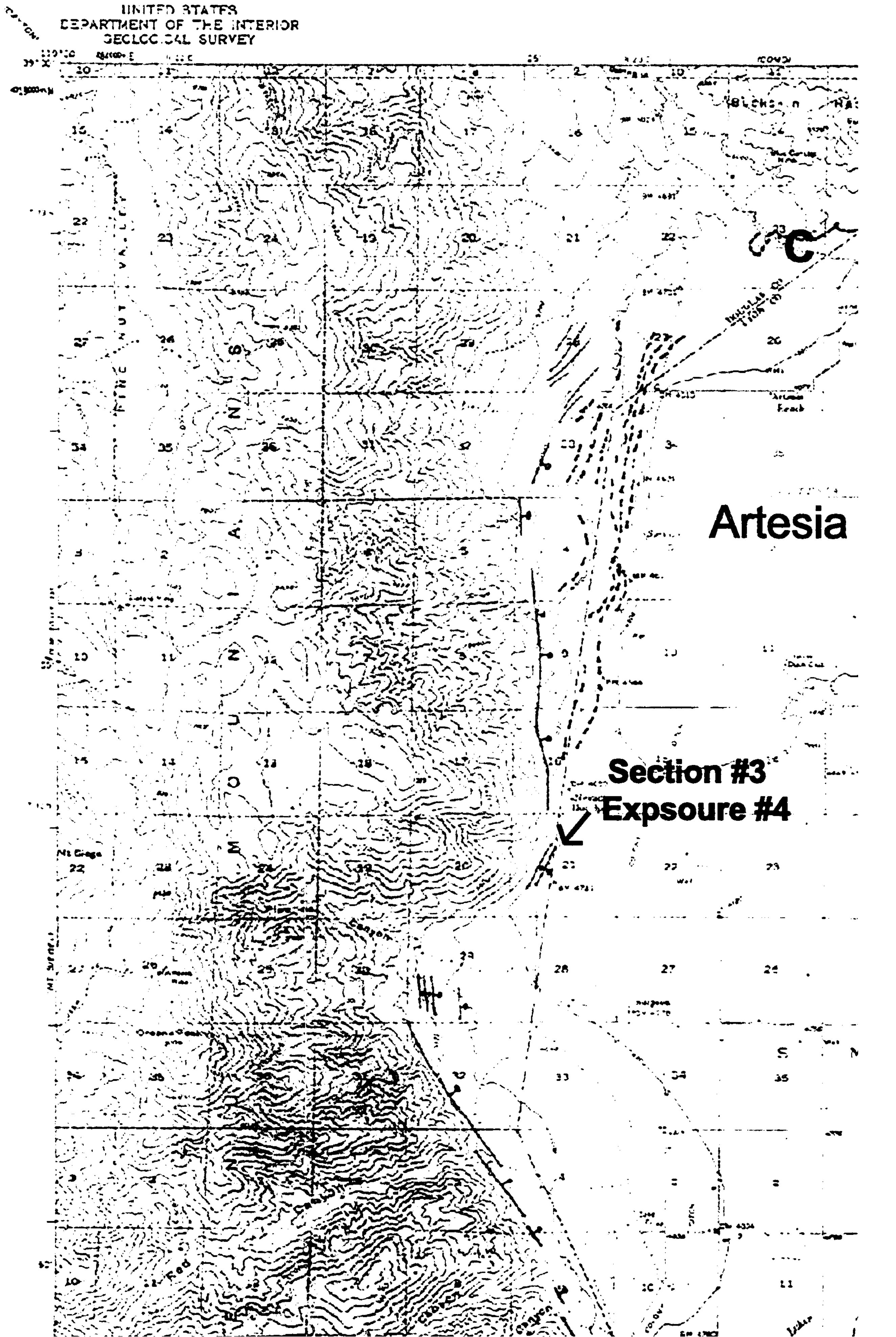
Cover desert pavement with desert varnish

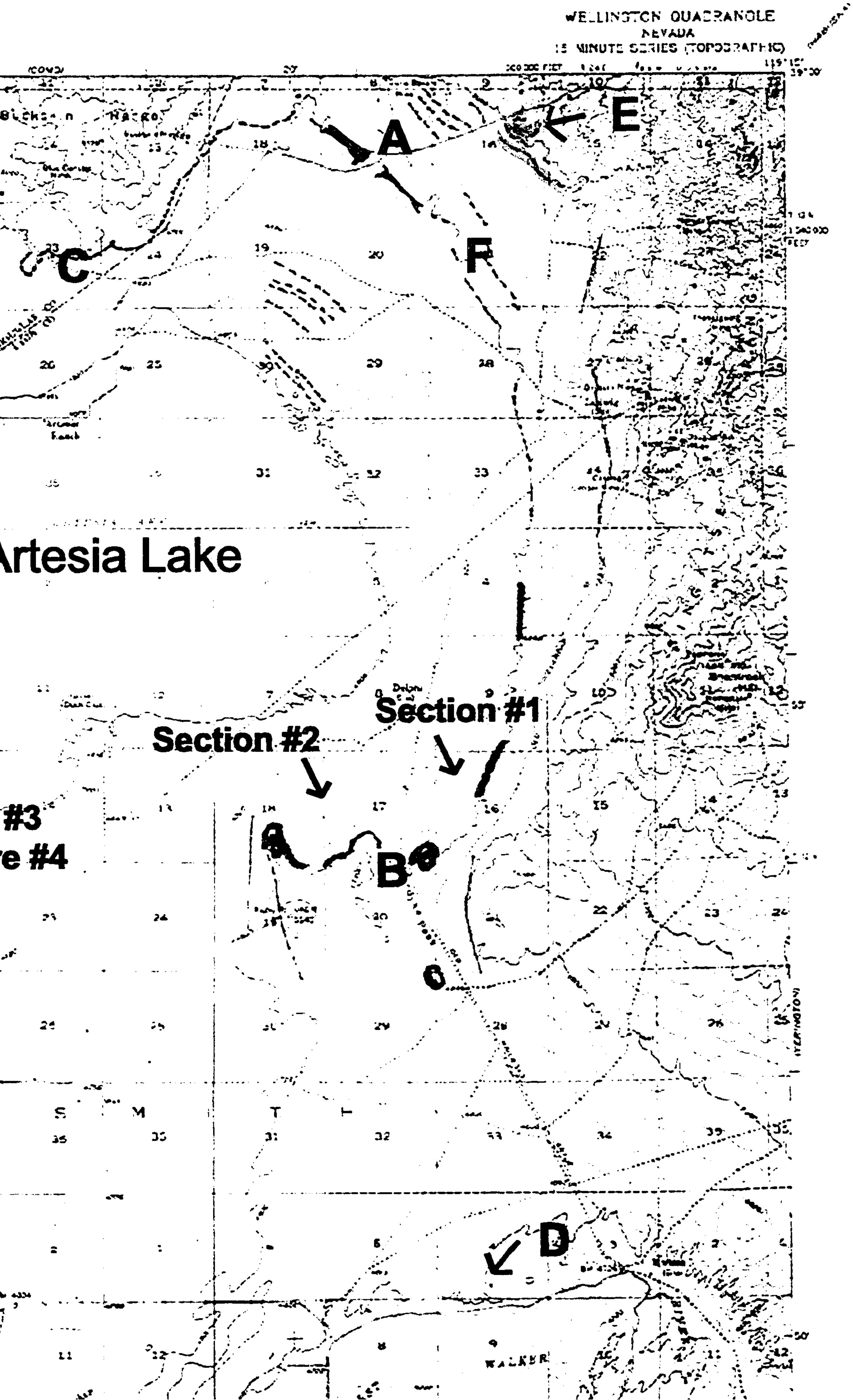
A/B 10YR, 6/4 dry; 10YR 5/4, mottled, <10% gravel, firm consistence (moist), prismatic to subangular blocky, many (>20%) weak peds, gritty, carbonate mottles, carbonate stage I to II, filaments, few nodules, 10-15% carbonate, slightly hard, ss, plastic, abrupt, smooth transition

B 2YR, 6/6 dry; 10YR 6/8 moist, mottled, loose, subangular blocky to granular, weak, weakly coherent(dry), noncoherent (moist), no cement, roots common, fewer $CaCO_3$ mottles than A/B horizon, carbonate stage I+, common filaments, non sticky, nonplastic, loamy sand abrupt smooth transition

K 10YR, 6/4, weak, platy, carbonate coatings on clasts, weak stage III, 50-90% of clasts coated, weak carbonate cement, non sticky, non plastic, loamy sand, the base is covered with debris from quarrying activities

Note: Terms for texture, cementation, soil structure, and carbonate stages are from Birkeland et al. (1991).


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Artesia
Section #3
Expsoure #4



EXPLANAT

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EXPLANATION

fault; ball on downdropped side; dashed where approximate or uncertain

shoreline; green highlights for those associated with deposits

bench not confirmed as shoreline and not associated with lacustrine deposits

probable beach (area of

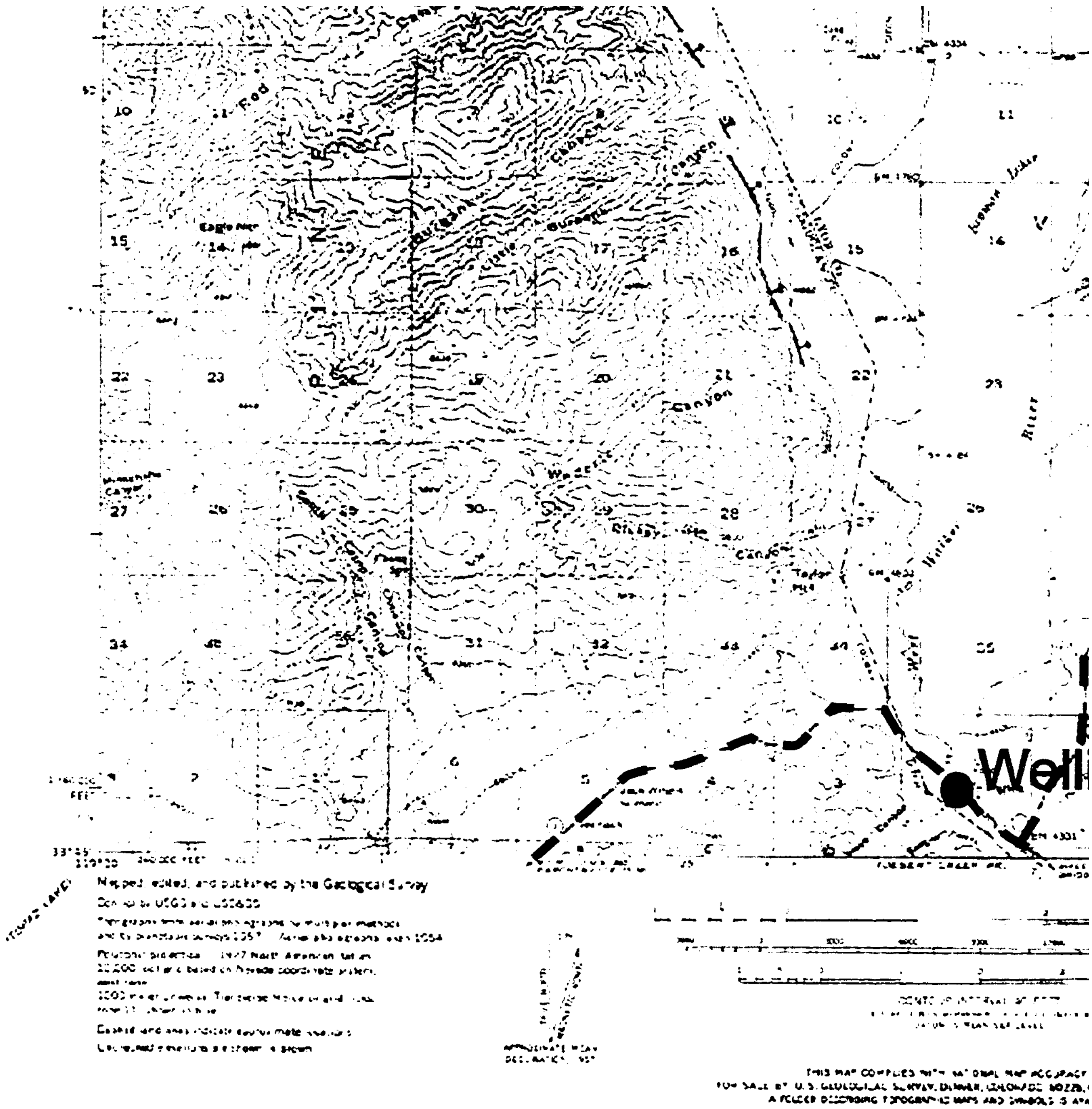

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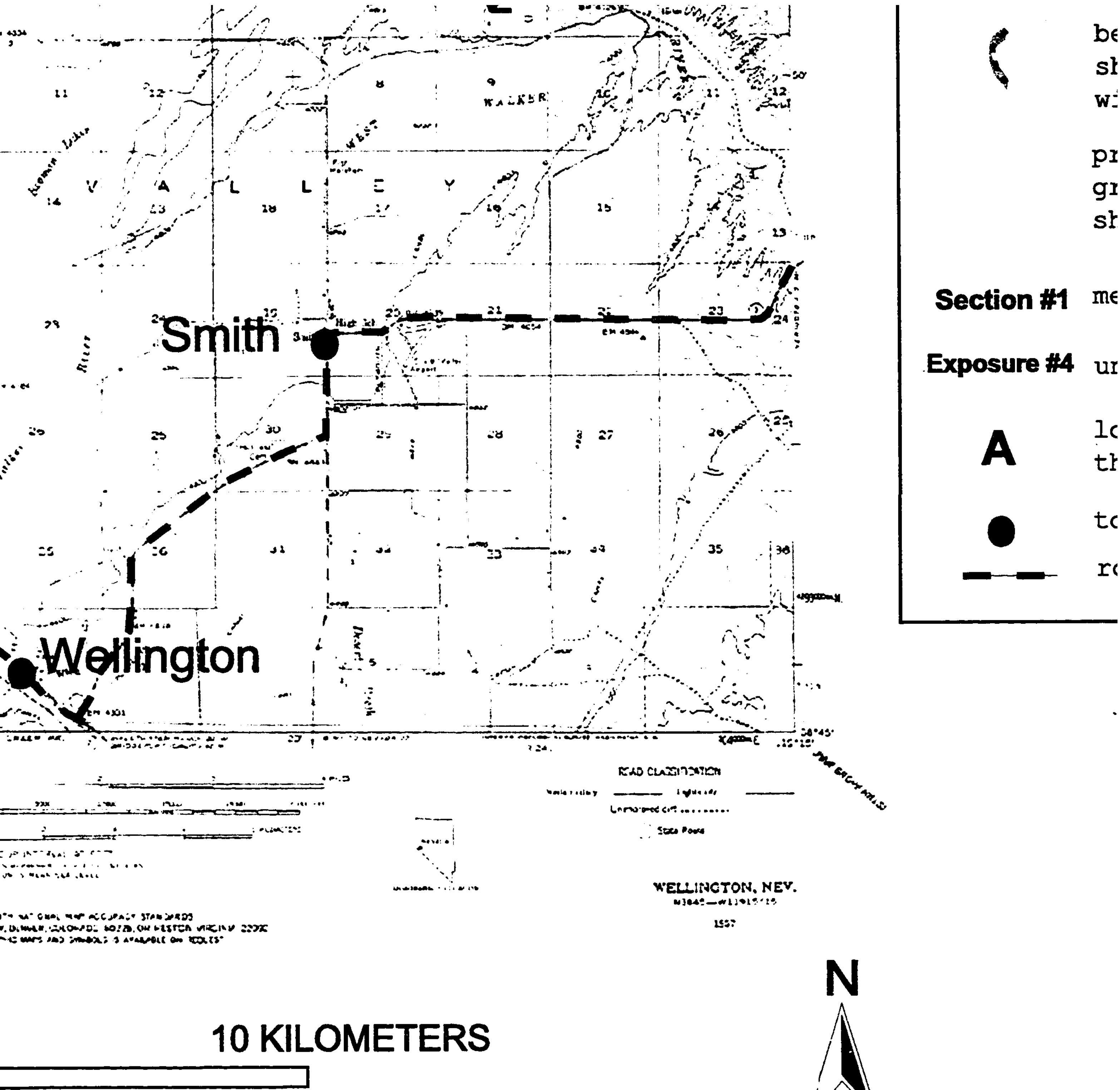
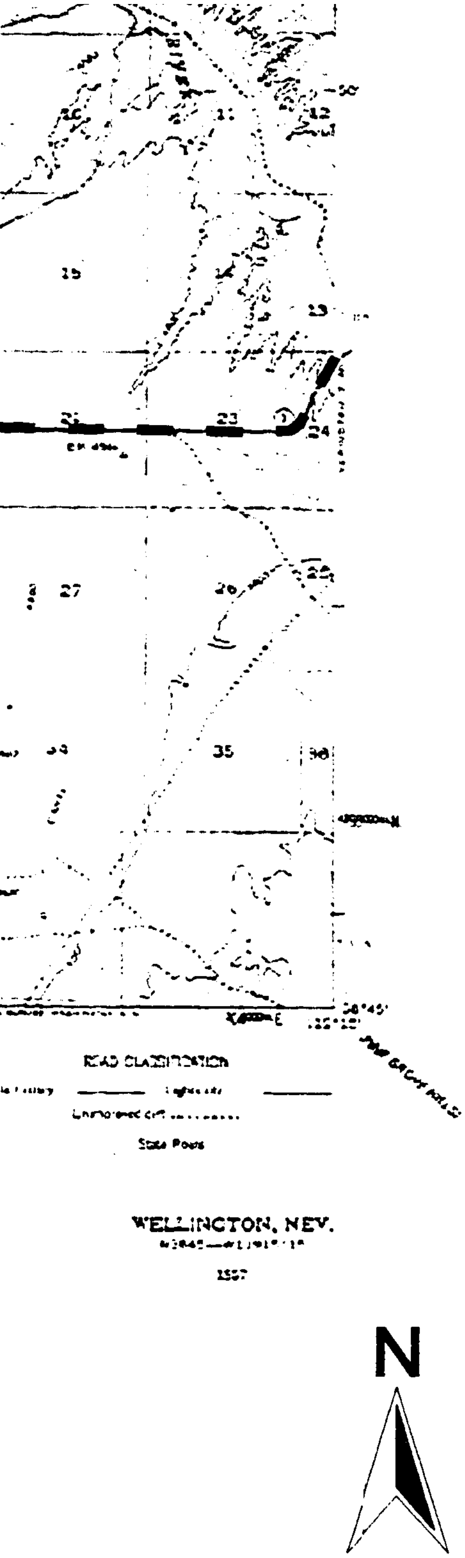
Plate 1. Map showing shorel
localities studied for this
15-Minute Quadrangle,

based on 1:20,000 scale aeria



orelines, beaches, faults, and
this project on the Wellington
gle, Smith Valley, Nevada,

aerial photographs (USDA, Soil



bench not confirmed as shoreline and not associated with lacustrine deposits

probable beach (area of gravel and sand near a shoreline or 1,477 m)

Section #1 measured section

Exposure #4 unmeasured exposure

A localities studied for this project

● town

road

, faults, and
ne Wellington
Nevada,

(USDA, Soil

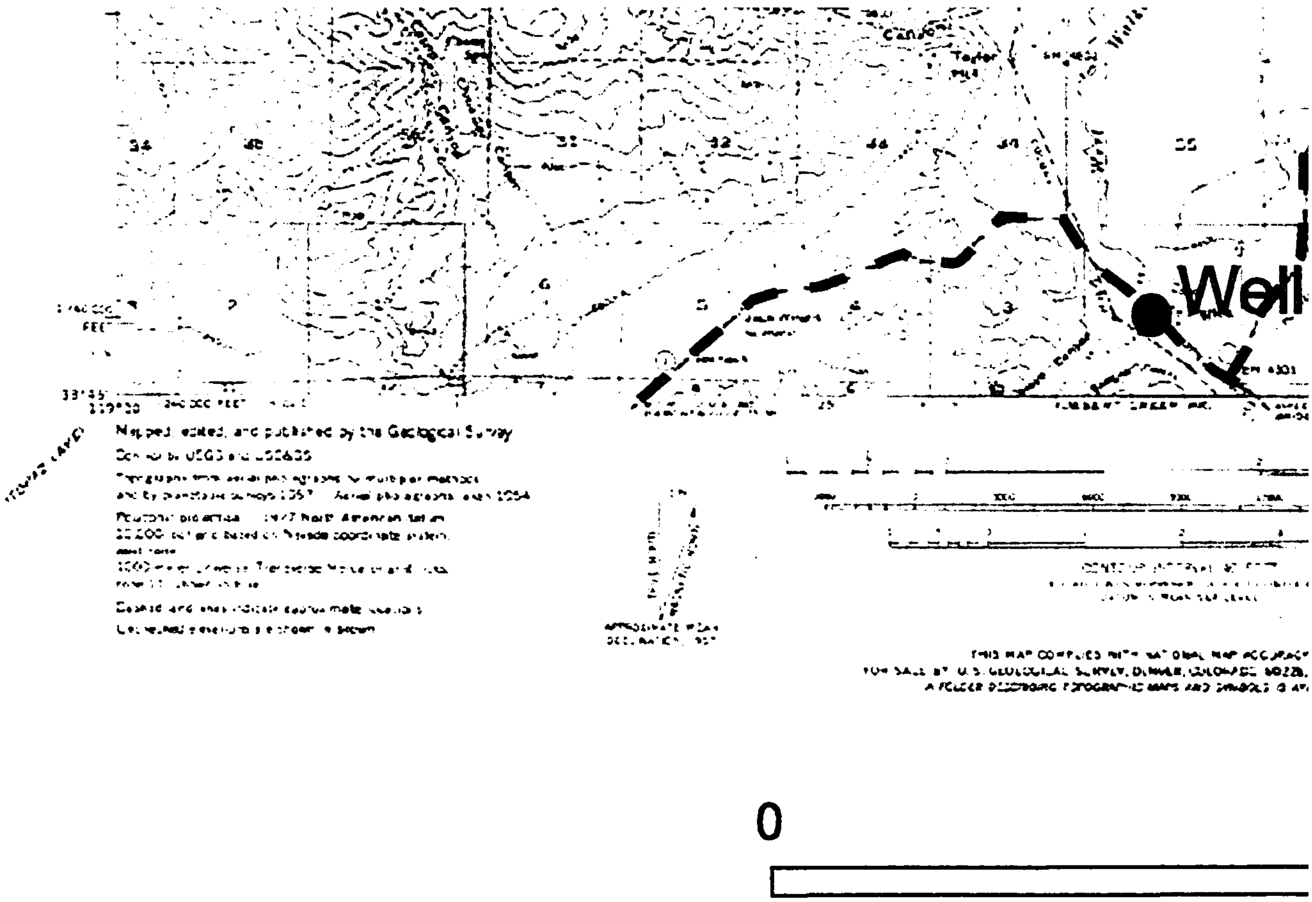
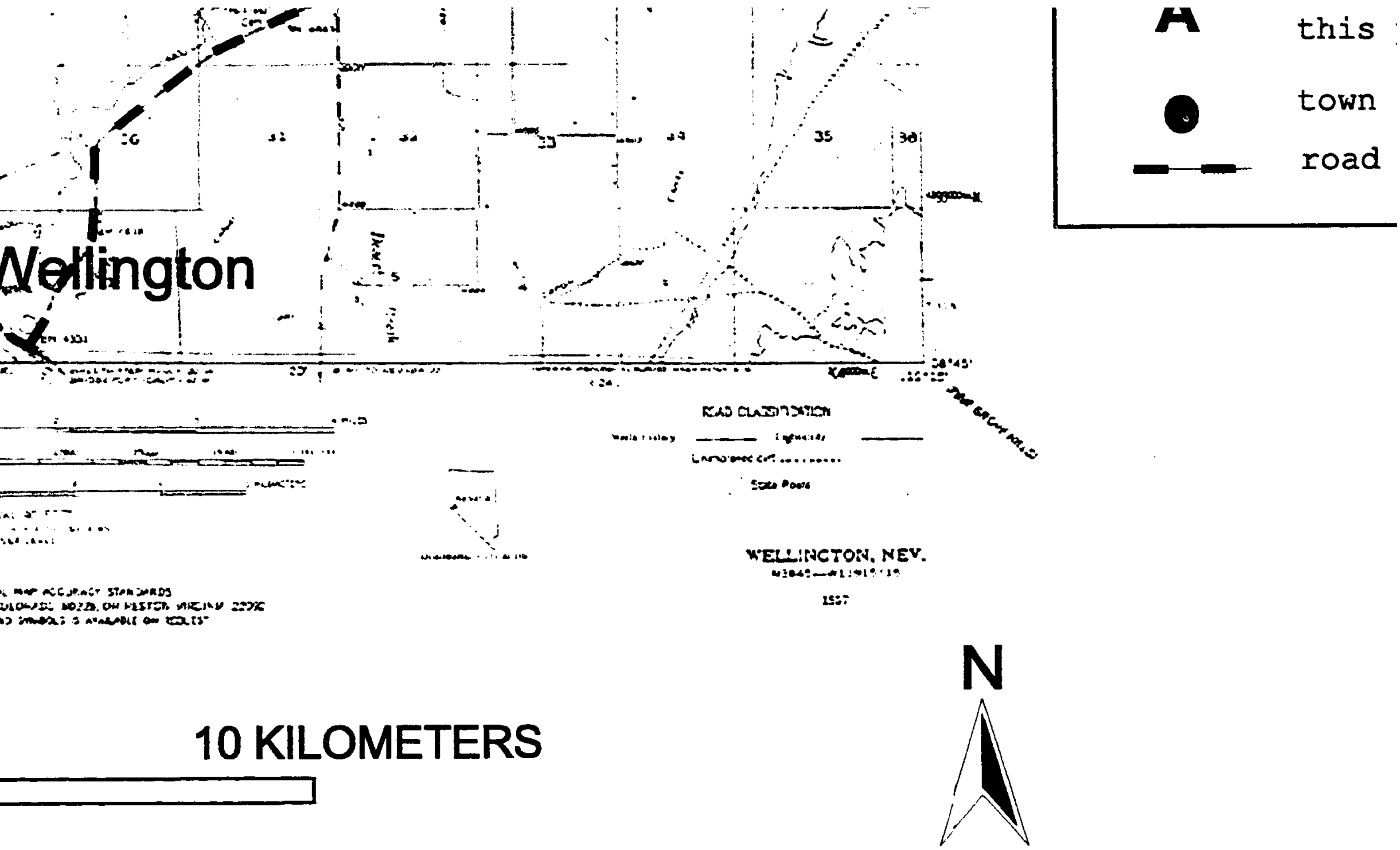


Plate 1. Map showing shorel
localities studied for this
15-Minute Quadrangle,

based on 1:20,000 scale aeria
Conservation Service, 1938)

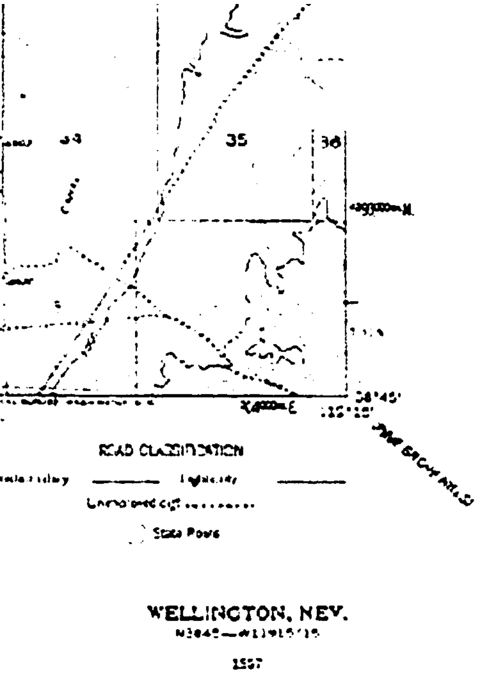
Stauffer, Heidi L., 2003, Timing of the last highstand

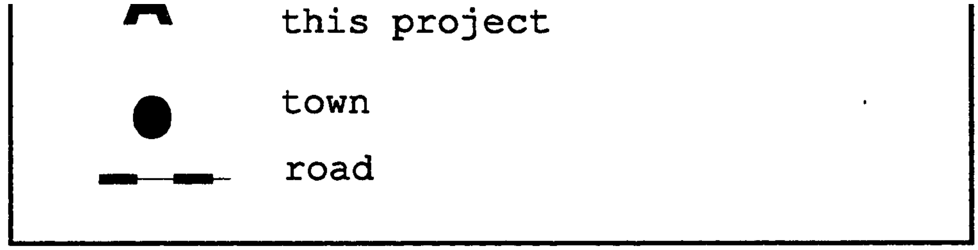


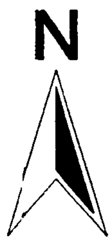
relines, beaches, faults, and
nis project on the Wellington
e, Smith Valley, Nevada,

erial photographs (USDA, Soil
38) and field reconnaissance

nstand of pluvial Lake Wellington, Smith Valley, Nevada.







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on, Smith Valley, Nevada.