Shoreline processes and the age of the Lake Lahontan highstand in the Jessup embayment, Nevada

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ABSTRACT

The well-developed shoreline record of pluvial Lake Lahontan in the Jessup embayment, Nevada, is used to refine the history of late Pleistocene lake-level fluctuations and to assess controls on shoreline development and distribution. Controls on the strength and type of shorelines developed include local slope, the amount and characteristics of sediment available for transport, the availability of accommodation space, and length of time the lake level resides at a particular shoreline elevation. At the Sehoo highstand and during the early part of the regression, strong storm winds and waves from the south-southeast set up a clockwise net shore-drift pattern near the head of the embayment. Although significant differences in local slope, geometry of the shoreline, and wave energy existed in the embayment, crestal heights of constructional shoreline features formed at the highstand vary <2.6 m in elevation and hence provide a relatively precise marker of the highstand elevation.

Radiocarbon dating of a camel bone preserved in high shoreline deposits indicates that the lake reached its highest elevation of 1338.5 m in the embayment and receded from that elevation immediately prior to 13 070 ± 60 yr B.P. Similar and slightly older radiocarbon ages on gastropod shells preserved in barrier deposits at 1327 m (13 280 ± 110 yr B.P.) and 1331 m (13 110 ± 110 yr B.P.) suggest that the final rise to the highstand was very rapid and that the lake maintained its highest stand for a very brief period of time, perhaps only for years or decades. The brevity of the highstand is reasonable in light of the recent formation of similar barrier features in modern Pyramid Lake, which formed in less than seven months due to a rapid increase in lake level.

INTRODUCTION

The deposits and landforms of pluvial Lake Lahontan in northwestern Nevada and northeastern California have long supplied evidence for the number, timing, and level of past lake cycles. Early studies concentrated on the stratigraphy of the deposits and developed relative age relationships between deposits of different lake cycles that are separated by subaerial deposits or paleosols (Russell, 1885; Morrison, 1964). Shortly after the inception of radiocarbon dating (Libby, 1955), an effort was initiated to constrain the timing of lake-level fluctuations by dating inorganic carbonate (tufa) and mollusk shells associated with different shoreline levels (Broecker and Orr, 1958; Broecker and Kaufman, 1965; Kaufman and Broecker, 1965). Over the past 25 yr, hundreds of radiocarbon ages have been generated that tightly constrain lake level fluctuations from about 30 ka to the present (Born, 1972; Benson, 1978, 1991, 1993; Thompson et al., 1986; Benson and Thompson, 1987a, 1987b; Dansie et al., 1988; Newton and Grossman, 1988; Benson et al., 1990, 1992, 1995). Estimates from most of these studies place the last major highstand between about 14.5 and 12.5 ka. The timing of earlier lake cycles has largely been determined from studies of the ages and depositional settings of numerous tephra deposits within the basin that have increased the known length of the lacustrine record to at least 1 Ma (Davis, 1978; Morrison and Davis, 1984; Reheis, 1996; Reheis and Morrison, 1997). The cumulative efforts of those who have studied the Lahontan basin have created one of the best documented and complete records of climatically induced changes in a continental setting.

In order to increase the resolution of an estimate on the timing and duration of the last major (Sehoo) highstand and to document fluctuations around the highstand, we initiated a process-based study of shoreline and offshore deposits and landforms in the Jessup embayment, a small pluvial bay located in the northwestern part of the Carson Sink that was inundated during the Sehoo lake cycle of Lake Lahontan (Fig. 1). Today, this former embayment contains a particularly well-preserved three-dimensional record of deposits and landforms formed during both transgressive and regressive stages of the Sehoo lake cycle, as well as deposits formed during an earlier lake cycle(s). Our initial focus is on description of the dynamic processes and conditions responsible for forming the various deposits and landforms in order to understand the lateral and vertical distribution of lacustrine facies within the embayment. This understanding is then used to interpret radiocarbon dates from highstand deposits and place new limits on the timing and duration of the Sehoo highstand.

Shoreline records in pluvial lake basins are also important to paleoenvironmental, paleohydrologic, and tectonic studies. Because constructional shorelines are rapidly formed and have a relatively high preservation potential, they are excellent recorders of minor lake-level fluctuations, the ages of which can be used to infer short-term changes in the hydrologic balance of a particular system. Net shore drift directions interpreted from shore deposits and landforms may be used to interpret paleowind directions and intensities that in turn can be used to "ground truth" global circulation models (GCMs) for specific times in the past. Shorelines are also paleohorizontal datums that are used to measure both broad upwarping (e.g., Gilbert, 1890; Crittenden, 1963; Bills and May, 1987; Adams, 1997) and brittle faulting (Adams, 1997). However, natural variability in elevation expressed along a particular shoreline is important to recognize when interpreting deformation data. In short, process-based studies of shorelines deposits and landforms can provide much information on multiple aspects of the histories of

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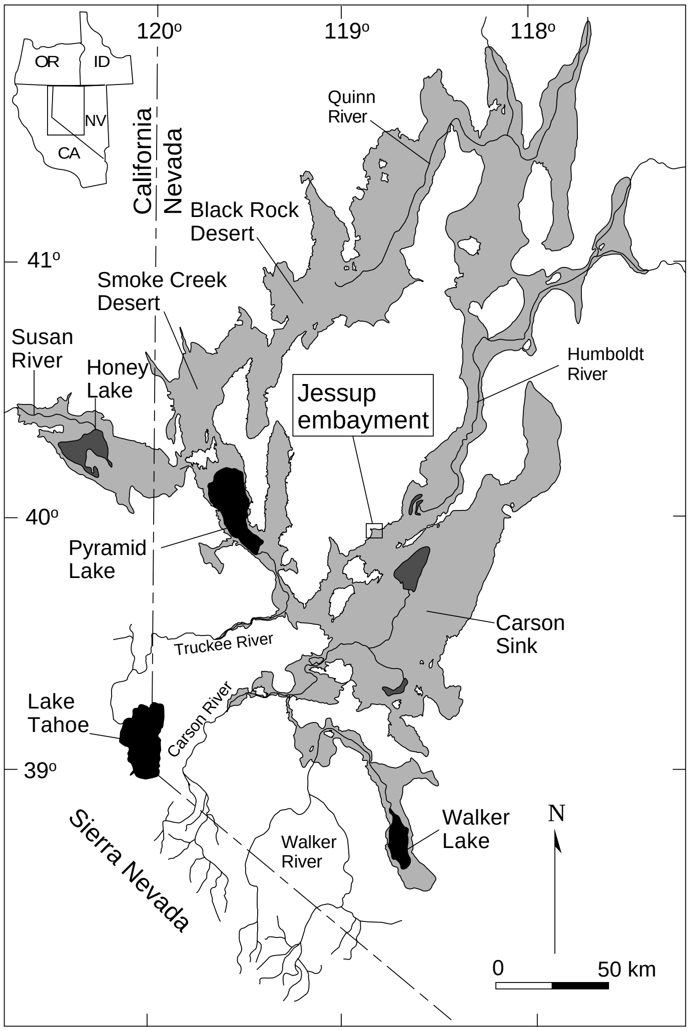

Figure 1. Map of Lake Lahontan as it appeared during the Sehoo cycle highstand. The locations of the Jessup embayment and other geographic features are also shown. CA—California; OR—Oregon; ID—Idaho; NV—Nevada.

closed lake basins in the western United States and elsewhere.

Lacustrine Deposits Within the Jessup Embayment

A diverse array of lacustrine deposits of varying relative ages was instrumental in refining the history of the Sehoo cycle of transgression and regression in the Jessup embayment. At the highstand the nearshore depositional environment consisted of a steep rocky shore, but as water level lowered, the depositional slope progressively decreased toward the flat floor of the Carson Sink. Figure 2 includes a stratigraphic column and schematic cross section that show relative age relationships between the different stratigraphic units. The spatial distribution of the various lacustrine units in the embayment is shown on the geologic and geomorphic map (Fig. 3), which is compiled from field mapping on 1:10 000 scale aerial photographs.

The Sehoo cycle beach gravel units (Qsg_1, Qsg_2, Qsg_3, and Qsg_4) look very similar in the field and are arranged into tabular sheets and barrier ridges. Beach gravels tend to be well rounded, well stratified, and well sorted within strata. Clast sizes range from pebbles to cobbles and occasionally boulders depending on source area and longshore transport distance. Most commonly, beach gravels are clast supported but often have a matrix of coarse sand to granules. Another distinguishing characteristic is a tendency for the gravels to be shape sorted within strata, which is also common for marine beach gravels (Bluck, 1967; Carr, 1971; Orford and Carter, 1982; Williams and Caldwell, 1988; Orford et al., 1991a). Relative ages among the beach gravel units were determined primarily from stratigraphic relationships between adjacent units and by the last time that they were affected by waves. Transgressive beach deposits (Qsg_1) are found stratigraphically beneath the Qss_1 unit, as well as at the crests and on the backsides of highstand barrier features (Fig. 3). During the major regression, waves reworked the surface sediments of the transgressive beach deposits (Qsg_1), creating the regressive beach deposits (Qsg_2). Unit Qsg_3 represents the maximum stand of a minor transgression to about the 1235 m level and unit Qsg_4 represents the regressive beach deposits from this minor fluctuation (Fig. 3). This fluctuation is demonstrated by stratigraphic relations; i.e., where the clean well-washed beach gravels of lower barrier 11 (Qsg_3) stratigraphically overlie tufa-coated barriers (unit Qss/t in Fig. 3) most likely formed during the Sehoo cycle regression (Fig. 2C).

Sand deposits are also common in the Jessup embayment and are mapped as the Qss_1 and Qss_2 units (Fig. 3). The dominant clast size in these units is medium to coarse sand; they also contain some well-rounded pebbles and angular fragments of branching tufa (tufa terminology from Benson, 1994). The Qss_1 and Qss_2 units differ only in their stratigraphic position with respect to the beach gravel units. Whereas unit Qss_1 is essentially coeval with the youngest part of unit Qsg_1 and with all of unit Qsg_2, unit Qss_2 is coeval with the youngest part of unit Qsg_3 and all of unit Qsg_4 (Fig. 2). The largest expanses of the Qss_1 unit are found to the south of the north island where the overall slope is about 2° (Fig. 3). The unit is also found below headlands and islands in the embayment in small pockets and where the local slope flattens from relatively steep (~6°–13°) to relatively gentle slopes (~2°–4°). Isolated patches of the Qss_1 unit are found on gently sloping terrace treads formed on overall steeper slopes on the southwest side of the east island (Fig. 3). The Qss_2 unit forms a thin sheet downslope of units Qsg_3 and Qsg_4 (Fig. 3). We interpret the sand bodies to result from the offshore movement of sand due to wave action when the lake was at relatively high levels. Other stratigraphic units present in the embayment will be discussed in the following section where appropriate.

Lacustrine Landforms

Lacustrine landforms within the Jessup embayment are also diverse and abundant, ranging from wave-formed terraces and beach cliffs to numerous forms of constructional features. Constructional shore features within the embayment are separated into spits, looped barriers, barrier ridges, progradational barrier complexes, and pocket barriers, according to the classification scheme outlined in Figure 4. The distribution of

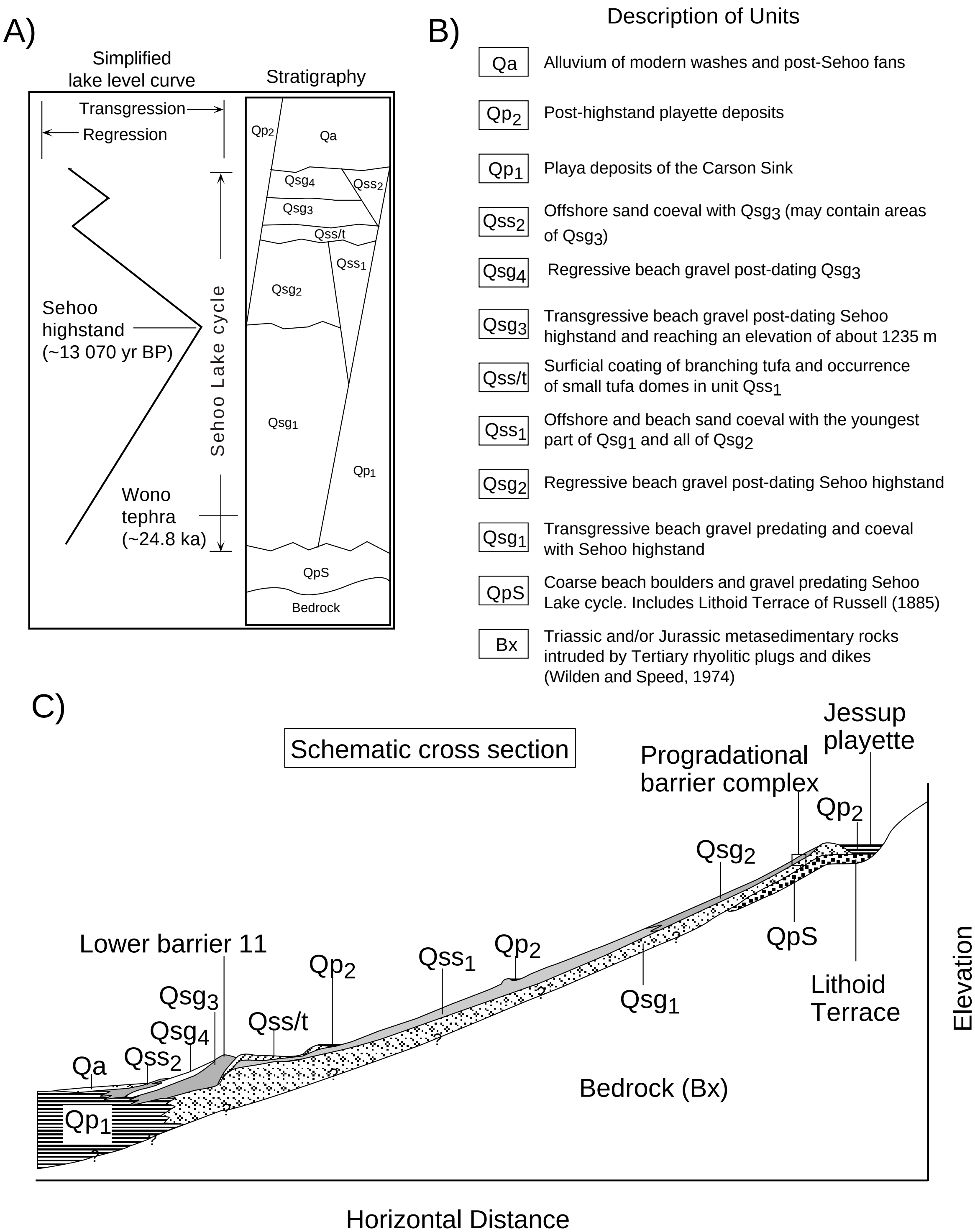

Figure 2. Stratigraphic framework of the Jessup embayment. (A) Stratigraphic column showing temporal relationships between different units and whether they were deposited during rising or falling water level during the Sehoo lake cycle. The age of the Wono tephra is from Davis (1983). (B) Description of mapping units in the embayment. More complete descriptions are included in the text. (C) Schematic cross section showing the spatial relationships between different units in the embayment. Unit thicknesses are exaggerated to show relationships.

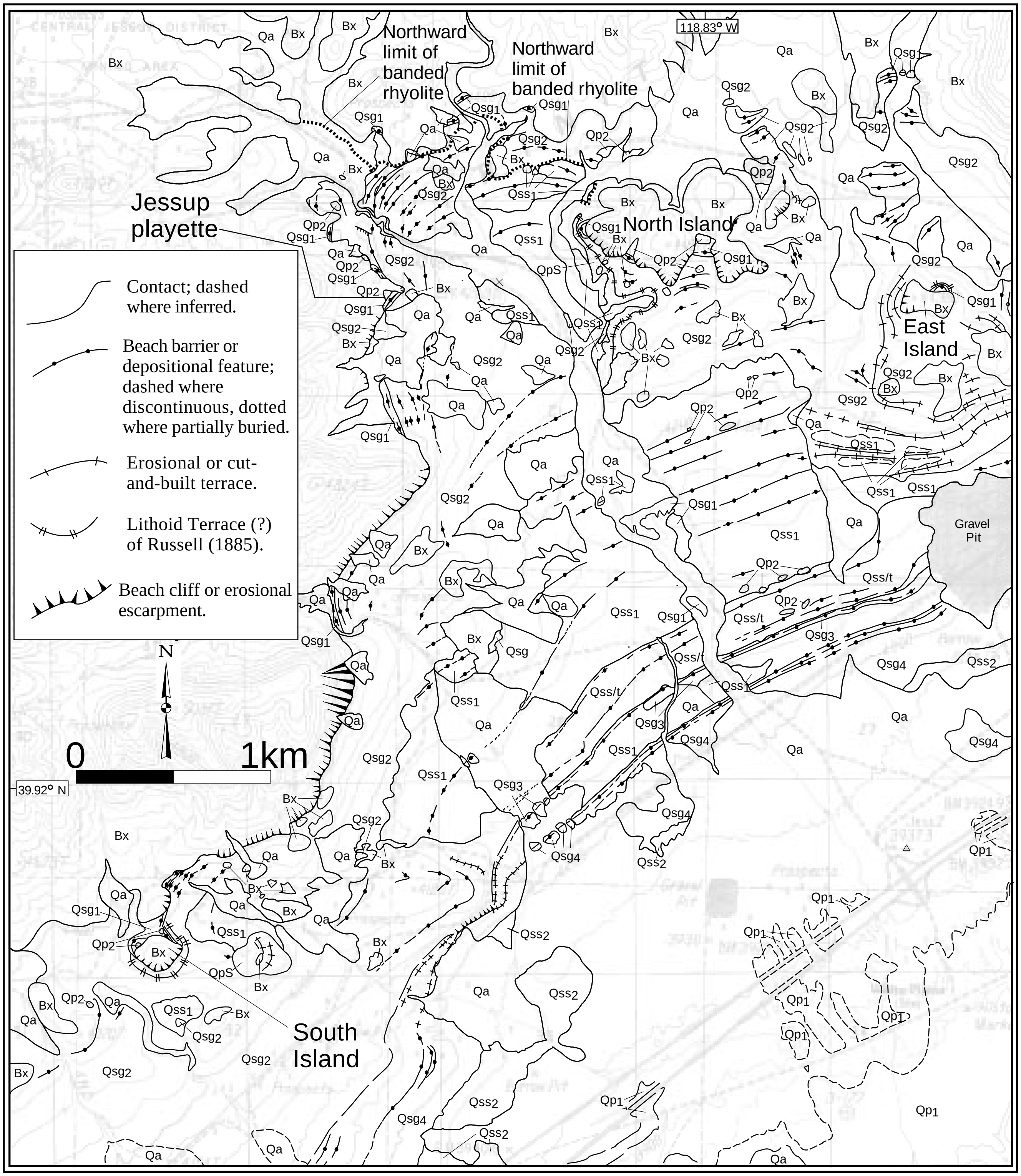

Figure 3. Geologic and geomorphic map of the Jessup embayment showing the distribution of deposits and landforms. The northward limit of banded rhyolite in surficial sediments is denoted by a coarse dotted line near the head of the embayment. Units are as in Figure 2. Base map is from U. S. Geological Survey, White Plains, Nevada, topographic map, scale: 1:24 000. See Figure 2B for explanation of abbreviations.

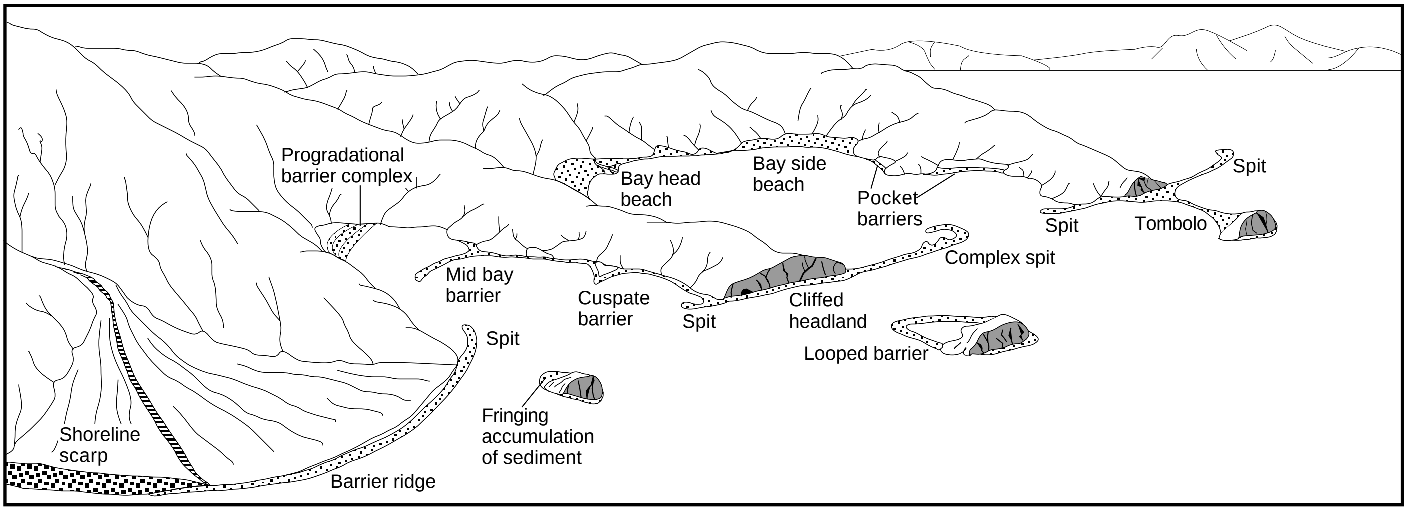

Figure 4. Shoreline classification scheme for pluvial features found in the Jessup embayment. After Strahler and Strahler (1992), King (1972), and Duffy et al. (1989).

these features within the Jessup embayment is shown in Figure 3. Discussion of several types of these landforms serves to elucidate the processes that controlled their development and distribution within the embayment. Radiocarbon dates within some of the deposits provide limits on the timing of their formation.

Wave-Formed Terraces. The most striking and easily recognizable shoreline features in the Jessup embayment are wave-formed terraces. Although terraces can be wholly erosional landforms, more commonly they result from erosional as well as depositional processes. Figure 5 is a block diagram through a series of terraces that shows a common configuration of erosional platforms fringed by a wedge of sediment built outward from the shoreline angle. Such features were termed cut-and-built terraces by Russell (1885). Wave-formed terraces are best developed on islands and headlands most exposed to a large fetch and composed of intermediate to basic volcanic bedrock.

The most prominent terrace in the Jessup embayment is also the highest, but is found about 5 to 7 m below the crests of the highest constructional barriers. This terrace is probably broadly correlative with Russell's (1885) "Lithoid Terrace" and is here referred to as such. It is best developed in the southwest corner of the embayment and on the west side of the north island where it is cut into intermediate to basic volcanic bedrock, ranges in width to 40 m, slopes gently lakeward, and usually has a well-developed cliff at its landward edge (Fig. 3). As with lower terraces, a wedge of cobbles and boulders is built out from the erosional platform, increasing its width. The outer edge of the depositional wedge of the Lithoid terrace is commonly very steep and exposes an interior cemented by dense laminated tufa (Lithoid tufa). The lower riser of the Lithoid terrace and lower cut-and-built terraces are commonly coated by a thin layer of branching tufa.

We interpret the Lithoid terrace (as did Russell, 1885) to represent a relatively long stillstand that predates the Sehoo cycle highstand. The relative length of the stillstand is demonstrated by the strong development of the Lithoid terrace both in terms of the large clast size (15–70 cm) and the width of the terrace tread (10–40 m). Relative age relationships are demonstrated by small Sehoo highstand barriers observed to be stratigraphically and elevationally above the Lithoid terrace (Fig. 3). The terrace tread of the Lithoid terrace is mapped as Qsg_2 because the surface sediments were most likely reworked by waves during the Sehoo regression. The lower riser on the southwest side of the north island is mapped as QpS because these sediments clearly make up the depositional wedge of the Lithoid terrace (Fig. 3).

A spit-like feature, known as the boulder spit, located in the southwestern part of the embayment (QpS, Fig. 3) may be correlative with the Lithoid terrace. It consists of large blocks (<1.5 m) of basalt arranged in a recurved fashion around a bedrock core. Some of the blocks are rounded; the interior of the deposit is cemented by dense laminated tufa and the exterior is coated with branching tufa. The north side of the deposit slopes more steeply than the angle of repose, but is supported by the tufa cement. The crest of the boulder spit is coincident with the Lithoid terrace but lies about 5 to 10 m below the crests of barriers marking the highstand of the lake and appears to lie stratigraphically beneath the Qsg_2 and Qss_1 units that surround the feature (Fig. 3). On the basis of its similarly well-developed character and elevation, the boulder spit probably formed at the same time as the Lithoid terrace and likely marks the highstand of a pre-Sehoo lake cycle.

Barrier Ridges. In the Jessup embayment, about 28 recessional barrier ridges were formed from an elevation of about 1334 m near the head of the embayment to about 1227 m near the mouth (Fig. 6). Elevations in this study were measured using a Total Station surveying instrument, which combines an electronic distance measuring (EDM) device with a theodolite. Local benchmarks provided elevation control. The accuracy of the instrument is to within 1 cm on shots of up to a few kilometers, but because the benchmark elevations are reported to the nearest 0.1 ft, the precision of the measurements is assumed to be well within ±0.1 m. Barriers are generally constructed from locally derived sediment, so near the highstand they consist of coarse gravel. As lake level receded over sand deposits (Qss_1) in the central part of the embayment, however, sand was incorporated into the barriers (Fig. 3). An exception to local derivation of sediment is represented by lower barrier 4 (Fig. 6) where it appears that the coarse gravel material composing this barrier ridge was moved by longshore drift from the west-southwest over the top of unit Qss_1, which lies at a depth of about 130 cm below the crest of the barrier.

The convex-up cross-sectional shape of the barriers commonly mimics their architecture; i.e., beds dip lakeward on the lakeward side of the barriers, flatten near the crests, and dip landward on the landward side of the barriers. The architecture indicates the landward transfer of sediment during short-duration stillstands by barrier rollover. This process is driven by storm waves

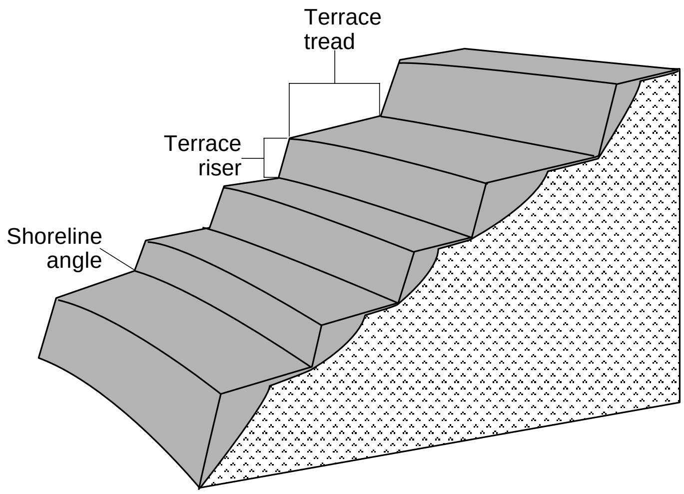

Figure 5. Block diagram showing a cross section through a flight of cut-and-built terraces. Note that each terrace tread consists of a combination of an erosional platform with a fringing wedge of sediment commonly composed of coarse cobbles and boulders.

where sediment derived from the front of the barrier is washed over the crest and deposited on the backside of the barrier (Carter and Orford, 1984; Orford et al., 1991b, 1995). The net result of continued barrier rollover is landward migration of the barrier landform. However, in shore locations with an abundant sediment supply, coupled with a relatively stable water level, multiple barrier ridges accrete lakeward and form a progradational barrier complex (Orford et al., 1991a).

The surface morphology, stratigraphy, and sedimentology of a well-developed progradational barrier complex located at the head of the embayment (Fig. 6) illustrate the mechanisms and processes by which large barrier complexes are emplaced. The surface of the complex consists of five individual ridges ranging in elevation from about 1332 to about 1334 m, which is about 6 to 8 m below the elevation of adjacent highstand features. The highest and most continuous ridge is in the center of the complex (~1334 m ; Lower barrier 0 in Fig. 6) and truncates lower ridges both lakeward and landward. A natural exposure along the northwest (landward) side of the progradational barrier complex provides evidence for the internal architecture of the complex, which consists of high-energy beach gravels arranged in discontinuous tabular and tabular cross-bedded bodies several tens of centimeters to several meters thick (Fig. 7). Clasts range to 30 cm in diameter and tend to be well rounded and well sorted according to size and shape within individual beds. Each of these tabular beds may represent discrete wave energy regimes (i.e., storms) when clasts of a particular size and shape were transported to the exclusion of dissimilar clasts. Most of the erosional disconformities within the section may represent short periods of time and are probably related to storm erosion and concurrent deposition. However, a disconformity at about 1331 m is marked by a layer of cemented beachrock and covered by a thin layer of branching tufa, which implies that this horizon remained at the surface, but under water, for some period of time. The tufa and beachrock horizon has been eroded by an overlying coarse cobble to boulder unit (unit 8; Fig. 7) in the southern half of the exposure (Fig. 7). On the basis of radiocarbon dating and crosscutting relationships discussed in the following section and in the section on Sehoo Lake cycle history, we propose that the tufa and beachrock horizon separates transgressive Sehoo beach gravels (units 1–7) in the lower part of the progradational barrier complex exposure from regressive Sehoo gravels (units 8–12) in the upper part of the exposure.

Tephra samples were collected from three horizons within the lower part of the progradational barrier complex exposure in an attempt to constrain the age of the deposit. Gastropod shells were also collected from two of the same horizons. The tephra samples were taken from a horizontally bedded sand layer near the base of the exposure (unit 1, ~1326 m), from a conspicuous fine-grained layer between two lower packages of tabular backsets(?) (units 2 and 3, ~1326 to 1326.5 m), and from just below the tufa and beachrock horizon about 15 m from the north end of the log (unit 7, ~1330.5 m) (Fig. 7). The three samples contained from 7% to 20% volcanic glass shards, so they are not true ash layers, but should be considered ashy clastic sediments (A. Sarna-Wojcicki, 1995, written commun.). The upper sample was collected from matrix between coarse pebbles to cobbles and has undergone some reworking within a high-energy beach environment. The middle and lower samples were probably also reworked because they are mixed with sand and also have low concentrations of glass shards.

Glass shards in all three of the ashy clastic sediment samples best correlate to one another and to a group of tephras known as the Walker Lake–Negit Island causeway set of "proto" Mono Craters layers estimated to be between about 65 to 80 ka in age (A. Sarna-Wojcicki, 1995, written commun.). These correlations indicate that the tephra layer or layers were originally erupted in early Wisconsin time and not during late Wisconsin time or the time of the Sehoo cycle. However, it is clear that the shards have been mixed with beach sediments, indicating that they have been reworked and do not represent original air fall.

We also collected *Vorticifex (Parapholyx) solida* shells (Burch, 1989) from both the upper and middle ashy clastic layers for accelerator mass spectroscopy (AMS) radiocarbon dating and additional shells from throughout the section for X-ray diffraction (XRD) studies. Shells from the upper ashy clastic sediment layer date from 13 110 ± 110 yr B.P. (ETH 12798), and shells from the middle ashy clastic sediment layer date from 13 280 ± 110 yr B.P. (ETH 12799) (Fig. 7) (I. Hajdas, 1994, written commun.). Although these radiocarbon estimates are in stratigraphic order, they do not agree with the age estimates provided by the tephra correlations.

There are two possibilities that may explain the disparate dates. The first possibility is that the shells and glass shards were deposited with the beach gravel sometime between 60 and 85 ka and subsequently both shell samples were recrystallized and incorporated the same amount of young carbon that provided identical, but anomalously young ages. The second possibility is that the beach gravel, shells, and glass shards were all deposited about 13.1 to 13.3 ka, which implies that the glass shards were derived from an existing deposit in the area. To ascertain which of these scenarios is most likely correct, we used XRD to determine the composition of shells from each of the ashy clastic sediment layers, shells from the upper part of the exposure, and shells from the shore of modern Pyramid Lake, which we interpret to represent recently living specimens of *Vorticifex*. According to Bøggild (1930), freshwater pulmonate gastropods such as *Vorticifex* are composed of aragonite when living. All of the shell samples that we examined were also composed of aragonite, without a trace of calcite, implying that the shells from the ashy clastic sediment layers have not been recrystallized and that their radiocarbon ages represent the age of the deposits. Amino acid analyses of these same

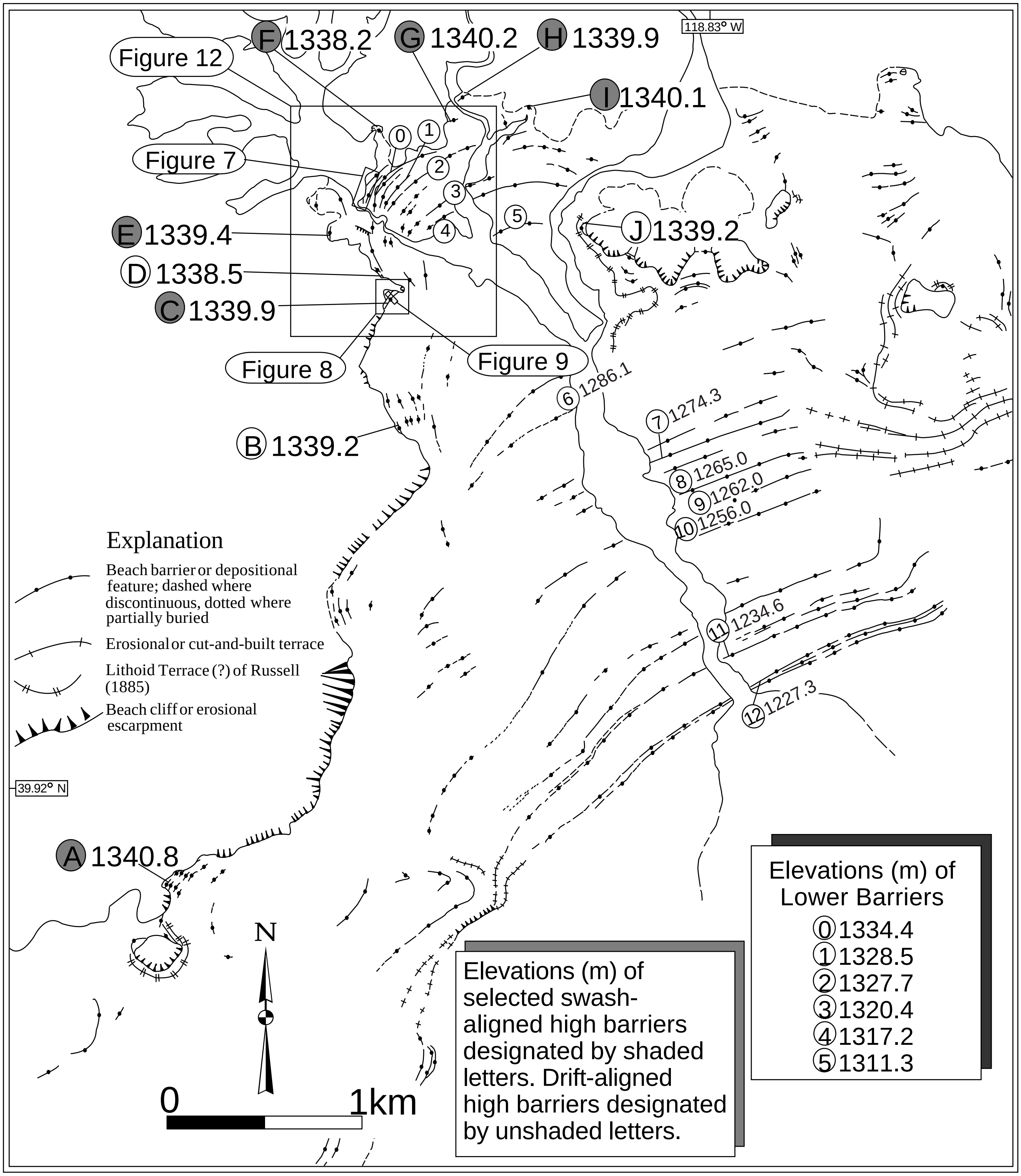

Figure 6. Location map showing shoreline elevations and figure locations. Swash-aligned highstand barriers and elevations are designated by shaded letters, and drift-aligned highstand barriers and elevations are designated by unshaded letters. Recessional barriers are designated by numbers. We interpret all of the high shorelines to date from the Sehoo cycle highstand. The differences in elevation (~2.6 m) are attributed to natural variability in the height of formation above a given water plane.

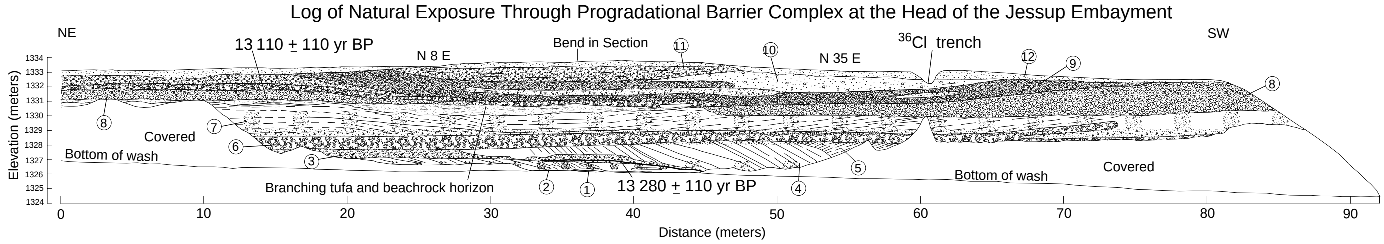

Figure 7. The progradational barrier complex at the head of the Jessup embayment showing main sedimentary features exposed in a stream cut. Circled numbers refer to the stratigraphic order of the depositional units and are discussed in the text where appropriate. Accelerator mass spectroscopy (AMS) radiocarbon ages (13 280 ± 110 yr B.P. and 13 110 ± 110 yr B.P.) on gastropod shells from the lower part of the section represent the times when these surfaces were the active beach.

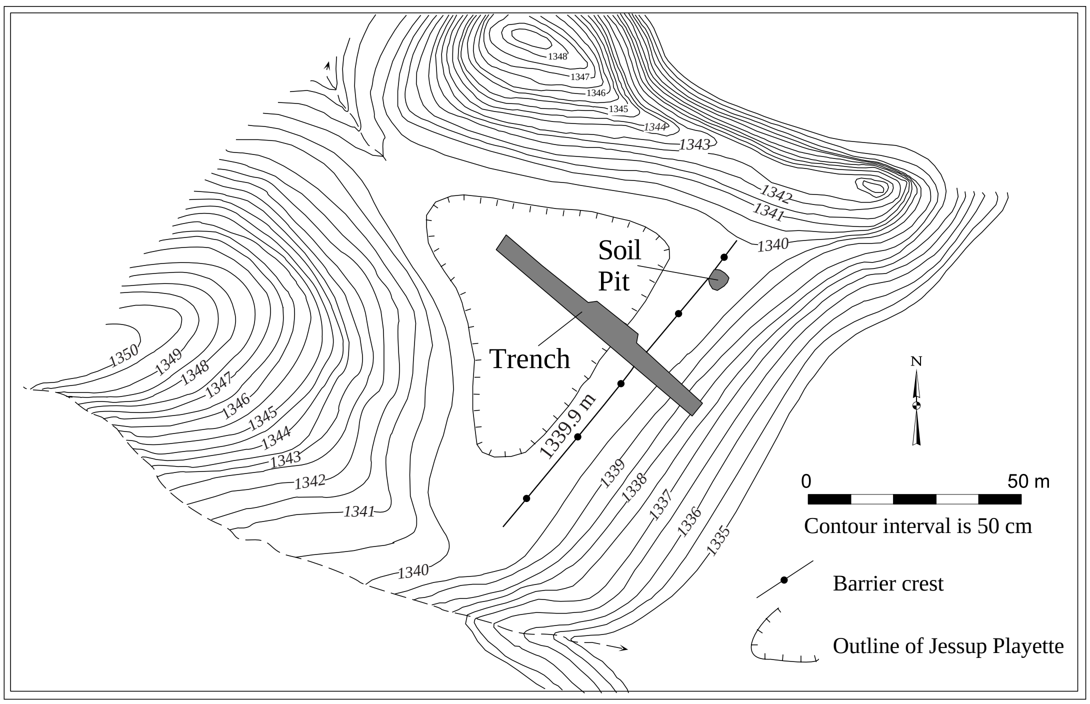

Figure 8. Topographic map of the Jessup playette trench site showing the location of the trench in relation to the highstand barrier and its associated playette. The enclosing barrier marks the highstand of pluvial Lake Lahontan.

shells indicate that the alloluecine/isoluecine ratios range from 0.117 to 0.123 (J. Bigelow, 1997, written commun.), which is consistent with Sehoo age ratios defined by McCoy (1981).

Pocket Barriers. Pocket barriers are constructional features emplaced across small drainages or indentations along the shore (Fig. 4) (Duffy et al., 1989). There are 12 highstand pocket barriers in the Jessup embayment, all of which are composed of well-washed beach gravel mapped as unit Qsg_1 (Fig. 3). These and other highstand features represent the upper elevational limit of the transgressive Sehoo cycle beach gravels (Figs. 2 and 3). Most of the pocket barriers have been dissected, but one located in the northwestern part of the embayment remains intact and encloses a small playette, hereafter referred to as the Jessup playette (Fig. 3 and shoreline C in Fig. 6). The term playette refers to a small playa, which generally consists of fine-grained horizontally bedded sediment (F. Peterson, 1995, personal commun.). A trench 60 m long and 5 m deep was excavated perpendicular to the barrier and into the playette to enable a more detailed understanding of shoreline processes and to gain an estimate of the timing of the highstand.

The barrier enclosing the Jessup playette is about 100 m long and has a crestal width of about 15 m (Fig. 8). It extends northward from a small beach cliff and is anchored on its northern end by a small headland (Fig. 3). The crest of the barrier lies at an elevation of 1339.9 m and the surface of the playette is about 20 cm lower (Fig. 8). The closed depression subsequently filled by the playette sediments was created by emplacement of the barrier across this small wash.

Figure 9 is a log of the trench exposure showing the relationships between the different sediment packages. The oldest package of sediment is located at the base of the exposure in the northwestern half of the trench (Fig. 9). This massive, well-consolidated unit consists of poorly sorted, angular mafic volcanic clasts (<10 cm) supported by a matrix of medium sand to gravel. Clasts tend to be somewhat concentrated at the unit's upper surface. Within the unit there are common fine to very fine iron-stained root casts. The unit appears weathered, but there is no iden-

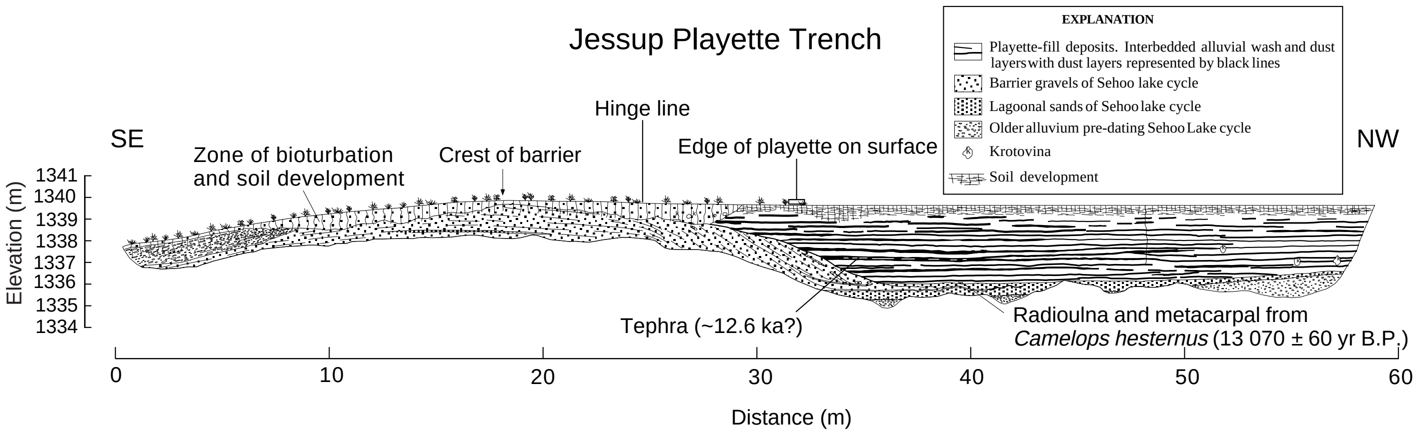

Figure 9. Log of the Jessup playette trench showing the stratigraphic relationships between the barrier gravels, lagoonal sands, and playette-fill deposits. An accelerator mass spectroscopy (AMS) radiocarbon date of 13 070 ± 60 yr B.P. on collagen extracted from the camel metacarpal bone provides a minimum limiting age on the highstand. The location of the camel bones is projected from the northeast wall to the southeast wall of the trench.

tifiable paleosol developed on its upper surface. This unit is interpreted to be alluvium that was deposited prior to the Sehoo lake cycle and is probably relatively thin, although the base was not reached. The contact with the next overlying unit is sharp and slopes gently to the southeast.

The next younger unit is referred to as the lagoonal sands and consists of a wedge-shaped package thickening to the southeast to a maximum of about 50 cm (Fig. 9). The base of the unit is composed of poorly sorted, matrix-supported cobbles and gravel grading upward to well-sorted fine to medium sand at the top of the unit. Gravel and cobbles near the base of the unit are angular, hematite-stained volcanic material, and increase in abundance to the northwest. The upper sandy part has a greenish cast, possibly indicating the presence of reduced iron. There is also limonite-hematite staining along common fine root casts and precipitated along horizontal bands. Cross-bedding (amplitude ~4–5 cm) is present in the upper part of the unit, and apparent local transport directions are both to the southeast and northwest.

A thin wedge of well-rounded beach gravel and sand is interfingered with the lagoonal sands about 35 to 45 m from the southeastern edge of the trench (Fig. 9). The gravels become finer and thin to the northwest. At about the 40 m mark the gravel wedge grades into a thin, iron-stained undulating coarse sand bed that continues to the northwest for about 5 m. About 12 cm of lagoonal sands overlie the interfingered gravel and coarse sand.

The lagoonal sands are interpreted to represent sediment deposited in a back-barrier lagoon during the highstand. The contemporaneity of the lagoonal sands and the highstand is demonstrated by the way in which the barrier gravels interfinger with the lagoonal sands (Fig. 9). Cross-bedding within the lagoonal sands is interpreted to represent in part the effects of overwash where sediment and water washing over the crest of the barrier and into the lagoon generated local currents. Sedimentation continued in the back-barrier lagoon after the time when the last waves washed gravel over the crest of the barrier and into the lagoon. The time interval between the last overwash event and the recession of the lake from the highstand was probably relatively brief and is represented by the thickness of lagoonal sands (~ 12 cm) above the leading edge of the barrier gravel (Fig. 9).

The barrier gravels represent the highest deposits of Lake Lahontan and tend to be well rounded, well stratified, and well sorted within strata. In cross section, the barrier is arranged into somewhat tabular beds that dip lakeward (8°–10°) on the lakeward side of the barrier, flatten near the crest of the barrier, and dip steeply (33°–34°) landward on the back of the barrier. These zones of dip directions are referred to as foresets, topsets, and backsets, respectively, according to their position within the barrier.

The steeply dipping (33°–34°) backsets are tabular in their central part and grade smoothly onto a horizontal surface within the lagoonal sands in an asymptotic relationship (Fig. 9). The tabular beds are in part defined by the alignment of platy clasts. Individual sand layers within the horizontal portion of the barrier tail ramp up into steeply dipping backsets. We interpret the sedimentologic relationships to demonstrate progressive accretion and migration of the backsets toward the northwest. Hence, during the highstand, the entire barrier was probably moving landward over the top of the lagoonal sands (Fig. 9).

At the time of the highstand, water level in the lagoon probably closely approximated water level in the lake. This assertion is supported by observations of modern barriers and their lagoons in Pyramid Lake that serve as excellent analogues to the enclosed highstand barriers of Lake Lahontan (Fig. 10). The modern barriers formed in the period from January to July 1997, after the level of Pyramid Lake was raised 3 to 4 m by an extreme runoff event down the Truckee River in January 1997. The barriers along the southwestern side of Pyramid Lake are similar in size and form to many of the highstand barriers in the Jessup embayment and elsewhere in the Lahontan basin, but differ in that most are finer grained, being composed of gravelly sand (Fig. 10). Water levels in the lagoons and in the lake were observed to be nearly identical, probably due to the high permeability of the barrier sediments (Fig. 10). Overwash deposits and small fans built into the lagoons by waves illustrate, in part, the manner in which the modern barriers and highstand barriers formed. Relatively horizontal topsets are formed as waves wash sediment over the crests of the barriers and backsets are formed as the same sediment cascades down a slip face into the lagoon. The inflection where the topsets steepen into the backsets is known as the hinge line, which in the Pyramid Lake barriers approximates lake level. By inference, paleowater levels can be approximated by the elevation of the hinge line commonly preserved in Sehoo barriers.

The hinge line preserved in the Jessup playette barrier is located about 25 m from the southeastern end of the trench at an elevation of about 1338.5 m (Fig. 9). On the basis of the elevation of the hinge line, we estimate that water level at the highstand of Lake Lahontan at this location was between 1338.5 and 1339.0 m. This estimate suggests that the barrier projected from 1 to 1.5 m above the level of the lake (Fig. 9).

The distal end of a radioulna (fused front fore limb) and a metacarpal (foot bone) from a *Camelops hesternus* were found at the contact between the lagoonal sands and the youngest package of sediments designated the playette-fill sediments (Figs. 9 and 11). AMS radiocarbon ages of 12 690 ± 60 yr B.P. (NSRL-2883) and 13 070 ± 60 yr B.P. (NSRL-3014) (T. Stafford, 1995, 1996, written communs.) for the radioulna and metacarpal, respectively, provide minimum age constraints for the lagoonal sands and barrier gravels and maximum age constraints for the playette-fill sediments (Fig. 9).

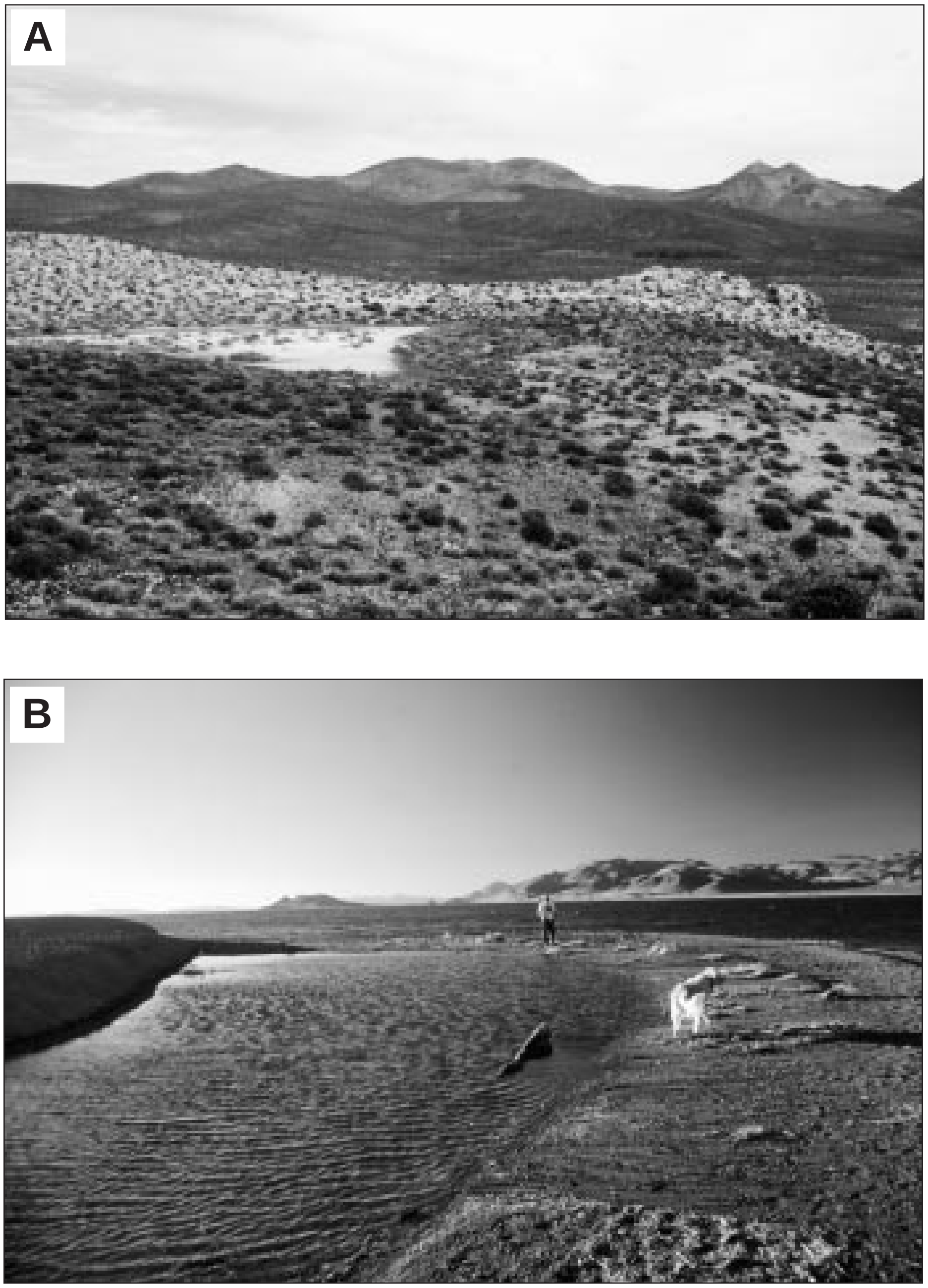

Figure 10. (A) The Jessup playette and the enclosing barrier looking northeast. There are about 20 cm of relief between the surface of the playette and the crest of the barrier. (B) Photograph of one of many barriers along the southwest shore of Pyramid Lake, which formed in a period of less than seven months in 1997. Water level in the lagoons closely approximated water level in the lake. The similarities between the modern barriers at Pyramid Lake and many highstand barriers suggests that the highstand barriers may have formed quite rapidly.

The playette-fill sediments consist of layers of sand separated by fine-grained beds of silt, fine sand, and clay (Fig. 9) that aggraded after the lake receded from its highstand. These sediments probably resulted from discrete slopewash events that flowed onto the intermittently inundated playette surface from the surrounding hills (Adams, 1997). A tephra located within one of the fine-grained layers about 1.2 m above the base of the playette-fill sediments closely matches a tephra with an extrapolated age of 12.6–12.7 ka that was derived from the Mono Craters area (A. Sarna-Wojcicki, 1996, written commun.). This age is consistent with the maximum limiting age placed on these sediments by the underlying camel bones.

Shoreline Processes

Controls on Shore Development. Lake level has dramatically fluctuated in the Lahontan basin over at least the past 1 m.y. (Davis, 1978; Morrison, 1991). Lacustrine deposits older than those of the Sehoo cycle are found in both the inner basin river trenches (Morrison and Davis, 1984; Morrison, 1991) as well as along the piedmont slopes of the basin (Morrison, 1964, 1991; Adams, 1997; this study). Therefore, the amount of geomorphic work represented by the terraces, barriers, beach cliffs, and sea stacks of the Lahontan basin likely is the cumulative result of multiple lake cycles spanning tens to hundreds of thousands of years. The Lithoid terrace and the boulder spit, which may date from oxygen isotope stage 6 (ca. 140 ka), are evidence that some shoreline landforms are preserved longer than the period of time between major lake cycles. Other terraces and deposits below the Lithoid terrace may also date from earlier lake cycles but, because of the Sehoo "overprint," are generally difficult to distinguish. However, on the basis of the distribution of the Lithoid terrace (Fig. 3) and pre-Sehoo cycle barrier deposits located in the central part of the embayment (Adams, 1997), the same type of shorelines form in the same locations in subsequent lake cycles. This sameness points to basic physical factors that control the distribution of shorelines and deposits.

The factors that appear to influence shore development include local slope, the amount and characteristics of sediment available for transport, the availability of accommodation space, and the length of time lake level resides at a particular shoreline elevation. The factors are not independent, but act in concert to produce unique combinations and distributions of shoreline features. Some of these same factors were originally

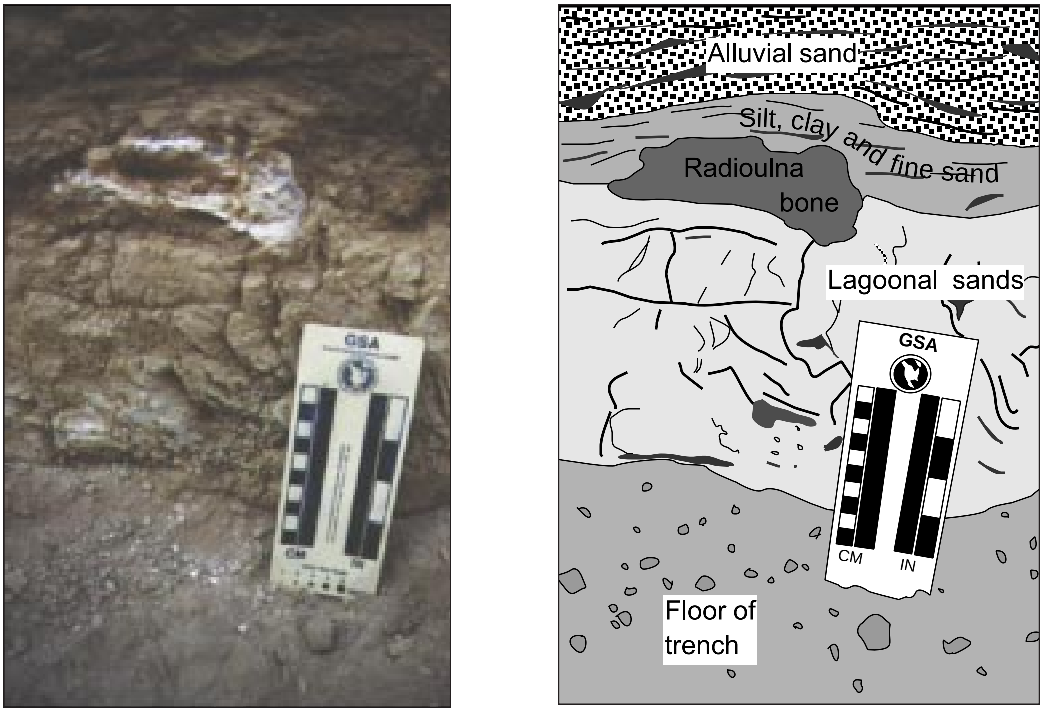

Figure 11. Photograph and drawing of in situ radioulna camel bone in the Jessup playette trench at the contact between the lagoonal sands and the playette-fill sediments. The metacarpal bone was found immediately adjacent to and in front of the radioulna.

identified from studies of ocean coasts (Forbes and Syvitski, 1994) and appear to be broadly applicable to large lacustrine systems such as Lake Lahontan.

Slope is a major controlling factor on the distribution of shore features. Barrier ridges are located where the overall slope is relatively gentle (<4°), such as in the central part of the embayment, but where the local slope is relatively steep (>6°), wave-formed terraces are more common. However, in terms of controlling shoreline forms, slope cannot be completely separated from sediment availability because in general there is more sediment available for construction of barrier ridges on lower gradient slopes. Examples of slope control in the embayment are found at the 1235 and 1227 m shoreline levels. Barrier ridges at these two levels are located in the central part of the embayment where the overall slope is about 2° (Figs. 3 and 6). To the southwest, these two shoreline levels are represented by terraces where they wrap around a relatively steep headland (>10°). Continuing to the southwest at the same elevations, the overall slope shallows to about 3° and the shoreline levels are again represented by barrier ridges (Figs. 3 and 6). The crests of the barriers lie 1–3 m above the shoreline angles formed by the terrace treads and adjacent upper risers. This same phenomenon was observed in the Lake Bonneville basin by Gilbert (1890, p. 122–125), who suggested that the shoreline angle approximates the still-water level of the lake whereas the crests of constructional features represent the effects of storm deposition.

Slope is also a controlling factor on the distribution of lacustrine sediment in the embayment. The upper parts of all slopes leading up to the highstand are covered with coarse beach gravel. Sand is only found on low gradient slopes and in topographic traps. When the lake was at high levels, direct wave agitation in the shore zone probably raised the sand-sized and smaller fraction of sediment into suspension, leading to a concentration of gravel and coarser material in the shore zone. The sand was probably moved offshore in sediment gravity flows and came to rest in topographic traps and on the low-gradient slopes. As lake level declined, the sand was probably further concentrated into the low-gradient central part of the embayment by the same process. The offshore movement of sand as well as the lateral movement of sediment accomplished by longshore drift highlight the complicated sediment dispersal mechanisms operating along steep coasts.

The amount and characteristics of sediment available for transport also influence shore development. Spits developed in the northwestern part of the embayment indicate strong longshore movement of sediment toward the head of the embayment at the highstand and during the early part of the regression. This abundant influx of sediment coupled with a relatively long stillstand helped build the progradational barrier complex at about 1334 m during the early part of the regression. Other shoreline locations at the same elevation do not display the same multiple ridges, which indicates that they were probably relatively sediment starved.

When a barrier does not have a continual source of sediment, storm waves wash gravel from the beach face over the crest of the barrier and onto the backside in a process called barrier rollover (Carter and Orford, 1984; Orford et al., 1991b, 1995). The effects of barrier rollover are clearly displayed in the Jessup playette trench by the way in which the barrier gravels interfinger with the lagoonal sands (Fig. 9). The orientations of the backsets indicate that the barrier migrated landward during the brief highstand, partially burying the lagoonal sands in the process.

Accommodation space is the space available for the building of a spit or barrier. Along an irregular shore, accommodation space is located in indentations or reentrants as well as off headlands or salients. The initial topography determines the volume of accommodation space available for deposition, and the rate at which sediment is supplied from along the shore or from fluvial sources determines the rate at which spits are built (Cowell and Thom, 1994). When a spit is built completely across a reentrant it becomes a barrier and sedimentation continues downdrift as the

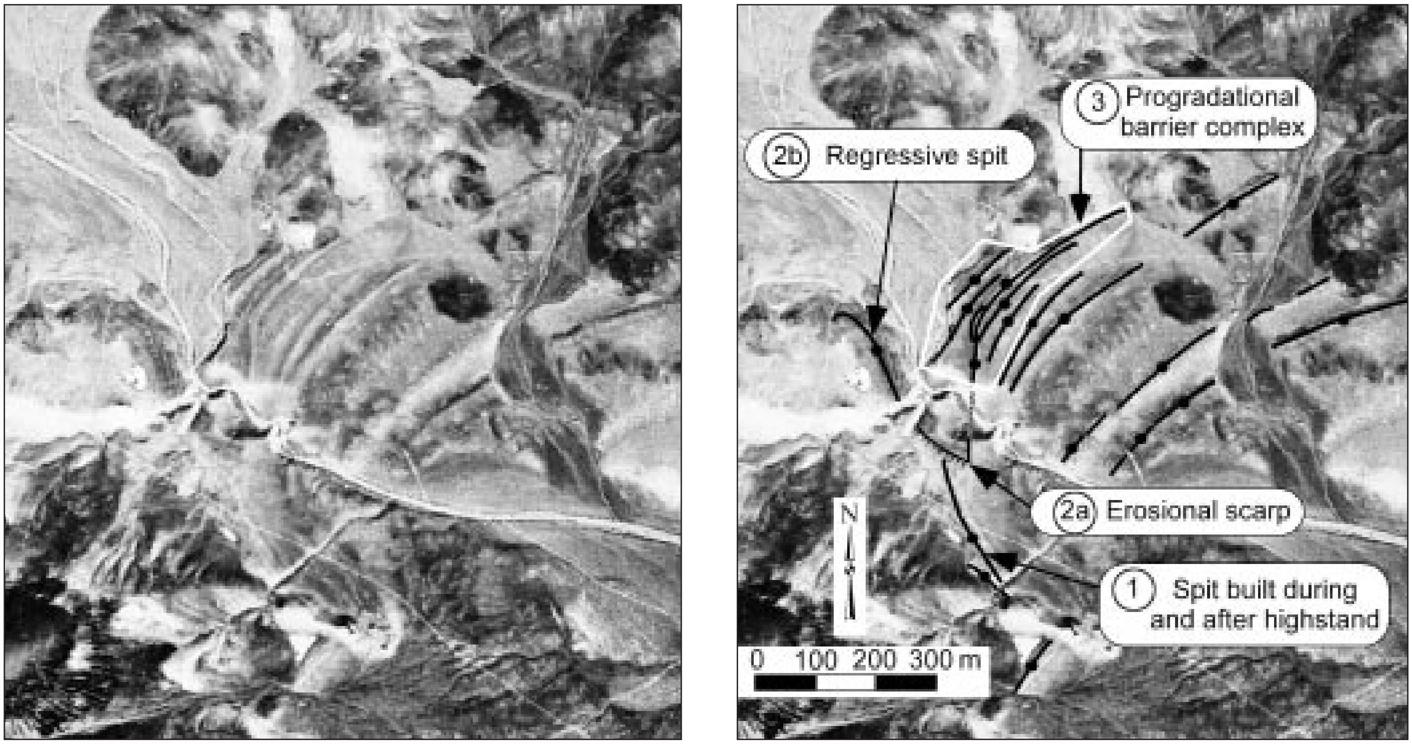

Figure 12. Aerial photograph interpretation of crosscutting relationships at the head of Jessup embayment (see Fig. 6 for location) demonstrating that surface ridges of the progradational barrier complex postdate the Sehoo cycle highstand. Symbols are as in Figures 3 and 6. Feature 1 is a spit that began building at the highstand and continued to elongate to the north as lake level began to recede. Feature 2a is an erosional scarp that truncates feature 1 (highstand and early recessional spit) and is probably contemporaneous with feature 2b, which is a spit built from south to north at a level about 8 m lower than adjacent highstand barriers. Feature 3 comprises the surface ridges of the progradational barrier complex, which also lie about 6 to 8 m below adjacent highstand barriers. We interpret these shorelines to indicate that, first, the highstand spit was built, and second, the end of the highstand spit was truncated and the regressive spit (feature 2b) was built. Third, the ridges of the progradational barrier complex were emplaced across the head of the embayment.

coastal drift cell is lengthened. The progradational barrier complex at the head of the embayment owes its large size in part to the probable high rate of sediment supply, but also because of its position between two rocky headlands which acted to support the complex (Fig. 12). In this case, the distance between the two headlands (300+ m) combined with the pre-Sehoo cycle topography of the site defines the accommodation space available for the alongshore growth of the complex.

The amount of geomorphic work accomplished at a given shoreline level is directly proportional to the amount of time that the lake stabilized at that level. That is, the longer a shoreline is occupied, the greater number of storm-driven waves would affect that shoreline and work to increase its development. The best-developed shoreline features in the Jessup embayment, which include the Lithoid terrace, the boulder spit, and the upper beach cliff, represent the longest period of lake-level stability. However, these features probably mark the highstand of a pre-Sehoo lake cycle. In contrast, all of the Sehoo cycle shorelines, including the highstand, are less developed and each represents a relatively short period of time. Among Sehoo cycle features, lake level probably resided for the longest period of time at about 1334 m, the elevation of the progradational barrier complex.

Longshore Drift Directions in the Jessup Embayment. The net longshore drift direction near the head of the embayment was clockwise, or from northwest to northeast (Fig. 3). This pattern was determined by mapping distinctive beach-sediment lithologies, interpretation of landforms and stratigraphy, and tracing the size and sorting of clasts in barrier deposits. A distinctive flow-banded rhyolite outcrops and is found in the sediments in the western part of the mapping area (Fig. 3). The northward limit of banded rhyolite clasts in alluvial and lacustrine deposits is denoted by a coarse dotted line in Figure 3. The farthest east that banded rhyolite is found in alluvial sediments is the southwestern part of the main drainage upstream from the progradational barrier complex at the head of the embayment (shoreline 0 in Fig. 6). Banded rhyolite is also found in all of the high shorelines from shoreline A through shoreline E (Fig. 6). To the north and east of these high shorelines the northward limit of the banded rhyolite descends to lower barriers 3 and 4, where it can be traced to the northwest side of the north island, a downdrift distance of about 1 km (Figs. 3 and 6). The high pocket barriers and their respective drainages to the east of the main wash (shorelines G, H, and I; Fig. 6) do not have any banded rhyolite within them. Instead, all of the sediment within each pocket barrier was most likely derived from local sources. The distribution of the banded rhyolite in both the high barriers and recessional barriers demonstrates that this distinctive lithology was progressively spread to the east in successively lower barriers during recession from the highstand.

Another method used to interpret net shore drift directions was noting the directions that spits were built. Shorelines B and D (Fig. 6) are both spits built during the highstand from south-southeast to north-northwest, which is consistent with a clockwise shore drift pattern at the head of the embayment. Spits built at lower elevations during the Sehoo cycle regression also indicate a clockwise shore drift pattern.

Lower barrier 4 is composed of coarse gravel on the surface (Qsg_2), but overlies a well-sorted sand at a depth of about 130 cm. We interpret this lower sand to be part of the offshore sand unit (Qss_1) and maintain that the upper, gravel part of the barrier drifted in from the west over the top of the Qss_1 unit when the lake had regressed to about 1317 m (Figs. 3 and 6).

The last piece of evidence we present for a clockwise drift direction at the head of the embayment is the eastward fining of sediment in lower barriers 3 and 4. Field observations indicate that toward the east along the crests of lower barriers 3 and 4, mean particle size decreases while the percentage of sand increases. These observations and interpretations point to a dominant clockwise drift pattern at the head of the embayment both at the Sehoo cycle highstand and during the Sehoo cycle regression.

The clockwise drift direction in the embayment and the fact that it faces south to southeast implies that wind and waves, which built the Sehoo highstand barriers and lower, regressive barriers, were primarily coming from the south or southeast. This observation is at odds with those of Morrison (1964, 1991), who stated that during Sehoo time, strong storm winds seldom came from the south or southeast. However, the large size of Sehoo beach clasts (to 50 cm), the excellent development of shore features, and the fact that the Jessup embayment faces south-southeast indicate that strong storm waves did come from these directions during Sehoo time.

Natural Variability in the Height of Constructional Shorelines. Constructional shore features are formed by storm waves moving sediment along the beach face and up and over the crests of the features. For a given lake level, the height at which different barriers are constructed above still-water level is not constant. Figure 6 shows the results of Total Station surveys of the elevations of constructional highstand features in the Jessup embayment that range from 1338.2 to 1340.8 m. Highstand shorelines in this area are among the highest in the Lahontan basin due to the effects of isostatic rebound (Adams and Wesnousky, 1994; Adams, 1997). Even though there is as much as 2.6 m of difference in the 10 highstand shoreline measurements (Fig. 6), we submit that all of these features were built during the Sehoo cycle highstand and the differences reflect natural variability in the height at which the crest of a depositional shoreline forms above a still-water plane. As a modern example of natural variability, constructional shorelines formed during the 1982–1983 winter by waves on the Great Salt Lake in Utah vary by about 2 m (Atwood, 1994).

The highest elevated barriers in the embayment tend to be predominantly swash aligned with a large, unobstructed fetch (tens of kilometers) and moderately steep slopes approaching the shore. For example, the highest elevated shorelines A, C, G, H, and I in Figure 6 are all swash-aligned pocket barriers with relatively steep frontal slopes. In general, drift-aligned features are slightly lower. However, the lowest elevated shoreline (shoreline F; Fig. 6) is a poorly-developed swash-aligned pocket barrier located in a relatively protected area. Variability in crestal heights of the barriers is controlled by the size of waves reaching a particular shore, which in turn is controlled by fetch, lake-bottom configuration, geometry of the shoreline (e.g., embayment vs. headland), and the presence or absence of offshore obstructions (i.e., islands or shoals) (King, 1972). With the complicated three-dimensional geometry and crenulate coastal outline of the Jessup embayment, it is surprising that the Sehoo cycle highstand can be approximated to within about 2.5 m.

Sehoo Lake Cycle History

Timing of the Sehoo Cycle Highstand and Regression. The timing of the Sehoo cycle highstand is constrained by the age of the camel bones found at the contact between the lagoonal sands and playette-fill sediments in the Jessup playette trench (Figs. 9 and 11). The contact marks the change in sedimentation rate and style from subaqueous deposition of sand in a back-barrier lagoon to subaerial and ephemeral shallow-water deposition of sand and silt in a closed depression. Hence, this contact is interpreted to represent recession from the highstand, after which lake water no longer percolated through the barrier or was cast over the crest during storms. The metacarpal was found in front of and adjacent to the radioulna, suggesting that the two bones were articulated when deposited and buried. The bones would probably have survived no longer than decades on the surface and were buried by the first pulse of sedimentation after the beginning of the recession. Furthermore, there is no evidence of weathering or pedogenesis at the contact between the lagoonal sands and playette-fill sediments. All of this suggests that the Sehoo cycle highstand occurred immediately prior to the deposition of the camel bones.

The radioulna has a radiocarbon age of 12 690 ± 60 yr B.P. (NSRL-2883) and the metacarpal has a radiocarbon age of 13 070 ± 60 yr B.P. (NSRL-3014). This discrepancy is probably due to differences in the degree of protein preservation and collagen yields during pretreatment of each of the samples. About 80% of the original bone morphology was preserved in the metacarpal, and the collagenous bone pseudomorph formed during decalcification retained much of the detail of the original bone (T. Stafford, 1996, personal commun.). In contrast, only about 10% of the original morphology of the radioulna was preserved. The metacarpal also yielded much higher amounts of collagen for radiocarbon dating. Whereas the radioulna yielded 0.2 wt% of collagen, the metacarpal yielded 5.1 wt% of collagen (T. Stafford, 1996, personal commun.). For comparison, a modern bone yields about 20 wt% of collagen (Stafford et al., 1987). According to Stafford et al. (1988), bone samples that yield an 80% pseudomorph upon pretreatment, such as the metacarpal, have a high to very high probability of yielding an accurate radiocarbon age. Bones that yield a 10% pseudomorph have a relatively low probability of yielding an accurate radiocarbon age (Stafford et al., 1988). On the basis of the much better protein preservation and much higher collagen yield of the metacarpal bone, we conclude that its radiocarbon age more accurately reflects the age of the bones. Hence, we interpret the time of recession of Lake Lahontan from the highstand to have occurred immediately prior to 13 070 ± 60 yr B.P.

Geomorphic and crosscutting relationships were used to determine the details of lake-level fluctuations around the highstand. At the highstand, a small spit complex (shoreline D; Fig. 6) began to build northwest from a small rocky promontory near the head of the embayment (Fig. 12). As lake level receded from the highstand, a second and slightly lower lobe of the complex continued to build to the north. During the time lake level had dropped about 3 m, the spit had extended about 250 m. Lake level then dropped another 2 m and the distal end of the upper spit was truncated. A lower spit was built about 250 m to the north-northwest from the northwest end of the erosional scarp while lake level stabilized at about 1334 m (Fig. 12). The lower or regressive spit is landward of the progradational barrier complex, the surface of which is also built at about 1334 m (Fig. 12). Once the barrier ridges were emplaced across the head of the embayment, wave action landward of the barriers would have ceased. Hence, the barrier ridges must postdate the regressive spit (feature 2b; Fig. 12) and by inference, the highstand. A ^{36}Cl surface exposure age of about 15 ka from the upper part of the complex (Fig. 7) (F. Phillips, 1995, written commun.) is not precise enough to confirm whether the ridges were emplaced prior to or after the highstand.

A literal interpretation of AMS radiocarbon dates on gastropod shells (13 110 ± 110 and 13 280 ± 110 yr B.P.) suggests that the lower part of the progradational barrier complex was deposited prior to the Sehoo cycle highstand (Fig. 7). Therefore, we propose that the lower part of the progradational barrier complex was formed during the transgression to the highstand and that the upper part was formed during the regression from the highstand. The contact between the transgressive and regressive packages of sediment is placed at the tufa and beachrock horizon (top of unit 7) because units 8 through 12, which comprise the surface ridges of the progradational barrier complex, all overlie this horizon and the presence of the tufa implies that this horizon remained under water for some period of time (Fig. 7).

If the lower part of the progradational barrier complex was deposited during the transgression, then by using the ages and error limits of the shell dates and of the preferred bone date (13 070 ± 60 yr B.P.), we estimate that the highstand could not have lasted more than about 150 yr and may have lasted only a few decades or less. The brevity of the highstand is reasonable in light of the recent formation of similar sized shoreline features in the Pyramid Lake basin, which formed in just a few months (Fig. 10). Well-developed terraces are lacking at the highstand level, which suggests that the highstand was of sufficient duration to form well-developed spits and barriers but not long enough to form terraces at this level.

Lake level continued to decline after it stabilized long enough to form the five barrier ridges of the progradational barrier complex. During the overall regression, the lake formed at least 20 additional barrier ridges as it fell to the floor of the Carson Sink (Figs. 3 and 6). The ridges were formed in locations where there was enough unconsolidated sediment for waves to arrange into barriers. The elevations and vertical spacing of the recessional barriers do not necessarily match the elevations and spacing of the erosional terraces cut into the east island (Fig. 3) because the terraces may have formed during the Sehoo transgression or during an earlier lake cycle.

Comparison with Previous Lake-Level Curves. The observations and interpretations from this study represent the first estimates of the timing and magnitude of the highstand based on radiocarbon estimates of organic carbon (bone) and shore features that actually represent the highstand of Lake Lahontan. Basin-wide observations indicate that constructional beach features most accurately reflect the highstand rather than the more widespread but lower terraces (Adams and Wesnousky, 1994, 1995; Adams, 1997). The data from this study are interpreted to indicate that the Sehoo highstand was relatively brief (years to decades?) and began receding immediately prior to 13 070 yr B.P.

During the past 20 yr, many lake-level curves have been proposed for the Lahontan basin that place the highstand between about 14.5 and 12.5 ka (Benson, 1978, 1991, 1993; Benson and Thompson, 1987a, 1987b; Benson et al., 1990, 1995; Thompson et al., 1986). However, the exact timing of the highstand has proved elusive. Previous studies have attempted to constrain the timing and magnitude of the highstand by dating tufa deposits found near the elevation of the highstand. In field visits to more than 200 high shoreline localities throughout the basin (Adams and Wesnousky, 1994, 1995; Adams and Fontaine, 1996; Adams, 1997), tufa was never observed at the high shoreline level. Commonly, tufa is found about 5 to 7 m lower on stable substrates in places that received high wave energy. However, we have not observed tufa on steep bedrock slopes or cliffs adjacent to and at the same elevation as highstand constructional shorelines. These observations suggest that, approaching the time of the highstand, lake-level rise may have been so abrupt and the duration of the highstand so short that tufa did not have time to precipitate. Alternatively, or in conjunction with this rapid, brief rise, the chemistry of the lake water may have changed because of the sudden influx of fresh water, so that geochemical conditions were not conducive to tufa precipitation. Both of these possibilities imply that Lake Lahontan received a sudden influx of water that caused an abrupt rise in lake level which lasted a relatively brief period of time, which is reflected in studies by Benson (1978, 1991, 1993) and Benson et al. (1995) as well as by the data from this study.

CONCLUSIONS

The shoreline record of Lake Lahontan in the Jessup embayment provides much information about the history of the Sehoo lake cycle as well as information about controls on shoreline development and shoreline processes along an irregular and high relief coast. Through detailed mapping of lacustrine deposits and shoreline features, combined with stratigraphic and sedimentologic studies, controls on shoreline development were determined to include local slope, the amount and characteristics of sediment available for transport, the availability of accommodation space, and the length of time lake level resides at a particular shoreline elevation.

During the Sehoo cycle highstand and early part of the regression, longshore drift was clockwise near the head of the embayment, indicating that strong winds and large storm waves were coming from the south or southeast. Constructional shoreline features built at the Sehoo cycle highstand vary by as much as 2.6 m in elevation. Crestal height variability is controlled by the amount of fetch, local slope, geometry of the shoreline, and the presence or absence of offshore obstructions.

The Sehoo cycle highstand reached an elevation of about 1338.5 m in the Jessup embayment and lasted a relatively brief time, probably years or decades. The lake receded from the highstand immediately prior to 13 070 ± 60 yr B.P., the age of camel bones found behind a highstand barrier in a paleolagoon. During the regression from the highstand, 28 distinct barrier ridges formed as the lake dropped back down to the floor of the Carson Sink at about 1185 m in elevation. Barrier ridges at about 1234 and 1227 m probably represent a minor transgression after the major regression.

The results of this study are useful not only for interpreting the history of the Sehoo lake cycle and the paleoclimate record associated with lake-level fluctuations, but the techniques employed here can also be applied to tectonic and paleoenvironmental (e.g., paleowind) studies of lacustrine basins in the western United States and elsewhere.

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