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The Lake Lahontan highstand: age, surficial characteristics, soil development, and regional shoreline correlation

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Abstract

The Lake Lahontan basin has been the site of numerous pluvial lakes during the Pleistocene. We address the question of whether or not the highest remnant shoreline features around the perimeter of the lake were produced during the most recent Sehoo highstand (~ 13 ka), the penultimate Eetza highstand (~ 140–280 ka), or both. To do so, we document surficial characteristics, morphologic preservation, and soil development on multiple Sehoo beach barriers in the Jessup embayment to define the range in characteristics displayed by latest Pleistocene beach features. Sehoo barriers generally exhibit original constructional morphology that has been little modified by erosion. Soils developed on Sehoo barriers are generally thin and weakly developed and are strongly influenced by the introduction of eolian fines into the predominately clast-supported coarse beach gravels. Similar observations from 13 other highstand barriers and from seven older-than-latest Pleistocene paleosols located around the basin form the basis for a regional comparison. Based on similar characteristics, including the degree of morphologic preservation and weak soil development, we conclude that the widespread and nearly continuous high shoreline around the perimeter of Lake Lahontan dates from the most recent major lake cycle in all areas except in the Walker Lake subbasin. In the Walker Lake subbasin, isolated early to middle Pleistocene lacustrine outcrops and landforms are elevated as much as 70 m above the late Pleistocene limit, but are differentiated by their degraded form and lack of continuity around the subbasin. Similar unambiguous landforms were not observed elsewhere and at similar elevations in the northern subbasins of Lake Lahontan.

Keywords: Lake Lahontan; highstand; soil development; shoreline correlation

1. Introduction

Lake Lahontan occupied most of the basins in northwest Nevada and the Honey Lake basin in adjacent northeast California during its last highstand at about 13 ka (Fig. 1). Well-developed shoreline features and coastal geomorphology displayed on the mountain fronts and piedmonts around the basin attest to vigorous wave energy caused by Pleistocene storms. The late Pleistocene (Sehoo) lake was, however, only the most recent in a series of lakes that have occupied the same basin through the Quaternary. As many as five major lake cycles in the last 1 Ma are identified by lacustrine deposits separated by nonconformities and/or weathering horizons and dated by volcanic tephras (Davis, 1978; Morrison, 1991; Reheis, 1996; Reheis and Morrison, 1997).

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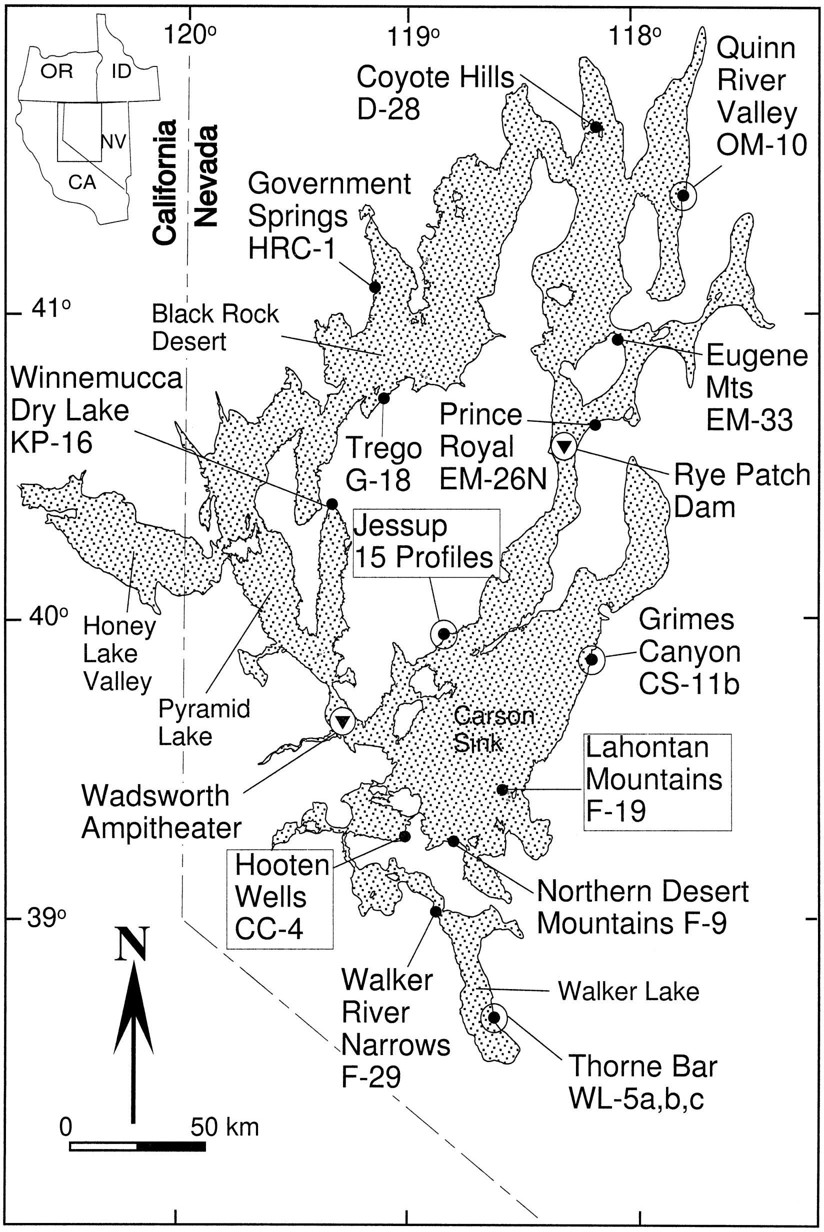

Fig. 1. Location map of the Lake Lahontan basin showing the distribution of soil study sites superimposed on the extent of the Lake at about 13 ka. Dated Sehoo profiles are delineated by boxes around their labels. Pre-Sehoo soils developed on coarse beach gravels are circled and pre-Sehoo soils developed on fluvial deposits are designated with circled inverted triangles.

Because the lakes were apparently never controlled by an external outlet, lakelevel fluctuations were related only to climatic changes. Hence, the highstand attained by each separate lake was directly controlled by climatic conditions prevailing at those times.

The complexity of the Lahontan lake level record has led different researchers to contrasting conclusions about the age of the high shoreline in the basin. I.C. Russell (1885), who accomplished the first comprehensive study of Lake Lahontan, concluded that the uppermost shoreline (Lahontan Beach) dated from the most recent lake cycle; whereas, the stratigraphically and elevationally lower Lithoid Terrace (LT) represented the highstand of the penultimate lake cycle. In the early part of this century, Jones (1925) and Antevs (1925), studying the lake's history, agreed that highstand features date from the most recent lake cycle. However, Morrison (1964, 1991) interpreted that the highest shoreline in the southern Carson Desert area dates from the penultimate (Eetza; ~ 130–350 ka) lake cycle and that the Sehoo highstand shoreline (~ 13 ka) is about 3 m lower. More specifically, Morrison (1991) states that the high shoreline dates from the middle Eetza highstand which he estimates to be about 280 ka (Oxygen isotope stage 8). This is in contrast to studies by Benson (1978, 1991, 1993) in the Pyramid Lake subbasin where deposits interpreted to relate to the high shoreline date from ~ 13.5 ka, or the Sehoo highstand. Mifflin and Wheat (1971, 1979), whose studies also covered the entire basin, postulated on the basis of surface morphology and soils that the age of the highest shoreline in the northern part of the basin dates from Sehoo-time but agreed with Morrison (1964) that the age of the highest shoreline in the southern part of the basin dates from Eetza-time. They called upon regional, down to the north tilting during the Eetza-Sehoo interpluvial to explain the different ages of the high shoreline (Fig. 2).

We report in this paper our work to test the hypothesis that the high shoreline of Lake Lahontan dates from more than one lake cycle. Our interest in

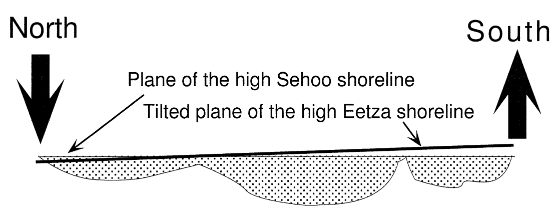

Fig. 2. Schematic diagram illustrating regional down to the north tilting hypothesis of Mifflin and Wheat (1979) that may have uplifted the Eetza shorelines above the Sehoo limit in the southern part of the basin. The diagram represents the approximately 350 km north–south length of Lake Lahontan.

the age of the highest Lahontan shoreline stems from a parallel effort to determine the isostatic rebound due to loading and unloading during and after the Sehoo lake cycle (Adams, 1997; Adams and Wesnousky, 1994, 1995). The magnitude and character of rebound are determined by measuring the elevations of constructional shorelines formed during the Sehoo highstand. Consequently, differentiating between Sehoo and older-than-Sehoo high shorelines is critical to the success of the rebound project.

If the highest shoreline features preserved around the perimeter of Lahontan date from both the Sehoo and Eetza lake cycles, they likely possess significantly different morphological and pedogenic characteristics because they are separated in time by more than 100,000 years. We first document the surficial characteristics, preservation, soil development, and spatial variability in soils developed on dated Sehoo barrier ridges in the Jessup embayment and two other dated Sehoo high shorelines in different parts of the basin. We then compare these observations to undated high shorelines as well as to buried soils lower in the stratigraphic section. The comparisons enable determination of whether or not the high shoreline of Lake Lahontan represents a single highstand that dates from Sehoo time.

2. Site and soil descriptions

2.1. Surficial characteristics, preservation, and soil development of Sehoo age barriers in the Jessup embayment

The Jessup embayment is a small bay located in the northwestern Carson Sink of the Lahontan basin (Figs. 1 and 3). The majority of surface lacustrine features in the embayment, including the highstand barriers, date from the Sehoo lake cycle which receded from its highstand at about 13 ka (Adams and Wesnousky, 1998). This age is based on an AMS radiocarbon date from camel bones found in a former lagoon enclosed behind a highstand barrier referred to as the Jessup playette barrier (Fig. 4). The bones were found at the contact between lagoonal sands and primarily subaerial sediment which filled the closed depression after the lake had receded from

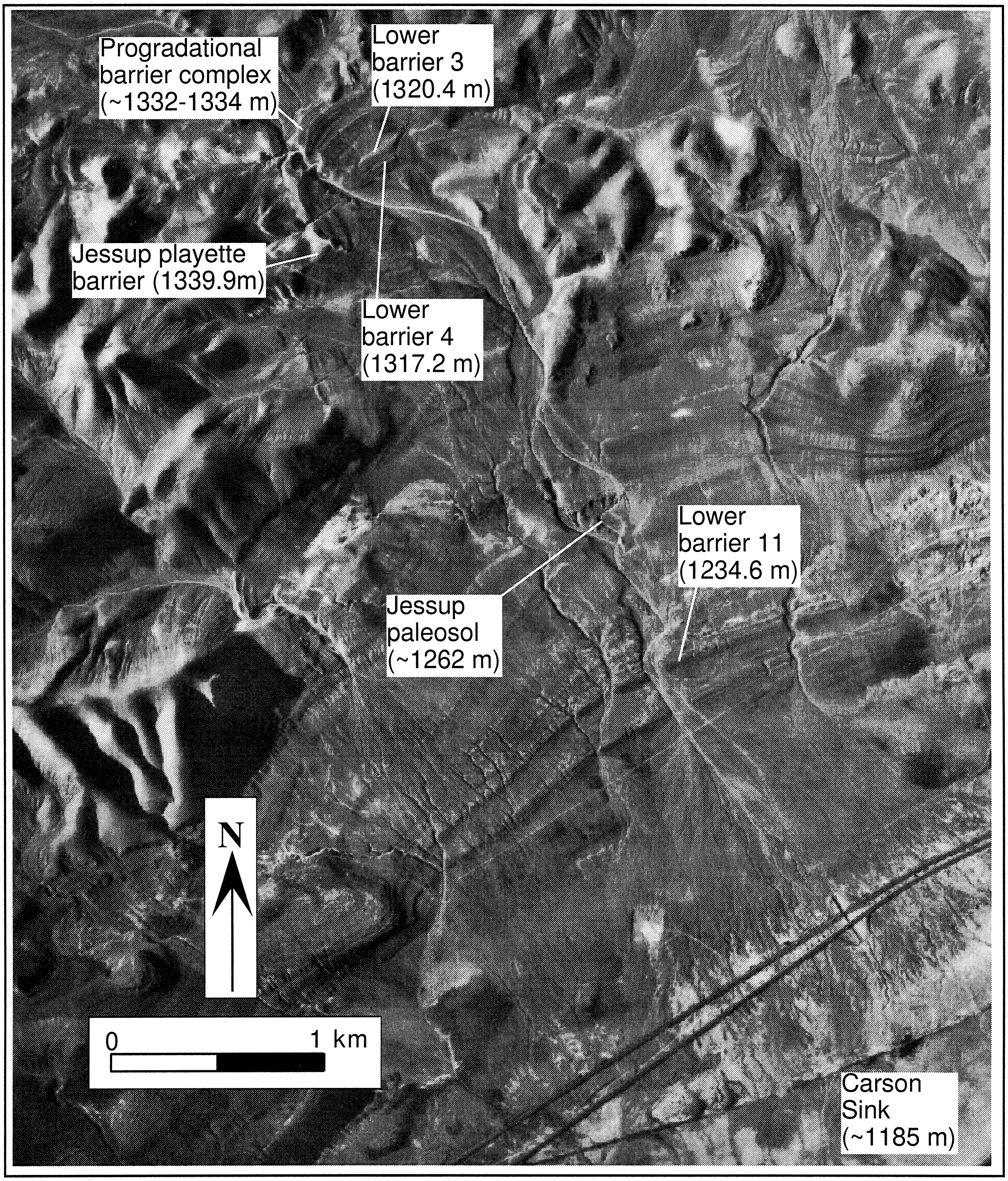

Fig. 3. Air photo of the Jessup embayment that shows the locations of soil study sites. Note well-developed shoreline features from the highstand to near the floor of the Carson Sink.

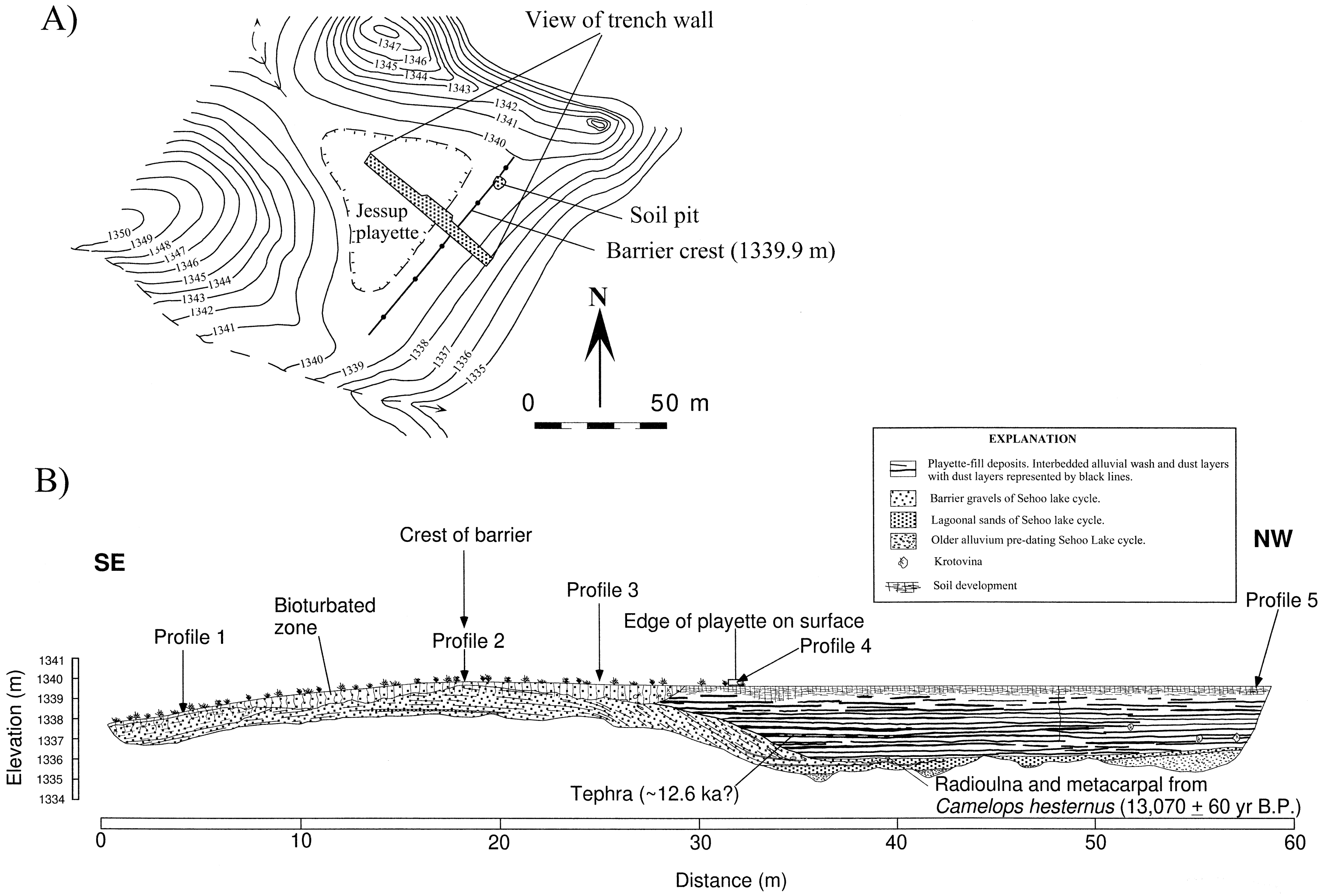

Fig. 4. (A) Topographic map of the Jessup playette barrier site showing the locations of the trench and adjacent soil pit. Contour interval is 1 m. (B) Simplified log of the Jessup playette trench showing locations of the described soil profiles and salient features related to soil development. Note convex-up cross section shape of barrier. View is to the southwest, but all soils were described on the northeast wall of the trench and their locations projected onto the southwest wall. The location of the camel bones was also projected from the northeast wall to the southwest wall. No vertical exaggeration.

the highstand. Thus, the age of the bones closely marks the beginning of the recession of Lake Lahontan from its highstand (Adams and Wesnousky, 1998). More than 20 barrier ridges were formed during the Sehoo regression as lakelevel dropped about 150 m to the floor of the Carson Sink (Fig. 3). Therefore, recessional barriers are younger than 13 ka but probably older than about 11 ka (Currey, 1988; Benson et al., 1992).

Shoreline features in the embayment and elsewhere in Lahontan were formed by direct wave action and consist of both erosional and constructional landforms. In this paper, we focus on constructional beach features which include spits, tombolos, and other types of barriers. Constructional shorelines are generally more useful than erosional shorelines in assessing the age of a stillstand because they include deposits as well as landforms. Therefore, soil development can be used in conjunction with the surficial characteristics of a particular constructional shoreline for relative age dating.

Beach barriers, both at the highstand and at lower elevations, are convex-up positive relief landforms in cross-section (Fig. 4). Because they rise above the local landscape, barriers also tend to have a relatively high preservation potential in comparison to terraces. The convex-up shape commonly mimics sedimentary architecture where barrier sediments are arranged into foresets, topsets, and backsets depending on bed position and dip direction within the barrier (Adams and Wesnousky, 1998). Barriers in the embayment are composed of well-sorted gravel or sand depending on location. Finer-grained barriers generally have more gentle proximal and distal slopes than do gravel barriers.

Preservation of Sehoo landforms and deposits in the Jessup embayment is generally excellent and features are easily discerned both on aerial photographs and in the field (Fig. 3). Post-depositional modification is rather limited and consists of either minor dissection or shallow burial by alluvial sediments or remobilized beach sediments. Because barriers are relatively horizontal features, dissection is generally limited to ephemeral stream cuts and small gullies. Stream cuts are narrow v-shaped notches where active channels occupy the entire width of the washes. An exception to the typical v-shaped channel is the main wash running from north to south down the axis of the embayment which is broader than it is deep (Fig. 3). In several locations, active washes are deflected by barriers causing the landward sides of the barriers to be eroded parallel to strike.

Not all highstand barriers have been dissected and several enclose small depressions which have accumulated sediment in post-Sehoo time. The most notable of these is the Jessup playette barrier (JPB) which dates from about 13 ka, as discussed above. The JPB is a small pocket barrier about 100 m long emplaced across the mouth of a small reentrant along the shore. About 4 m of subaerial and shallow water sediment has accumulated behind the barrier, raising the surface of the playette to within about 20 cm of the crest of the barrier (Fig. 4).

Surface characteristics of the JPB are typical of other highstand barriers around the embayment and coarse clastic recessional barriers in terms of vegetation, clast size, rounding, sorting, rock varnish development, and the presence of rodent mounds. Vegetation consists of shadscale, greasewood, and other desert shrubs spaced about 1 to 3 m apart. Surface clasts range in size from 0.5 to 15 cm with a median size of about 1 to 4 cm. Lithologies include basalt, rhyolite, other volcanics, and metasedimentary rocks. Surface clasts are subrounded to well-rounded except for those that have undergone post-depositional splitting, which is common for platy rhyolite clasts. Basalt clasts have moderate varnish whereas varnish development on other lithologies is weak or absent. In this study, weak varnish is discontinuous and found primarily in small irregularities, whereas moderate varnish is relatively continuous across the surface of the clast. The surface of the barrier has been bioturbated as evidenced by small ($\sim$ 15 cm relief) debris piles associated with rodent burrows. Clasts in these piles appear less-varnished and weathered than adjacent surface clasts.

We excavated a trench across the crest of the barrier and into the playette in order to examine the sedimentology and stratigraphy of the site and to look for materials suitable for dating (Fig. 4). The trench, as well as an adjacent soil pit excavated on the crest of the barrier, also allows us to characterize soil development from multiple soil profiles on a surface of a single age and to assess spatial variability in soil development. All soils in this study were described according to the techniques and terminology outlined in Birkeland (1984) and Soil Survey Division Staff (1993). Laboratory particle-size analyses were performed by wet sieving and pipette sampling after Janitzky (1986). Five soil profiles were described and analyzed in different positions in the

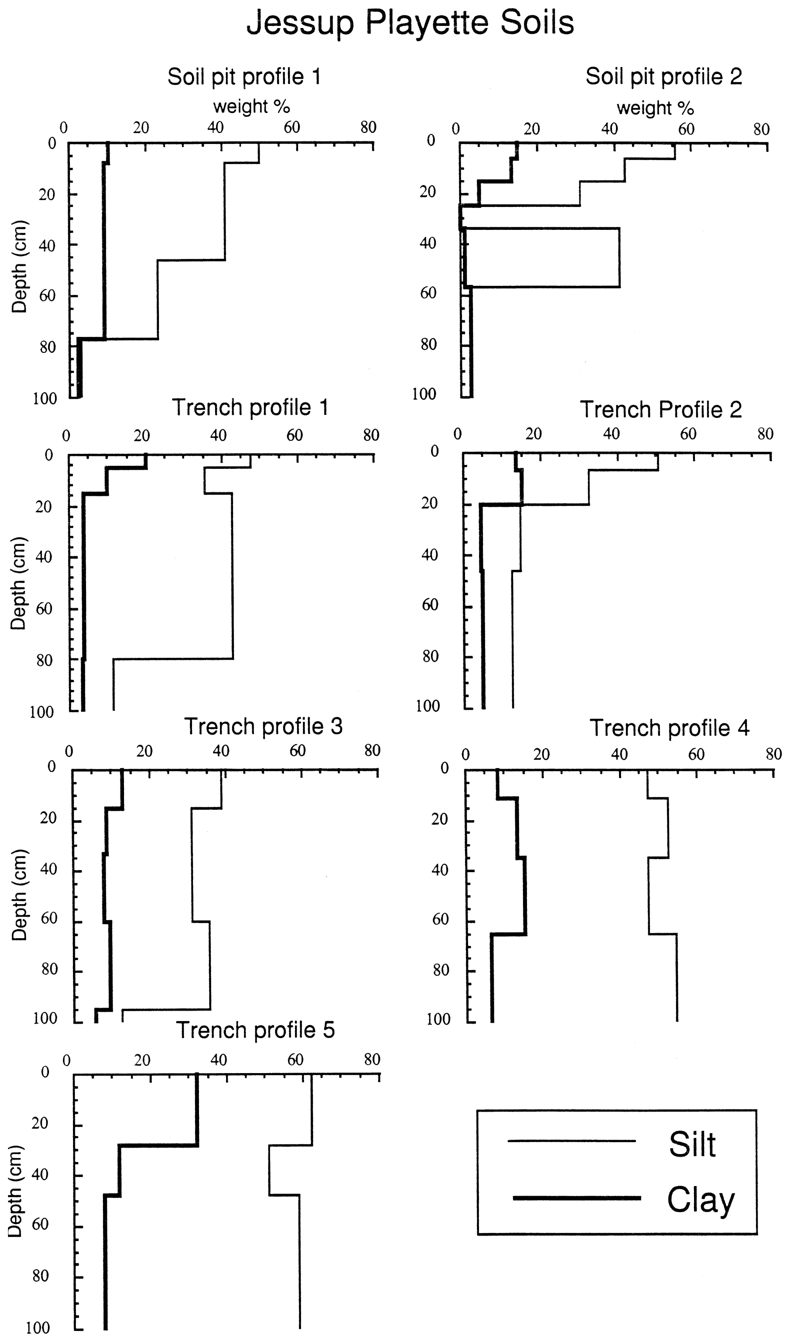

Fig. 5. Clay and silt accumulation plots for the Jessup playette barrier.

Table 1
Soil data from the Jessup playette and high barrier[a]

Horizon	Depth (cm)		Color[b]		Texture[c]	Size (% wt)			Structure[d]	Consistency[e]			$CaCo_3$, effervescence[f] (matrix, clasts)	Pores[g]	Roots[h]	Lower boundary[i]
	Top	Base	Dry	Moist		Sand	Silt	Clay		Dry	Moist	Wet				
Trench Profiles																
JPT Profile 1																
Av	0	5	10YR 7/3	10YR 5/4	L	32.3	47.6	20.1	1CPR, 2MGR	lo, sh	fi	vs, p	es	2vf, fv	1f	aw
2Bw	5	15	10YR 6/4	10YR 4/4	GSL	54.8	35.5	9.7	1, 2MCR, SBK	lo, sh	fr	so, ps	0, tdc	0	2vf	cw
3Bk	15	80	10YR 6/4	10YR 4/4	VGSL	53.5	42.7	3.8	0	lo	lo	so, po	es, tdc	0	1f	cw
3Ck	80	150+	ND		G, C and F	85.5	11.2	3.3	NA		NA		tdc	NA	0	ND
JPT Profile 2																
Av	0	7	10YR 7/3	10YR 5/3	SiL	36.0	50.5	13.5	2CPR	sh to h	fr	ss, ps	es	3f, mv	1f	aw
2Bw	7	20	10YR 6/3	10YR 5/4	GSL	52.5	32.6	15.0	0 to 1MCR	lo to so	lo	so, po	e, tdc	0	2vf to f	cw
3Bk	20	46	10YR 7/3	10YR 6/4	VGLS	80.9	14.6	4.5	0	lo	lo	ss, po	es, tdc	0	1 to 2f	cw
3Ck	46	150+	ND		G	82.5	12.5	5.0	NA		NA		tdc	NA	0	ND
JPT Profile 3																
Av	0	15	10YR 7/3	10YR 5/3	L	48.5	38.7	12.8	2CPR, 1CPL	so to sh	fr	ss, ps	e	2,3 fv	1f	aw
2Bw	15	33	10YR 6/4	10YR 4/4	GSL	60.2	31.1	8.7	0 to 1MCR	lo to so	lo	so, ps	0 to e, tdc	0	2vf to f	cw
2Bk	33	60	10YR 7/3	10YR 5/4	GSL	61.2	30.8	8.0	0 to 1MSBK	lo to so	lo	so, po	es, tdc	0	2f	cw
2Bw	60	95	10YR 6/4	10YR 4/4	G to VGSL	55.1	35.5	9.4	0 to 1MSBK	lo to so	lo	so, ps	e, tdc	0	1f	gw
3Ck	95	200+	ND		G	81.8	12.6	5.7	NA		NA		tde	NA	0	ND
JPT Profile 4																
A	0	11	10YR 7/2	10YR 4/3	L	44.4	47.3	8.3	2CPR, 1MPL	lo to so	lo	so, po	e	1fv	1f	aw
2Av	11	35	10YR 7/3	10YR 5/3	SiL	34.4	52.5	13.1	2CPR to 2MPL	so to sh	lo	ss, ps	es	2fv	1f	cw
3Bw	35	65	10YR 6/4	10YR 4/4	L	37.6	47.2	15.2	0 to 1M, CSBK	so to sh	lo	so, ps	0 to e	2fv	1f	gw
3C	65	150+	ND		SiL	38.9	54.5	6.6	NA		NA		0	NA	0	ND

JPT Profile 5																
Av	0	28	10YR 8/3	10YR 5/4	SiCL	5.8	62.3	31.9	2CPR to 3CPL	so to sh	fi	ss, p	es	3fv	2vf to f	cw
2BC	28	48	10YR 6/4	10YR 5/4	SiL	37.2	51.0	11.7	0 to 1 MCR	lo to so	lo	ss, ps	0	0	1f	cw
2C	48	170+	10YR 6/4	10YR 4/4	SiL	33.3	58.8	8.0	NA		NA		0	NA	0	ND
Soil Pit Profiles																
JPBP Profile 1																
Av	0	8	10YR 7/2	10YR 4/2	L	40.1	49.7	10.2	2CPR to 2F, MPL	so to sh	fr	ss, ps	0 to e	3fv	1 to 2vf	aw
2Bw	8	46	10YR 6/4	10YR 4/4	VGL	50.2	40.9	9.0	0 to 1FSBK	lo to so	lo to vfr	so, po	0 to e, tdc	0	2vf	cw
2Bk	46	77	10YR 8/3	10YR 6/4	EGSL	68.1	22.9	9.0	0	lo	lo	so, po	ev, tdc	0	2vf	cw
2C	77	170+	ND		G	94.9	3.1	2.0	NA		NA		tdc	NA	0	ND
JPBP Profile 2																
Av	0	6	10YR 7/2	10YR 5/3	SiL	29.3	55.8	14.9	3CPR, 2MPL	so to sh	fr	ss, ps	0 to e	3fv	1vf	as
2Bt	6	15	10YR 5/3	10YR 4/4	GL	44.0	42.8	13.2	0 to 1VF, FCR	lo	fr	ss, ps	0	0	2vf to f	aw
2Bk	15	25	10YR 7/3	10YR 5/4	VGL	63.9	31.0	5.1	0 to 1VFCR	lo	lo	so, po	ev, tdc	0	2vf to f	as
matrix free zone	25	34	NA		G	No fine fraction			NA		NA		tdc	NA	1vf	as
4Bk	34	57	10YR 7/3	10YR 5/4	VGSL	57.7	41.0	1.3	0	lo	lo	so, po	ev, tdc	0	1vf	cw
4Ck	57	200	ND		G	94.7	2.8	2.5	NA		NA		tdc	NA	0	ND

[a] Descriptions and abbreviations follow criteria in Soil Survey Division Staff (1993), except: Av = vesicular A horizon.
[b] From Munsell Color (1990); NA, not applicable; ND, not determined.
[c] G, gravelly or gravel; VG, very gravelly; EG, extremely gravelly; C, cobbly or cobbles; F, flaggy or flagstones; S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; SiL, silt loam; L, loam.
[d] 0, single grained; 1, weak; 2, moderate; 3, strong; VF, very fine (very thin); F, fine (thin); M, medium; C, coarse (thick); VC, very coarse (very thick); GR, granular; CR, crumb; Pl, platy; PR, prismatic; CPR, columnar; ABK, angular blocky; SBK, subangular blocky; NA, not applicable.
[e] **Dry:** lo, loose; so, soft; sh, slightly hard; h, hard. **Moist:** lo, loose; vfr, very friable; fr, friable; fi, firm. **Wet:** so, non-sticky; ss, slightly sticky; s, sticky; po, non-plastic; ps, slightly plastic; p, plastic; NA, not applicable; ND, not determined.
[f] **Matrix:** e, slightly effervescent; es, strongly effervescent; ev, violently effervescent. **Clasts:** tdc, thin discontinuous carbonate coatings.
[g] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ir, irregular; v, vesicular; NA, not applicable; ND, not determined.
[h] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ND, not determined.
[i] a, abrupt; c, clear; g, gradual; d, diffuse; s, smooth; w, wavy; i, irregular; ND, not determined.

Table 2
Soil data from regressive barriers in the Jessup embayment[a]

Horizon	Depth (cm)		Color[b]		Texture[c]	Size (% wt)			Structure[d]	Consistency[e]			$CaCo_3$, effervescence[f] (matrix, clasts)	Pores[g]	Roots[h]	Lower boundary[i]
	Top	Base	Dry	Moist		Sand	Silt	Clay		Dry	Moist	Wet				
Progradational barrier complex																
Avk	0	12	2.5YR 6/3	10YR 3/3	SL	57.6	36.8	5.6	1FPL to 1FSBK	lo to so	lo	so, ps	es	3fv	1, 2f	aw
2Bwk	12	21	10YR 6/3	10YR 4/3	VGSiL	25.9	61.7	12.4	2MSBK	sh	fr	so, ps	e to es, tdc	2vfir	2vf	aw
2Bk	21	41	10YR 6/4	10YR 4/3	VGSiL	38.4	53.7	7.9	0 to 1FSBK	lo	lo	so, po	es, tdc	1fir to 0	1 to 2vf	aw
2BC	41	51	10YR 7/3	10YR 4/4	EGL	49.0	41.7	9.3	0	lo	lo	so, po	ev, tdc	0	2vf to f	aw
3Ck	51	150+	ND		G		ND		NA		NA		tdc	NA	0	ND
Lower Barrier 3																
LB-3 Profile 1																
Av	0	14	10YR 7/4	10YR 5/3	SL	68.5	25.3	6.2	3VCCPR, 1CPL	lo	lo to vfr	so, po	0 to es	3fv	1vf	aw
2Bk	14	39	10YR 7/3	10YR 5/4	VGSL	71.4	15.7	13.0	0 to 1FSBK	lo to so	lo	so, po	es, tdc	0	1vf, f	cw
2Ck	39	55	ND		VGS	92.5	4.9	2.6	NA		NA		0, tdc	NA	0	aw
3Ck	55	150+	ND		G	95.5	3.4	1.1	NA		NA		0, tdc	NA	0	ND
LB-3 Profile 2																
Av	0	9	10YR 7/2	10YR 4/2	GL	47.0	45.4	7.7	2CPR	lo to sh	lo	so, ps	es	3fv	0	aw
2Bk	9	16	10YR 7/3	10YR 5/3	GSL	73.1	13.4	13.4	0 to 1MCR	lo to so	lo	so, po	es, tdc	0	2f	cw
2Ck	16	30	ND		G	87.7	4.8	7.6	NA		NA		0, tdc	NA	0	aw
3Ck	30	150+	ND		G	97.6	2.6	0.8	NA		NA		0, tdc	NA	0	ND
Lower Barrier 4																
LB-4 Profile 1																
Av	0	10	10YR 7/2	10YR 5/3	L	48.9	42.3	8.9	2CPR	so to sh	lo	so, po	0 to e	3fv	1f	cw
2Btk	10	23	10YR 6/2	10YR 5/3	VGSCL	66.7	11.8	21.5	0 to 1MCR	lo to so	fr	so, ps	es, tdc	0	1, 2f	gw
2CK	23	105	ND		G	92.2	4.8	3.0	NA		NA		0, tdc	NA	1, 2f; 1m	as
3C	105	132	ND		GS	91.1	6.8	2.1	NA		NA		0, 0	NA	0	as
4C	132	200+	ND		S	91.8	8.2	0.0	NA		NA		0, 0	NA	0	ND

LB-4 Profile 2																
Av	0	10	10YR 7/3	10YR 4/3	SL	49.5	44.0	6.4	0 to 1CPR	so to sh	lo	so, po	e to es	3fv	1f	cs
2Bw	10	30	10YR 6/3	10YR 5/4	EGSL	77.3	14.6	8.2	0 to 1 MCR	lo to so	lo	so, po	0 to e, tdc	0	1, 2f	aw
2Ck	30	120	ND		G	89.1	10.9	0.0	NA		NA		0, tdc	NA	1, 2f	as
3C	120	140	ND		GS	91.1	6.8	2.1	NA		NA		0, 0	NA	0	as
4C	140	200+	ND		S	91.8	8.2	0.0	NA		NA		0, 0	NA	0	ND
Lower Barrier 11																
LB-11 Profile 1																
Av	0	12	10YR 6/2	10YR 5/3	L	39.3	42.0	18.7	2CPR to 2MPL	so to sh	fr	so, ps	es	3fv	1f	aw
2Bk	12	40	10YR 7/3	10YR 5/3	VGLS	79.2	20.2	0.6	0 to 1MCR	lo	lo	so, po	es, tdc	0	1, 2f	cw
2Ck	40	200+	ND		G	92.8	6.1	1.2	NA		NA		s, tdc	NA	0	ND
LB-11 Profile 2																
Av	0	12	10YR 7/3	10YR 4/3	L	47.9	34.8	17.3	0 to 2CPR	lo to so	lo	so, po	es	2, 3fv	1f	cw
2Btk	12	24	10YR 7/3	10YR 5/3	GL	39.2	34.6	26.2	0 to 2M, CSBK	so to sh	fr	ss, ps	es, tdc	2fv	1f	gw
2Ck	24	200+	ND		G	95.0	3.4	1.6	NA		NA		0, tdc	NA	0	ND

[a] Descriptions and abbreviations follow criteria in Soil Survey Division Staff (1993), except: Av = vesicular A horizon.

[b] From Munsell Color (1990); NA, not applicable; ND, not determined.

[c] G, gravelly or gravel; VG, very gravelly; EG, extremely gravelly; C, cobbly or cobbles; F, flaggy or flagstones; S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; SiL, silt loam; L, loam.

[d] 0, single grained; 1, weak; 2, moderate; 3, strong; VF, very fine (very thin); F, fine (thin); M, medium; C, coarse (thick); VC, very coarse (very thick); GR, granular; CR, crumb; Pl, platy; PR, prismatic; CPR, columnar; ABK, angular blocky; SBK, subangular blocky; NA, not applicable.

[e] **Dry:** lo, loose; so, soft; sh, slightly hard; h, hard. **Moist:** lo, loose; vfr, very friable; fr, friable; fi, firm. **Wet:** so, non-sticky; ss, slightly sticky; s, sticky; po, non-plastic; ps, slightly plastic; p, plastic; NA, not applicable; ND, not determined.

[f] **Matrix:** e, slightly effervescent; es, strongly effervescent; ev, violently effervescent. **Clasts:** tdc, thin discontinuous carbonate coatings.

[g] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ir, irregular; v, vesicular; NA, not applicable; ND, not determined.

[h] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ND, not determined.

[i] a, abrupt; c, clear; g, gradual; d, diffuse; s, smooth; w, wavy; i, irregular; ND, not determined.

trench across the barrier and into the younger playette-fill sediments and two additional profiles were described and analyzed from the adjacent pit (Fig. 5). Soils developed in the playette (profiles 4 and 5, Fig. 4) have parent materials consisting of silt and sand with few to no gravel clasts. Soils in the barrier are developed in coarse, clast-supported beach gravel where original bedding is present within 10 to

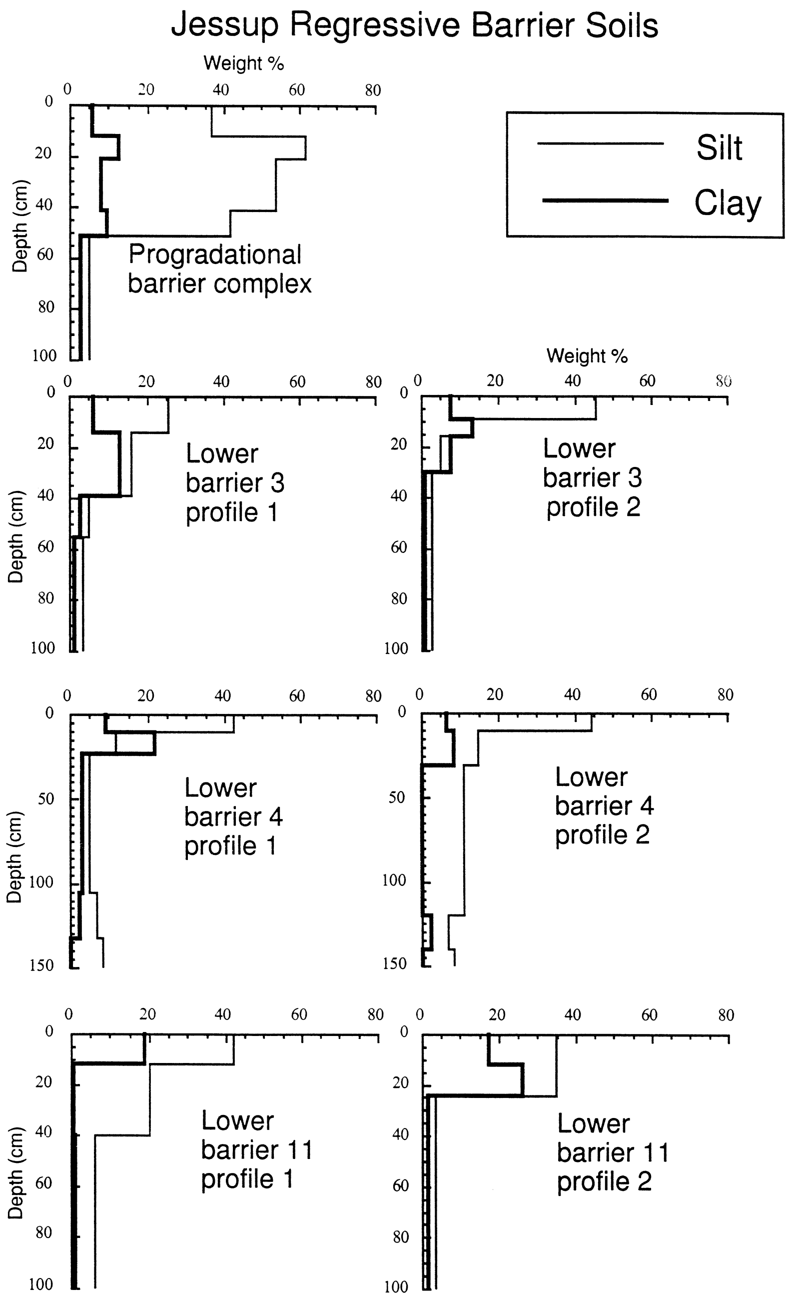

Fig. 6. Clay and silt accumulation plots for the Jessup regressive barriers.

100 cm of the surface (Fig. 4). The fine earth fraction (< 2 mm) most commonly fills the interstices between the gravel and cobbles.

Bioturbation, mainly by burrowing rodents, has mixed abundant eolian fines with the barrier gravels and caused the apparent migration of gravels to the northwest over the top of the younger playette-fill sediments (Fig. 4). The contact between the northwestern limit of gravel and vegetation with the playette surface is abrupt, linear, and occurs at about the 33 m mark on the trench log (Fig. 4). However, the gravels there merely consist of a thin sheet overlying the playette-fill sediments. Rodents probably occupied the barrier soon after the lake receded and began mixing surface eolian fines with the gravel. As the playette filled toward the crest of the barrier, bioturbation continued and the accumulating playette fines were incorporated into a thick, gravelly bioturbated wedge in the vicinity of soil profile 3 (Fig. 4). Abundant krotovinas (infilled burrows) are present throughout the bioturbated zone. In the vicinity of profile 1 (Fig. 4), the depth of bioturbation was apparently limited by coarse (< 25 cm) well-sorted disc-shaped cobbles.

Although multiple soil profiles described on the JPB display varying characteristics, soil development is generally weak (Table 1). Soils are characterized by silt-and clay-rich Av horizons, Bw horizons with little or no evidence of chemical weathering of clasts, and Bk horizons in which original bedding is still preserved. Weak soil development is also shown by textures below the Av horizons ranging from gravelly to extremely gravelly loam to loamy sand, structural grades ranging from single-grained to moderate, and dry consistencies ranging from loose to slightly hard. Fig. 5 shows the depth distribution of silt and clay in soil profiles described from the Jessup playette and barrier. Even though some clay is present at depth, evidence for clay translocation in the form of clay skins was not observed.

Carbonate is present in all of the soil profiles described on the JPB and adjacent playette and is indicated by a reaction with dilute HCl. In the playette profiles (JPT Profiles 4 and 5, Table 1), the depth of carbonate accumulation is limited to the upper 30 or 40 cm of the profiles and its lower limit is roughly coincident with the lower limit of recognizable soil structure (Fig. 4). In the beach gravel profiles, thin discontinuous carbonate coatings occur on the undersides of clasts to depths of greater than 200 cm, far deeper than all other indications of soil development. In terms of carbonate accumulation stages (Gile et al., 1966; Machette, 1985), all soil profiles are characterized as stage 1.

Soil profiles were described on the crests of four regressive barriers including the progradational barrier complex (PBC) and lower barriers 3, 4, and 11 (Fig. 3). Surface characteristics of the regressive barriers in the embayment are similar to those of the JPB in terms of vegetation, clast characteristics, varnish development, and presence of rodent burrows. All of these landforms consist of coarse, well-bedded clast-supported gravel. Table 2 presents field and laboratory data for soils on the regressive barriers. Whereas a single profile was described from the PBC, two profiles each were described from lower barriers 3, 4, and 11. Locations of the paired descriptions from the soil pits on lower barriers 3, 4, and 11 were selected to maximize the observed variations within the soils.

Soils developed on the regressive barriers are similar to, but just as variable as those developed on the JPB in terms of silt and clay accumulation, structural grade, and dry consistency (Figs. 5 and 6; Tables 1 and 2). Certain soil horizons visible within the pits are not laterally continuous and only extend through a horizontal distance of one to several meters. For example, the two profiles in lower barrier 11 were described just 4 m apart, but spatial variability displayed in clay content of the B horizons exceeds the total variability observed in all profiles in the embayment (Tables 1 and 2). Also, the Btk horizon of profile 2 from lower barrier 11 has the highest clay content and the only clay skins observed in any profile even though this barrier is the youngest surface on which soils were examined (Tables 1 and 2).

2.2. The Lahontan Mountains site (F-19); (UTM Zone 11, N4364800, E362000)

The Lahontan Mountains are located in the southeastern Carson Sink (Fig. 1). Because of the large fetch to the west and north, shorelines tend to be very well-developed. To the west of Sehoo Moun-

Table 3
Soil data from highstand barriers in the Lake Lahontan Basin[a]

Horizon	Depth (cm)		Color[b]		Texture[c]	Size (% wt)			Structure[d]	Consistency[e]			$CaCo_3$, effervescence[f] (matrix, clasts)	Pores[g]	Roots[h]	Lower boundary[i]
	Top	Base	Dry	Moist		Sand	Silt	Clay		Dry	Moist	Wet				
D-28																
A	0	5	2.5Y 6/3	2.5Y 4/3	VGSL	43.1	50.7	6.2	0 to 1FSBK	lo, sh	ND	so, po	0	0	2f	as
Av	5	14	2.5Y 6/3	2.5Y 4/3	SiL	35.9	51.5	12.6	2FSBK	so, sh	ND	ss, ps	0	2fv	2f	as
2Bw	14	25	10YR 6/2	10YR 4/2	VGL	49.6	34.5	15.9	0 to 1FSBK	lo, so	ND	ss, ps	es, tdc	0	2f	cw
2Ck	25	100+	NA		EGLS	77.3	18.0	4.7	NA		NA		es, tdc	0	2f ≤ 80	ND
EM-33																
Av	0	3	2.5Y 6/3	2.5Y 5/3	SiL	34.2	50.2	15.6	1FPL, 1FCR	lo, sh	fr	so, ps	e	3vf, fv	1vf	aw
2Bw	3	14	2.5Y 7/3	2.5Y 5/4	VGL	39.3	47.0	13.7	1FSBK	lo, sh	fr	so, po	e	2vfv	2f	cw
2Bk	14	26	10YR 7/4	10YR 6/4	EGSL	69.9	17.8	12.3	0 to 1FCR	lo	lo	so, po	es, tdc	0	1vf	aw
2C	26	100+	NA		EGLS	86.3	9.0	4.7	NA		NA		tdc	0	0	ND
OM-10																
Av	0	4	2.5Y 6/3	10YR 3/3	L	47.3	44.4	8.3	1CPR, 1FPL	lo, so	ND	so, ps	0	2vf, fv	2vf, f	aw
2Bw	4	30	10YR 7/3	10YR 4/3	VGSiL	39.1	50.5	10.4	0 to 1MCR	lo, so	fr	so, ps	0	2vf, f	2vf, f	gw
2Bk	30	41	2.5Y 6/3	2.5Y 4/3	EGL	45.4	44.6	10.0	0 to 1MCR	lo, so	lo, fr	ss, ps	es, tdc	2vf, fv	2, 3vf, f	gw
2C	41	100+	NA		EGLS	79.5	16.7	3.8	NA		NA		es, patchy	0	0	ND
EM-26N																
Avk	0	17	2.5Y 6/3	2.5Y 4/3	GL	41.5	46.6	11.9	2FPL, 1MSBK	so, sh	ND	so, ps	es	2fv	1, 2vf	cw
2Bk	17	37	2.5Y 7/3	2.5Y 5/3	VGSL	53.5	34.2	12.3	0 to 1FSBK	lo, so	ND	so, ps	ev, tdc	0	1vf	gw
2Ck	37	100+	NA		EGLS	86.6	9.8	3.6	NA		NA		ev, t, thc	0	0	ND
HRC-1																
Avk	0	8	2.5Y 6/3	2.5Y 4/3	GL	33.2	50.0	16.8	1FPL, 1FSBK	so, sh	ND	ss, po	e, patchy	2fv	1vf	as
2Bw	8	28	10YR 4/3	10YR 5/4	EGL	25.2	48.5	26.3	0 to 1FCR	lo, so	ND	s, p	0	0	2vf, f	cs
3Ck	28	100+	NA		G, C	49.3	32.8	17.9	NA		NA		e, tdc	0	2vf ≤ 70	ND

G-18																
Av	0	6	2.5Y 6/3	2.5Y 4/3	SL	72.0	21.1	6.9	0 to 1MCR	lo	ND	so, po	0	2fv	0	cw
2Bw	6	19	2.5Y 7/3	2.5Y 6/4	SL	57.2	31.8	11.0	1MCR, 1MSBK	lo, so	ND	so, po	e	2fv	1f	cw
2Bk	19	25	2.5Y 7/3	2.5Y 4/4	SL	57.2	23.8	19.0	2MCR	so, sh	ND	ss, p	es	2fv	1f	cw
2C	25	100+	NA		S	95.2	2.5	2.3	NA		NA		0	0	0	ND
KP-16																
A	0	3	10YR 5/3	ND	SL	71.3	23.0	5.7	0	lo	ND	so, po	0	0	0	aw
Bwl	3	28	2.5Y 6/3	10YR 4/3	L	51.5	37.9	10.6	1MGR	lo, so	ND	ss, ps	0	0	1m	aw
Bw2	28	41	10YR 5/4	ND	SL	59.2	31.9	8.9	0	lo	ND	so, po	0	0	1m	gw
C	41	100+	NA		GS	97.1	1.8	1.1	NA		NA		0	0	0	ND
CS-11b																
Av	0	8	10YR 7/2	2.5Y 5/3	SiL	24.9	51.2	23.9	2MPR, 2FPL	sh, h	fr	ss, ps	ev, tdc	2vfv	1vf	aw
2Bt	8	23	2.5Y 5/4	2.5Y 4/4	SL	67.0	20.0	13.0	1FCR	so, sh	lo	so, p	es, tdc	0	1vf	cw
2Bw	23	44	2.5Y 5/4	2.5Y 4/4	GLS	79.1	13.3	7.6	0 to 1FCR	lo	lo	so, po	es, tdc	0	0	cw
2Ck	44	100+	NA		VGS	88.9	7.8	3.3	NA		NA		es, thcc	0	0	ND
F-19																
Av	0	6	10YR 6/3	10YR 3/2	GCL	36.9	35.7	27.4	2FPL, 2FSBK	so, sh	fr	ss, ps	e	2, 3vfv	1f	aw
2Bw	6	15	2.5Y 7/3	2.5Y 4/4	VGL	39.1	47.7	13.2	0, 1FSBK	lo, so	lo, fr	ss, ps	e	1vfv	2vf, f	cw
2Bk	15	22	2.5Y 7/3	2.5Y 4/4	VGL	40.5	49.1	10.4	0, 1FCR	lo, so	lo	so, ps	es, tdc	1vfv	2vf, f	cw
2Ck	22	100+	NA		G	51.6	41.2	7.2	NA		NA		tdc	NA	0	ND
F-9																
Av	0	4	2.5Y 7/3	2.5Y 4/4	GSiL	35.7	51.1	13.2	2FSBK, 1FPL	so, sh	fr	ss, ps	e	2fv	1vf	aw
2Bw	4	22	10YR 5/4	10YR 3/3	EGL	35.8	43.1	21.1	0 to 1FSBK	lo, so	lo, fr	so, ps	0	0	1vf, f	cw
2Bk	22	32	10YR 5/3	10YR 3/3	EGSL	48.0	44.0	8.0	0 to 1FSBK	lo	lo	so, ps	e, tdc	0	1, 2vf, f	cw
2Ck	32	100+	NA		G	53.1	39.6	7.3	NA		NA		tdc	0	0	ND

(continued on next page)

Table 3 (*continued*)

Horizon	Depth (cm)		Color[b]		Texture[c]	Size (% wt)			Structure[d]	Consistency[e]			$CaCo_3$, effervescence[f] (matrix, clasts)	Pores[g]	Roots[h]	Lower boundary[i]
	Top	Base	Dry	Moist		Sand	Silt	Clay		Dry	Moist	Wet				
CC-4																
Av	0	9	10YR 6/3	10YR 4/3	VGSL	57.0	34.1	8.9	0, 1F, MSBK	lo, so	ND	so, ps	0	2, 3fv	1, 2vf	cw
2Bw	9	22	10YR 6/3	10YR 4/3	EGL	44.2	31.8	24.0	0 to 1FSBK	lo	ND	so, ps	tdc	0	3vf, f	gw
2Bk	22	40	10YR 5/3	10YR 4/3	EGL	51.6	32.3	16.1	0 to 1FSBK	lo	ND	so, ps	es, thdc	0	3vf, f	gw
2Ck	40	100+	NA		G	58.5	25.0	16.5	NA		NA		thdc	0	0	ND
F-29																
Av	0	8	10YR 6/3	10YR 4/4	SL	68.5	24.8	6.4	1FSBK	lo, so	ND	so, ps	0	3fv	1f	as
2Bt	8	22	10YR 5/4	10YR 4/4	GSL	74.0	7.6	18.4	0 to 1VFSBK	lo	ND	so, po	0	0	2f	cw
2C	22	100+	NA		GS	97.0	2.2	0.8	NA		NA		0, tdc	0	0	ND
WL-5c																
sand	0	3	2.5Y 8/3	2.5Y 5/4	SL	72.0	22.4	5.6	1FCR	lo, so	ND	so, po	0	ND	ND	aw
Avk	3	9	2.5Y 8/2	2.5Y 5/4	GSL	56.3	33.1	10.6	3FSBK, 1MPL	sh	ND	ss, ps	es	0	ND	cw
2Btjk	9	20	2.5Y 8/2	2.5Y 7/4	VGSCL	55.1	24.8	20.1	2F, MSBK	sh	ND	s, ps	es, tdc	0	ND	aw
2Ckq	20	90+	NA		EGS	92.6	3.8	3.6	0		NA		e	0	ND	ND

[a] Descriptions and abbreviations follow criteria in Soil Survey Division Staff (1993), except: Av = vesicular A horizon.

[b] From Munsell Color (1990); NA, not applicable; ND, not determined.

[c] G, gravelly or gravel; VG, very gravelly; EG, extremely gravelly; C, cobbly or cobbles; F, flaggy or flagstones; S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; SiL, silt loam; L, loam.

[d] 0, single grained; 1, weak; 2, moderate; 3, strong; VF, very fine (very thin); F, fine (thin); M, medium; C, coarse (thick); VC, very coarse (very thick); GR, granular; CR, crumb; Pl, platy; PR, prismatic; CPR, columnar; ABK, angular blocky; SBK, subangular blocky; NA, not applicable.

[e] **Dry:** lo, loose; so, soft; sh, slightly hard; h, hard. **Moist:** lo, loose; vfr, very friable; fr, friable; fi, firm. **Wet:** so, non-sticky; ss, slightly sticky; s, sticky; po, non-plastic; ps, slightly plastic; p, plastic; NA, not applicable; ND, not determined.

[f] **Matrix:** e, slightly effervescent; es, strongly effervescent; ev, violently effervescent. **Clasts:** tdc, thin discontinuous carbonate coatings.

[g] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ir, irregular; v, vesicular; NA, not applicable; ND, not determined.

[h] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ND, not determined.

[i] a, abrupt; c, clear; g, gradual; d, diffuse; s, smooth; w, wavy; i, irregular; ND, not determined.

tain, the northernmost of four small former islands has a small, teardrop-shaped beach deposit on its south side that probably accumulated in the lee of the island because of strongly refracted waves traveling from the north. The deposit is well-preserved and has been little modified since the recession of the lake. The upper surface lies at an elevation of 1335.6 m and is several meters above and appears to stratigraphically overlie the adjacent Lithoid Terrace (LT) which fringes the island.

At this location, the LT is a broad (< 10 m) erosional terrace excavated into basalt bedrock. The surface of the terrace is littered with large boulders (< 2m), many of which appear water worn and some which exhibit cavernous weathering. Russell (1885) interpreted the LT to represent the highstand of the penultimate lake cycle. Our studies of the Jessup embayment on the opposite side of the Carson Sink also indicate that the LT at least predates the Sehoo highstand and may represent the highstand of a previous lake cycle (Adams and Wesnousky, 1998).

In contrast to the LT, the surface characteristics of the overlying constructional beach deposit are quite different. Surface clasts are subangular to well-rounded, range in size from 1 to 15 cm and have a median size of about 5 cm. All clasts are composed of basalt and many are well-varnished. At depth, the deposit consists of clast-supported, well-rounded cobbles with a median size of 10 to 20 cm. A well-developed stone pavement is set into a silt and clay rich Av horizon. Vegetation consists mostly of widely spaced shadscale, other desert shrubs, and a few bunches of annual grasses.

A ^{36}Cl surface exposure age of < 15 ka (Fred Philips, New Mexico Tech, personnel comm., 1995) indicates that the constructional beach deposit is Sehoo in age. Soils data for this landform presented in Table 3 and in Fig. 7 support this interpretation. In general, soil development is characterized as weak, which is indicated by very gravelly loamy textures, single-grained to weak structure, loose to soft consistencies, and the relative thinness of the profile (Table 3). However, particle-size analysis of the fine earth fraction indicates that significant amounts of silt are present to a depth of about 100 cm (Fig. 7). Carbonate in the form of thin discontinuous coatings (Stage 1) on the undersides of clasts is also present to a depth of more than 100 cm.

2.3. The Hooten Wells site (CC-4); (UTM Zone 11, N4348300, E324400)

The Hooten Wells site consists of an undissected highstand looped barrier located in the southeastern corner of Churchill Valley (Fig. 1). The barrier prescribes an arc of about 70 m and encloses a small playette where fine sediment has accumulated since the recession of Lake Lahontan. The flat crest of the barrier lies at an elevation of 1333.2 m and declines slightly toward each end. Rhyolite clasts on the barrier comprise a loose pavement consisting of subangular to subrounded clasts ranging in size to 30 cm with a median size of about 3 to 5 cm. Large clasts tend to be more angular and the largest clasts are moderately varnished with the highest concentrations of varnish in small pockets. Vegetation consists of desert shrubs, bunch grasses, and annual herbs and flowers.

The drainage area associated with the playette is limited to a relatively small hillside directly upslope from the playette and the backslope of the looped barrier. Small, recent debris flow lobes are deposited at the edge of the playette at the base of the hillside. A 1.3 m deep pit near the center of the playette reveals a series of eight silty Av horizons, seven of which are buried (Fig. 8). Each distinct Av horizon is characterized by common to many vesicular pores and ranges in thickness from about 5 to 20 cm. Carbonate is present in some but not all of the Av horizons as indicated by a reaction to dilute HCl. The upper four Av horizons are separated by silty to sandy Bw horizons (Fig. 8). Four buried stone pavements separate some of the horizons and consist of single stone layers of small and mostly angular rhyolite clasts, some of which still have minor amounts of varnish preserved. A 3 cm thick layer (Sample KDA95CC-4-T1) identified as the Mazama Tephra (Andrei Sarna-Wojcicki, USGS, personal communication, 1997) occurs at a depth of about 80 cm (Fig. 8). The base of the exposure consists of coarse angular rhyolite clasts with a matrix of fine sandy loam. It is possible that the playette-fill sediments continue to a greater depth, but digging by hand became prohibitively difficult.

We interpret the playette fill sediments to represent minor debris flow events derived from the adjacent hillside and separated by periods of stability and incipient soil formation. Each of the Av horizons and associated relict stone pavements represents a period of stability where the playette surface probably appeared much as it does today. We do not interpret each of the soil horizons to represent discrete flow events, because there were probably numerous sediment pulses deposited on the playette surface as shown by minor sedimentary structures and erosion surfaces. Intervals lacking sedimentary structures may have been deposited by fine sediment settling out of standing bodies of muddy water, similar to the process proposed for the Jessup playette sediments (Adams and Wesnousky, 1998). Five of the eight Av horizons overlie the Mazama Tephra, which indi-

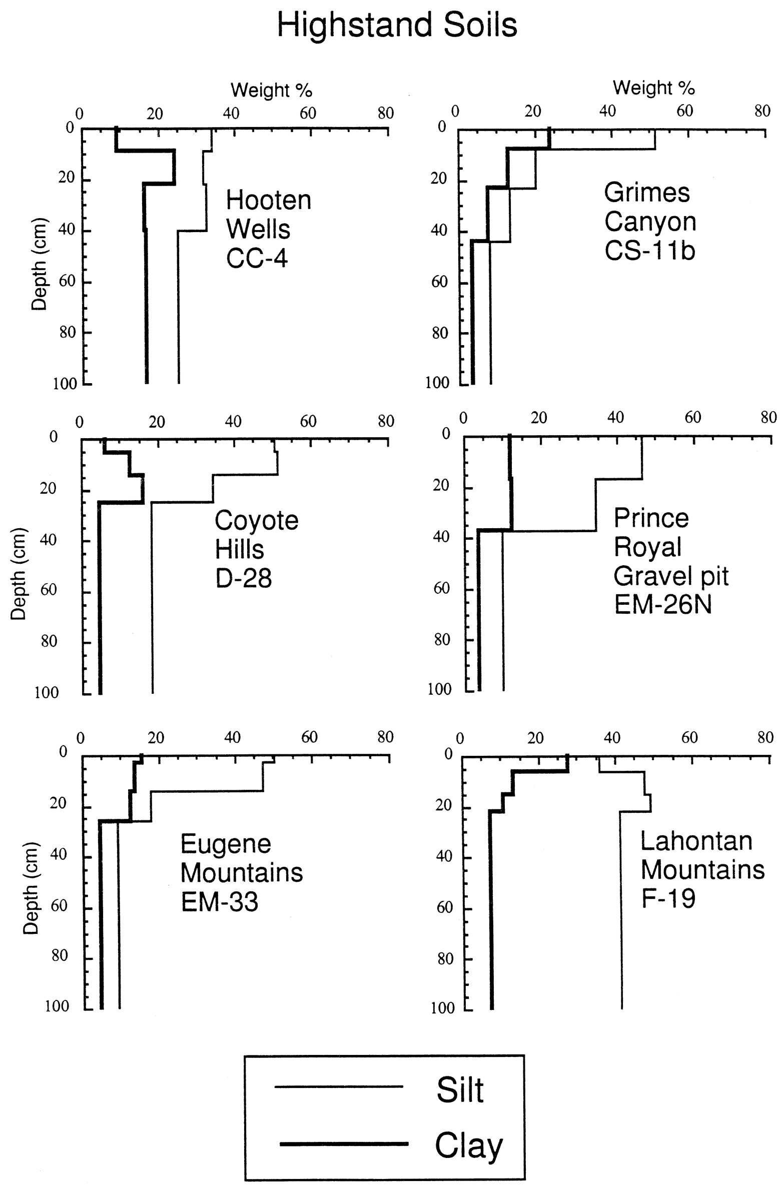

Fig. 7. Clay and silt accumulation plots for highstand soils located around the basin.

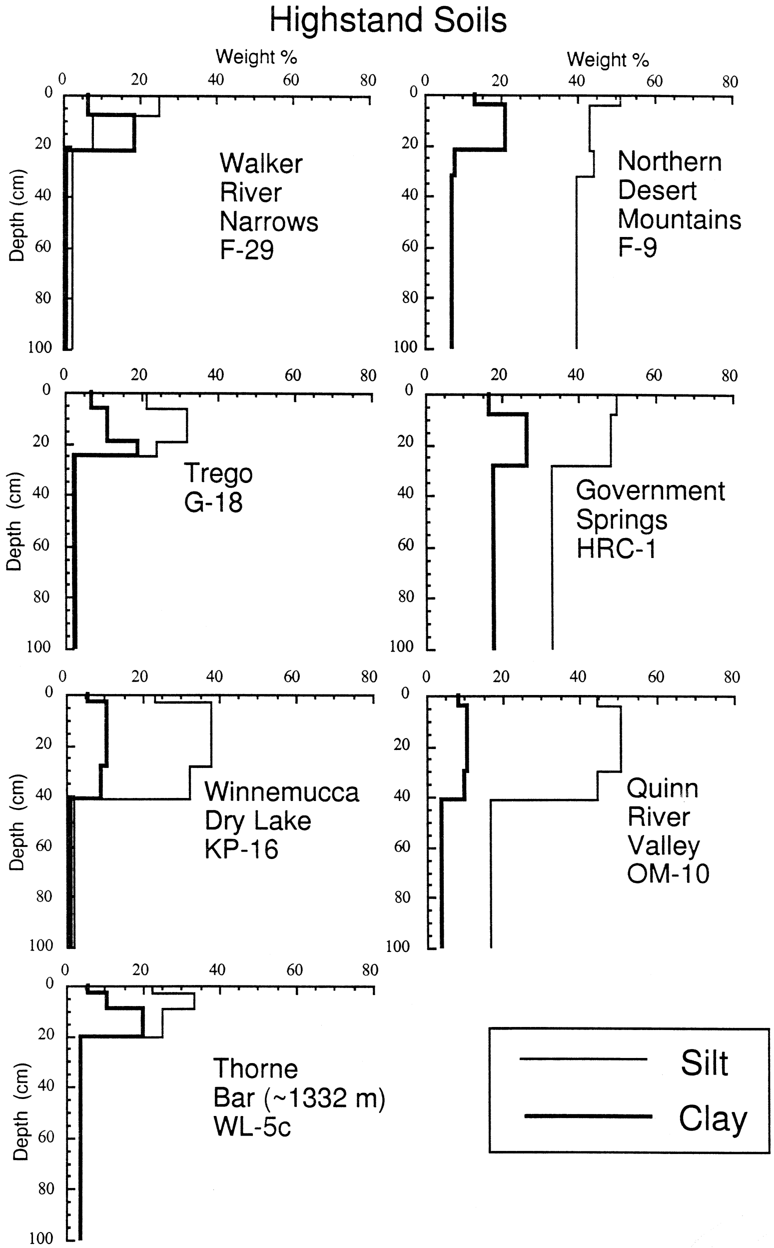

Fig. 7 (*continued*).

cates that there have been at least five periods of stability or non-deposition since about 6.9 ka, the age of the tephra (Bacon, 1983).

The closed depression occupied by the playette was formed by the emplacement of the looped barrier and hence, the Holocene age of the playette-fill sediments provide a minimum limiting age for the barrier. The poorly developed soil on the barrier (Table 3 and Fig. 7) supports the interpretation that the barrier was emplaced during the Sehoo highstand. An interesting feature of this profile is the relatively thick (< 1 mm) carbonate rinds on some

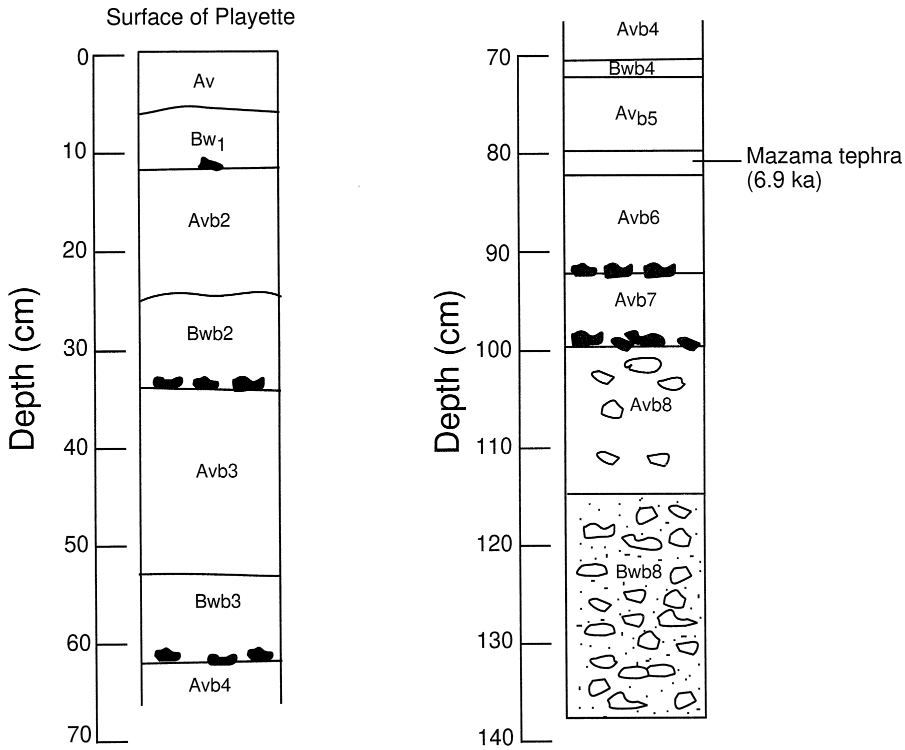

Fig. 8. Simplified stratigraphic column from the enclosed playette at the Hooten Wells site (CC-4). Silty Av horizons have well-developed vesicular pores and are interpreted to have formed at the surface. Black stones designate buried stone pavements that display poorly developed (or preserved?) rock varnish. The Mazama tephra (6.9 ka) is located at a depth of about 80 cm.

of the beach clasts at depth. Rinds are not preferentially distributed on the clasts and some appear to be chipped or mechanically abraded. It is likely that some of these clasts and their associated rinds were reworked from older beach sediments.

2.4. Other highstand locations

The surficial characteristics, preservation, and soil development of eleven other highstand shorelines were examined to compare them to the Sehoo barriers at Jessup, the Lahontan Mountains, and Hooten Wells. These features include pocket barriers, looped barriers, cuspate barriers, bay head barriers, progradational barrier complexes, and spits (Appendix A). In general, all of the highstand barriers are located at the top of local shoreline sequences and clearly mark the uppermost boundary of wave-produced landforms. Some of the barriers have been dissected by ephemeral washes while others still enclose depressions or small playettes on their landward sides. The original constructional morphology of all of the barriers remains little modified by gullying or deposition. Surface characteristics vary in detail from barrier to barrier and appear to depend largely on the size and lithology of clasts that make up the feature. Stone pavements are generally absent on coarse sandy barriers but are moderately to well-developed on coarser barriers. Varnish is best-developed on mafic volcanic and fine-grained dense metasedimentary rocks and is usually poorly developed or absent on other lithologies. Carbonate clasts at the surface display solution weathering in the form of pits, irregular grooves, and raised calcite veins. Discontinuous eolian silt and fine sand mantles (0–20 cm thick) are present on some of the barriers and are usually associated with a cryptogamic crust. Soils developed on all of these features can generally be described as weak (Table 3 and Fig. 7). Weak soil development is shown by relatively thin profiles, the lack of structure or only weak or moderate structure, and loose to soft consistencies. The surficial and pedogenic characteristics of all eleven highstand sites are very similar to the Sehoo barriers at Jessup, the Lahontan Mountains, and Hooten Wells. More detailed descriptions of eleven highstand sites are found in Appendix A.

2.5. Pre-sehoo paleosol sites

Seven soil profiles from pre-Sehoo deposits are also described to enable a comparison and contrast of soil development in older deposits with the Sehoo deposits. Five of the seven are buried soils, while two near the southern end of Walker Lake are still at the surface. The profiles were formed on deposits reflecting diverse sedimentary environments and different lithologic composition and they may not date from the same period. The soil profiles at Wadsworth Amphitheater and Rye Patch Dam (Fig. 1) were located utilizing descriptions in the literature (Morrison and Davis, 1984) and are developed in alluvial deposits of the Wyemaha Alloformation (AF) which post-dates the Eetza AF, but predates the Sehoo AF (Morrison, 1991; Morrison and Davis, 1984). Considering that the last highstand of the Eetza lake cycle was at about 130 ka (Morrison, 1991) and that the Sehoo lake did not begin to rise until approximately 30 ka (Benson et al., 1995), sediment correlated with the Wyemaha AF in different areas may have been deposited over the span of 100,000 years. Consequently, the period of time over which these soils developed may vary by tens of thousands of years.

The paleosols at Wadsworth amphitheater (~ 1260 m) and Rye Patch dam (~ 1280 m) display stronger soil development in terms of clay accumulation, structural grade, and consistency (Table 4 and Fig. 9) than any of the surface soils described at Jessup or at highstand locations around the basin (Tables 1–3, and Figs. 5–7). Therefore, we infer that the Wadsworth and Rye Patch paleosols were subject to soil-forming processes for longer than the Sehoo-age soils. Differences between the two paleosols could also relate to differences in parent material because the Wyemaha AF in the Wadsworth amphitheater consists of coarse sand and gravel, whereas the Wyemaha AF at Rye Patch dam consists of predominately well-sorted silt and clay with small amounts of fine sand (Table 4).

The three remaining paleosols are developed in coarse clastic beach deposits and are buried by younger Sehoo beach deposits. The paleosols at the Quinn River Valley site and at Grimes Canyon are located within two and nine meters of the highstand, respectively (Fig. 1). The paleosol at Jessup is located at an elevation of about 1265 m, or approximately 75 m below the highstand (Fig. 3). All three paleosols show a greater degree of development than the surface soils. Better development is displayed in terms of greater clay accumulation, higher structural grade, harder consistency, and thicker profiles (Table 4). Indeed, the paleosols at Quinn River Valley and Grimes Canyon are almost 2 m thick (Fig. 9).

The Walker Lake subbasin of Lake Lahontan has long been recognized as having anomalous topographically high lacustrine deposits and landforms (Russell, 1885; Mifflin and Wheat, 1979). Recently, a systematic examination of the subbasin (Reheis, 1996; Reheis and Morrison, 1997) has revealed new multiple locations where lacustrine deposits are present at elevations of 1400 m, or about 70 m above the Sehoo limit. Landforms associated with these deposits are largely degraded, discontinuous, and few in number. Preliminary ages for the pre-Eetza deposits range from early to middle Pleistocene (2.5 Ma to less than 760 ka) (Reheis, 1996).

The best-preserved anomalously high lacustrine landforms are in the Thorne Bar complex, which is located along the southeastern shore of Walker Lake (Figs. 1 and 10). This complex consists of a series of nested cuspate barriers which mark the former shores of different lake cycles. The well-defined Sehoo limit (~ 1332 m) consists of an almost continuous barrier ridge in the shape of a ‘v’ with its apex pointing west. On aerial photographs, the high Sehoo barrier exhibits a smooth appearance and is continuous, although it is obscured by younger fan sediments both north and south of the complex (Fig. 10). Along its northwest side, the Sehoo barrier encloses a small playette. That part of the Sehoo barrier fronting the playette is designated WL-5c and the soils and surficial characteristics are reported in Table 3 and Appendix A.

Two distinct shoreline levels above the Sehoo limit can be discerned both on aerial photographs

Table 4
Soil data from Pre-Sehoo age lacustrine and related deposits in the Lake Lahontan Basin[a]

Horizon	Depth (cm)		Color[b]		Texture[c]	Size (% wt)			Structure[d]	Consistency[e]			$CaCo_3$, effervescence[f] (matrix, clasts)	Pores[g]	Roots[h]	Lower boundary[i]
	Top	Base	Dry	Moist		Sand	Silt	Clay		Dry	Moist	Wet				
Wadsworth Amp																
Btkl$_b$	0	19	10YR 5/3	10YR 4/3	L	43.2	32.0	24.8	2MPR, 2FSBK	lo, sh	ND	s, p	e, es	0	1fvf, f	cw
Btk2$_b$	19	52	10YR 6/4	10YR 5/4	SCL	59.1	18.8	22.1	2FSBK to 2FPL	sh, h	ND	ss, p	e, es	0	1f	gw
Cl$_b$	52	90	NA		SL	66.7	24.8	8.5	NA		NA		0	0	0	gw
C2$_b$	90+		NA		LS	86.9	9.5	3.6	NA		NA		0	0	0	ND
Rye Patch Dam																
Btk$_b$	0	36	10YR 6/4	10YR 5/4	SiCL	13.2	56.1	30.7	3FPR, 3FSBK	sh, h	ND	s, p	es	0	0	cw
Bk$_b$	36	60	10YR 6/4	10YR 5/4	SiCL	4.8	60.8	34.8	2FPR, 2F, MSBK	sh	ND	s, p	es	0	0	gw
C$_b$	60+		NA		SiL	5.3	75.2	19.5	NA		NA		0	0	0	ND
Quinn River Valley (OM-10)																
Bt$_b$	0	47	10YR 6/4	2.5Y 5/4	VGSL	58.6	26.8	17.4	2FSBK	sh, h	fi	s, p	es, patchy	ND	0	cw
Btk1$_b$	47	100	10YR 5/6	10YR 5/8	VGCL	33.6	30.2	36.2	3VF, FSBK	h, vh	fi	s, p	es, tdc	ND	0	dw
Btk2$_b$	100	175+	10YR 6/4	10YR 4/6	VGSCL	54.7	19.9	25.4	2FSBK to 2FPL	sh, h	fr to fi	s, p	es, dtc	ND	0	ND
Jessup paleosol																
Bt1$_b$	0	15	2.5Y 6/3	2.5Y 5/3	L	41.5	35.9	22.6	3MSBK, 3FPL	h, vh	ND	s, p	e, patchy	0	0	aw
Bt2$_b$	15	60	10YR 6/4	10YR 5/4	GCL	42.6	22.0	35.4	2MPR, 3MSBK	sh, vh	ND	s, p	es, patchy	0	0	gw
Ck$_b$	60	250+	NA		GSL	77.4	7.8	14.8	NA		NA		es, patchy	0	0	ND
Grimes Canyon																
Btl$_b$	0	57	10YR 5/3	10YR 5/4	EGSCL	62.6	10.3	27.1	2FSBK	sh, h	ND	s, p	0, e, patchy	0	0	cs
Bt2$_b$	57	155	10YR 6/3	10YR 5/3	EGC	10.6	14.7	74.7	3F, MSBK	vh, eh	ND	s, p	e, es, patchy	0	0	cs
Bt3$_b$	155	192	10YR 5/3	10YR 4/3	EGC	21.8	23.8	53.4	3MSBK	eh	ND	s, p	es	0	0	cs
Bedrock	NA		NA		NA		NA		NA		NA		NA	NA	NA	mantle?

Thorne mid																
sand	0	3	2.5Y 6/2	10YR 4/4	LS	87.5	9.3	3.2	0	so	ND	so, po	e	0	ND	aw
Avk	3	9	10YR 7/3	10YR 5/4	SL	75.4	17.9	6.7	2MPL, 2MCR	sh	ND	ss, po	es	0	ND	aw
2Btjk	9	16	2.5Y 7/3	10YR 5/4	SL	58.2	29.2	12.6	1MCR	so	ND	ss, ps	es, ev	0	ND	cw
2Bkl	16	30	10YR 7/3	10YR 5/4	SL	70.0	21.6	8.4	0 to 1MCR	lo	ND	so, po	ev	0	ND	cw
2Bk2	30	45	10YR 7/3	10YR 6/4	SL	74.1	18.3	7.6	0	lo	ND	so, po	ev	0	ND	dw
3Bqk	45	64	10YR 6/4	10YR 5/4	SL	74.3	12.0	13.7	0 to 1MCR	lo, sh	ND	so, po	ev	0	ND	dw
3Cqk	64	100+	10YR 6/3	10YR 5/3	SL	74.6	10.1	15.3	0	lo	ND	so, po	e, es	0	ND	ND
Thorne upper																
sand	0	3	2.5Y 7/3	10YR 5/4	S	91.4	7.0	1.6	0	lo	ND	so, po	0	0	0	aw
Av	3	8	2.5Y 8/3	10YR 6/3	SL	61.0	33.3	5.7	2FPL, 3FCR	so	ND	so, po	e	3vf, fv	1f, m	cw
Bt	8	16	10YR 8/3	10YR 6/4	L	51.2	35.2	13.6	1FPL, 2MSBK	sh	ND	s, ps	es	3vf	2f, 3vf	cw
2Btjk	16	31	10YR 7/3	10YR 6/4	VGSL	67.9	23.7	8.4	1, 2F, MSBK	so	ND	s, ps	es	0	3vf, 1, f	cw
2Bky	31	55	10YR 7/3	10YR 6/4	EGSL	58.1	28.4	13.5	1FSBK	so	ND	s, po	e	0	3vf, 1f	as
3Bkq	55	95	10YR 6/3	10YR 6/4	EGSL	68.1	18.2	13.7	0	lo	ND	so, po	e	0	1f	as
4Ckq	95	110+	2.5Y 8/2	2.5Y 7/3	EGSL	76.1	17.6	6.3	0	lo	ND	so, po	e	0	0	ND

[a] Descriptions and abbreviations follow criteria in Soil Survey Division Staff (1993), except: Av = vesicular A horizon.

[b] From Munsell Color (1990); NA, not applicable; ND, not determined.

[c] G, gravelly or gravel; VG, very gravelly; EG, extremely gravelly; C, cobbly or cobbles; F, flaggy or flagstones; S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; SiL, silt loam; L, loam.

[d] 0, single grained; 1, weak; 2, moderate; 3, strong; VF, very fine (very thin); F, fine (thin); M, medium; C, coarse (thick); VC, very coarse (very thick); GR, granular; CR, crumb; Pl, platy; PR, prismatic; CPR, columnar; ABK, angular blocky; SBK, subangular blocky; NA, not applicable.

[e] **Dry:** lo, loose; so, soft; sh, slightly hard; h, hard. **Moist:** lo, loose; vfr, very friable; fr, friable; fi, firm. **Wet:** so, non-sticky; ss, slightly sticky; s, sticky; po, non-plastic; ps, slightly plastic; p, plastic; NA, not applicable; ND, not determined.

[f] **Matrix:** e, slightly effervescent; es, strongly effervescent; ev, violently effervescent. **Clasts:** tdc, thin discontinuous carbonate coatings.

[g] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ir, irregular; v, vesicular; NA, not applicable; ND, not determined.

[h] vf, very fine; f, fine; m, medium; 1, few; 2, common; 3, many; ND, not determined.

[i] a, abrupt; c, clear; g, gradual; d, diffuse; s, smooth; w, wavy; i, irregular; ND, not determined.

and in the field (Fig. 10). Above these levels, the complex has no preserved morphology but well-bedded tufa-cemented beach gravels are exposed in ephemeral washes and well-rounded beach gravels occur as surface lags up to an elevation of about 1402 m (Reheis, 1996). The highest landform is a very degraded cuspate barrier which is located at an elevation of about 1360 m (Reheis, 1996). There are many shallow gullies developed on its flanks and in places gullies on opposite sides of the barrier almost meet at the relatively horizontal crest, effectively removing original surface morphology (Fig. 10). The next lower landform is present at an elevation of about 1350 m and is also an eroded cuspate barrier. Only the massive southern half of the barrier is relatively intact. The northern arm of the v-shaped

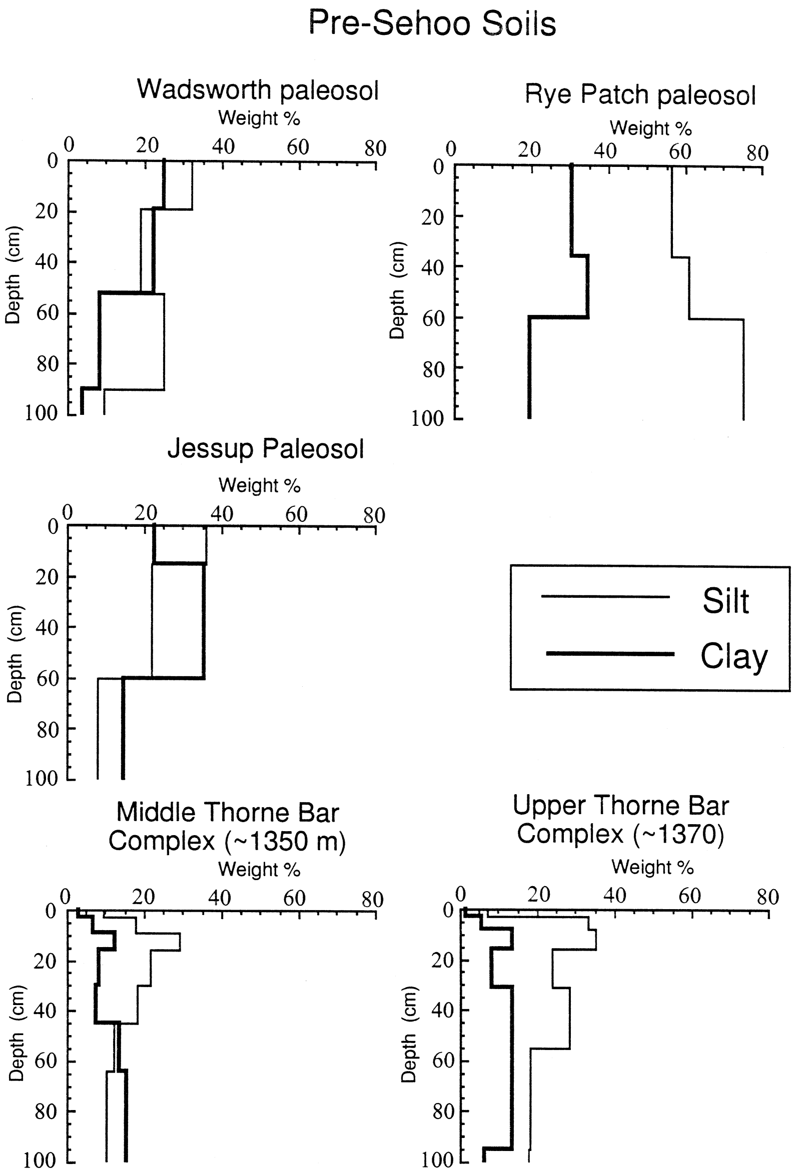

Fig. 9. Clay and silt accumulation plots for pre-Sehoo soils in the Lahontan basin.

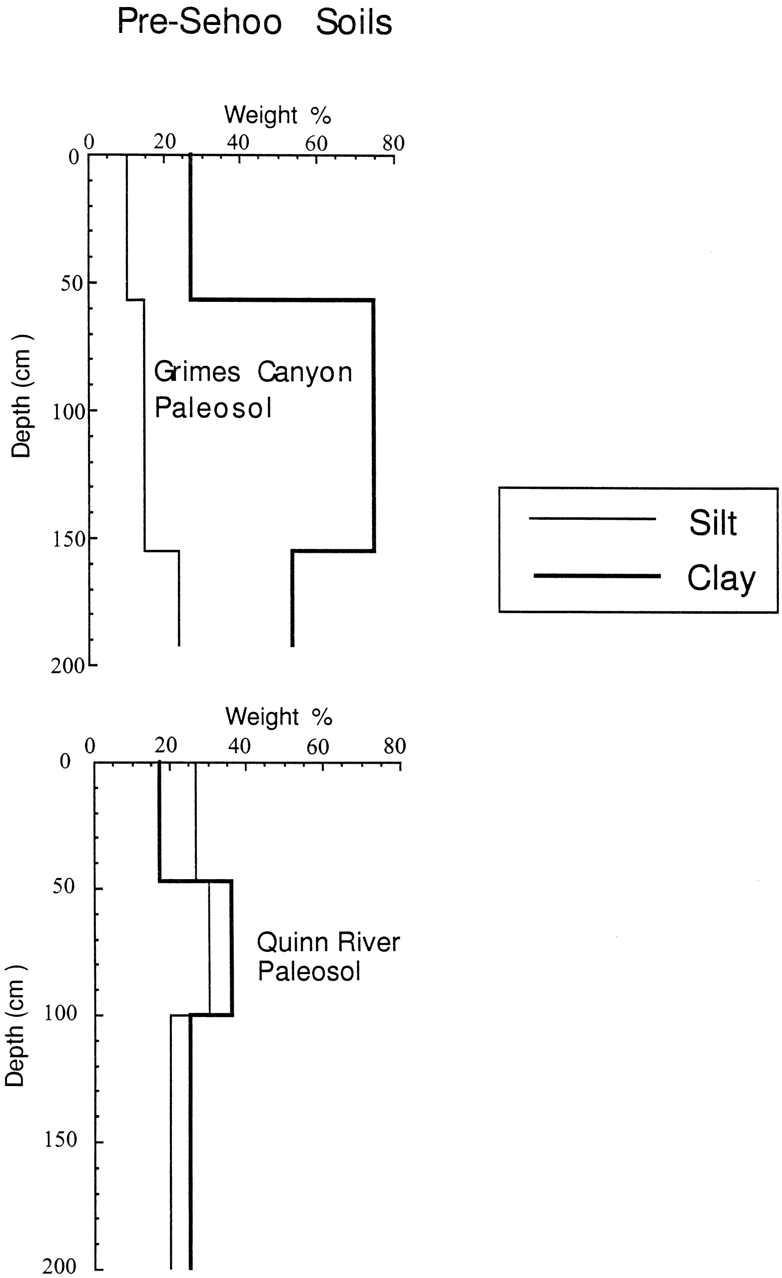

Fig. 9 (*continued*).

barrier appears to have been largely eroded with only a small remnant remaining. Although the crest of the 1350 m barrier is relatively horizontal, its flanks also display shallow gullies that extend almost to the relatively horizontal, wide crest.

Soils developed on the 1350 m and 1360 m barriers are moderately developed in terms of the number of horizons and clay accumulation (Table 4 and Fig. 9). Carbonate accumulation in both profiles is characterized as stage II. However, they have

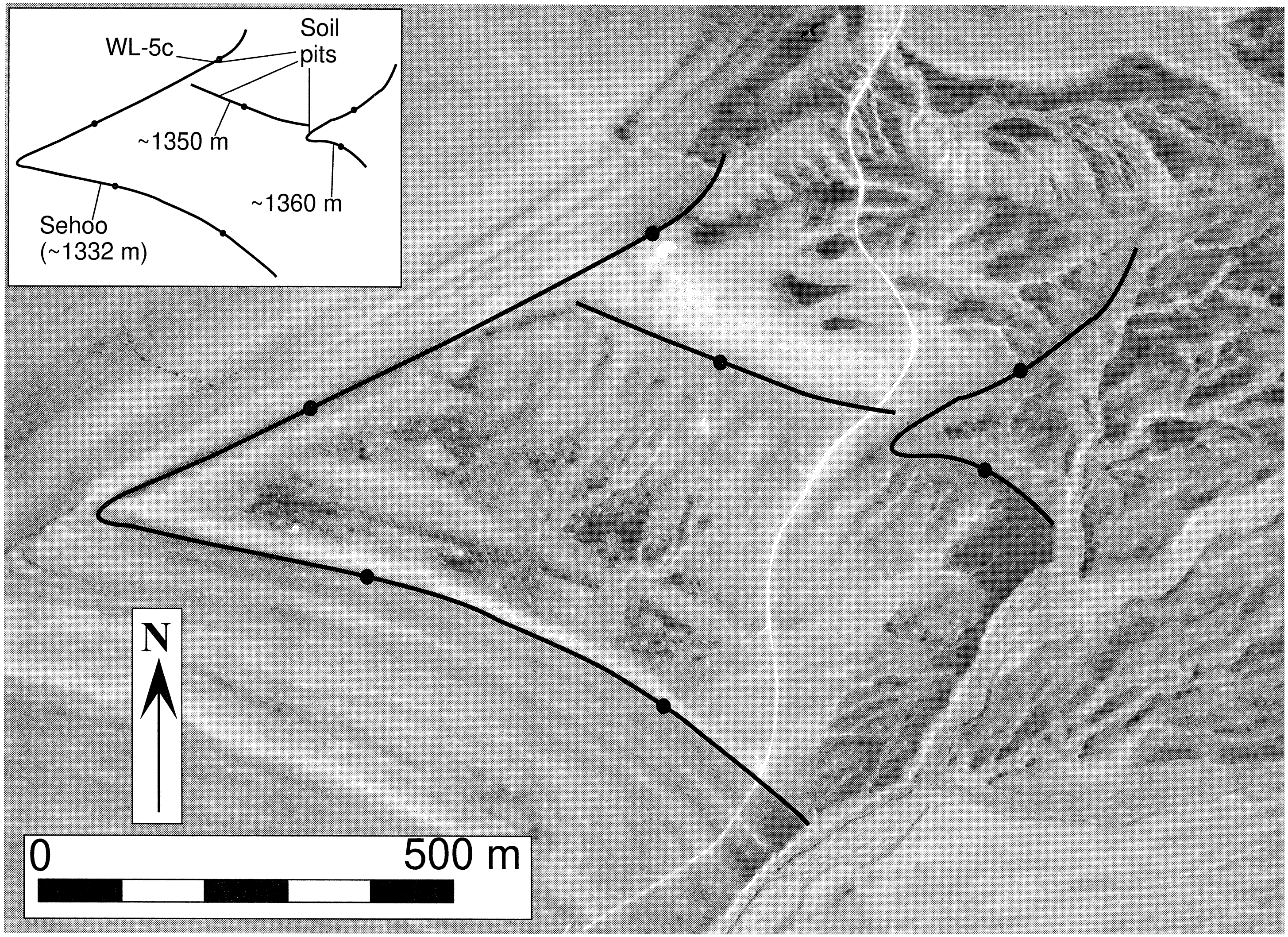

Fig. 10. Air photo of the Thorne Bar complex on the southeastern side of Walker Lake. Note that the Sehoo shoreline is smooth, nearly continuous and little dissected, whereas the older and higher barriers are degraded and display a dendritic drainage network developed on them. Thick lines with filled circles indicate barrier crests.

weak to moderate structural grades and loose to slightly hard consistencies which are more typical of Sehoo soils than the buried paleosols (Tables 1–4). Overall, the soils are not drastically different than the well-developed Sehoo profiles we have described, but the clearly degraded nature of the two upper barriers suggests significant erosion. Thus, the soils developed on them may not accurately reflect the relative age of the landforms. For example, early Pleistocene (> 700 ka) surfaces and soils at Cima volcanic field in the Mojave Desert have undergone similar degradation (Wells et al., 1985) which might imply that some landforms in arid environments acquire maximum soil development in the first several hundred thousand years, but subsequently experience degradation and stripping as decreasing infiltration capacity causes increased runoff and erosion.

3. Regional shoreline correlation

3.1. General characteristics of known Sehoo barrier ridges

The surficial characteristics, preservation of morphology, and soil development observed on dated beach ridges in the Jessup embayment and at the Lahontan Mountains and Hooten Wells sites provides a basis for comparison with beach features observed around the perimeter of Lake Lahontan. Although the Sehoo beach ridges at these three locations display a certain amount of variability in terms of surficial characteristics and soil development, they are very similar to one another. Preservation of original constructional morphology is generally excellent and subsequent modification is commonly limited to localized dissection by ephemeral washes. Soils developed on the Sehoo barriers are characterized by Av horizons with textures ranging from sandy loams to loams to silt loams and an occasional clay loam texture (Tables 1–3). Textures in the underlying Bw or Bt horizons commonly range from gravelly to extremely gravelly sandy loam to loam. However, the 2Btk horizon of lower barrier 4, profile 1 (Table 1) has a very gravelly sandy clay loam texture due to its low silt content and the 2Bk1 horizon of the progradational barrier complex (Table 2) textures as a very gravelly silt loam due to its high silt content. Structural grades in the B horizons most commonly range from single grain to weak with occasional moderate grades (Tables 1–3). Dry consistencies range from loose to slightly hard. All of the dated Sehoo soils are characterized as carbonate stage 1 (Gile et al., 1966; Machette, 1985).

Soil development observed on the Sehoo barriers is not unlike that reported by Nettleton et al. (1975) for post-Sehoo surfaces near Fernley, Nevada and for post-Mazama basin fill deposits in Dixie Valley, located immediately to the east of the Lahontan basin (Alexander and Nettleton, 1977). The degree of soil development on the barriers is also similar to the degree of development reported for latest Pleistocene and early Holocene beach ridges (Reheis et al., 1989; McFadden et al., 1992) and associated piedmont deposits (Wells et al., 1987) in the Mojave Desert.

The surface and soil characteristics at Jessup, the Lahontan Mountains, and Hooten Wells are inferred to broadly represent the range of properties present in Sehoo-age beach barriers. This variability dictates that there is not a single 'type geosol', nor are the surficial characteristics and preservation identical on every Sehoo barrier. Instead, there is a range in characteristics and soil development that should be taken into account when making age correlations between similar features across the Lahontan basin.

3.2. Comparison of known sehoo beach ridges to others around the basin

The amount of clay accumulated in a profile as a function of depth is often used to compare soil development between different soil profiles (e.g., Birkeland, 1984). Fig. 11A shows the amount of clay accumulation as a function of depth for all of the known Sehoo profiles. There is a certain amount of variability in the amount and depth distribution of the clay, but most profiles plot in the same general area. In Fig. 11B, the clay profiles of the eleven undated highstand sites are plotted together with the Sehoo profiles. Note that the two groups of profiles are virtually indistinguishable. Therefore, we suggest that the other eleven profiles probably also date from

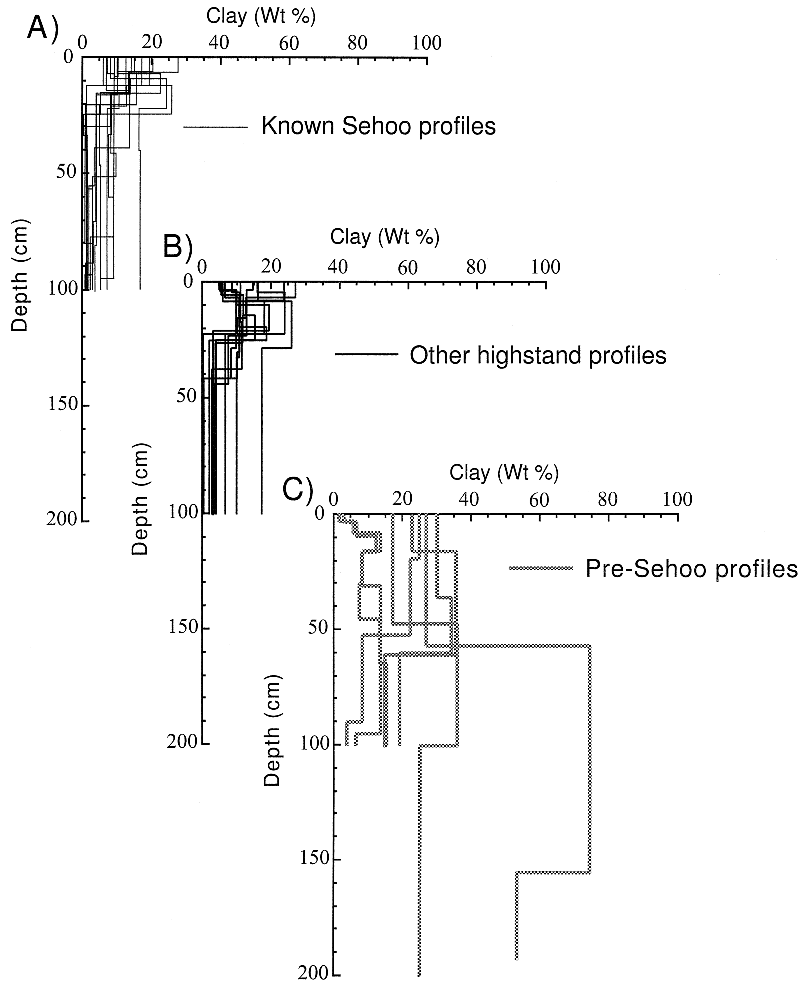

Fig. 11. (A) Clay accumulation plots for the Sehoo barriers at Jessup, the Lahontan Mountains, and Hooten Wells. (B) Clay accumulation plots for other highstand soil profiles from around the basin. (C) Clay accumulation plots for pre-Sehoo soil profiles.

the Sehoo highstand. By comparison, all of the pre-Sehoo profiles, except for the two from the Thorne Bar, plot well outside the variability expressed by the Sehoo profiles (Fig. 11C). The depth distributions of clay for the pre-Sehoo profiles express much more variability than do the other profiles, both in terms of depth and in the amount of clay accumulated (Fig. 11C). This variability may indicate that the pre-Sehoo profiles were developed on deposits of multiple ages, and hence, possess profiles of different ages.

To help quantify and further compare soil development characteristics between known Sehoo barrier ridges and the other undated sites around the basin, we use the clay accumulation index (CAI) of Levine and Ciolkosz (1983). This index compares the amount of clay accumulated in all B horizons with the amount originally present in the C horizon or parent material according to the equation:

$$\Sigma[(Bc - Cc) \times T] = CAI$$

where: Bc = B horizon clay content (wt.%), Cc = C horizon clay content (wt.%), T = Thickness of each B horizon. If there is more clay in a C horizon than in an overlying B horizon, the CAI value for that B horizon is reported as one. Fig. 12 shows a log plot

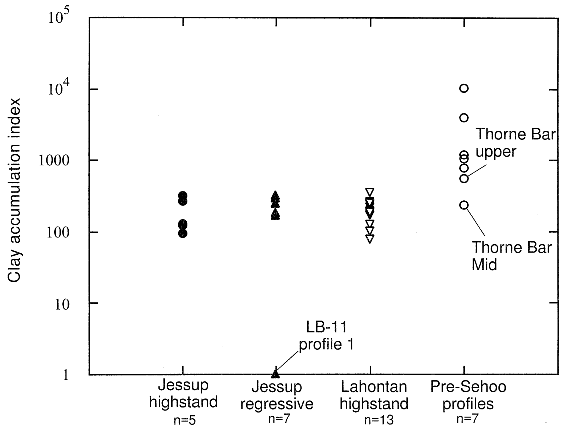

Fig. 12. Clay accumulation index (Levine and Ciolkosz, 1983) values for all soils described in this study.

of CAI values for all soil profiles in this study. Most values for the Sehoo–age Jessup highstand and regressive profiles and the other highstand soils range from about 100 to 350. The low value for lower barrier 11 profile 1 resulted from slightly more clay (1.2% vs. 0.6%) present in the 2Ck horizon than the overlying 2Bk horizon. In contrast, CAI values for the buried paleosols range from about 750 to 10,200 (Fig. 12). The two older than Sehoo surface soils from the Thorne Bar complex have intermediate values of about 230 and 560 (Fig. 12), but may be truncated and not represent the true ages of these surfaces.

When combining the previously described surface and soil characteristics (Tables 1–3) (Fig. 11) and the CAI values (Fig. 12), we observe that the characteristics of the eleven undated highstand barrier features located throughout the basin are virtually indistinguishable from the dated Sehoo barriers at Jessup, the Lahontan Mountains, and Hooten Wells. Nine additional field descriptions of highstand soils at similar sites around the basin, reported in Adams and Wesnousky (1996), are also nearly identical to the dated Sehoo soils. Based on similarity of soil development, the preservation of constructional morphology, and similarity of surficial characteristics, the relatively continuous highstand shoreline throughout the Lahontan basin is most readily interpreted to represent the most recent highstand and not one or more earlier lake cycles.

4. Soil forming processes on beach barrier ridges

All of the surface soils in this study are greatly influenced by eolian additions of fine sand, silt, and clay. Eolian additions to the surfaces of beach barriers are evidenced by the nearly ubiquitous Av horizons and the less common loess caps that blanket some of the barriers to a depth of up to 40 cm. Incorporation of eolian material into the soil profiles is supported by the presence of fine sand, silt, and clay at depth and the lack of evidence for weathering of beach gravels. Eolian addition of fines to soil profiles is increasingly recognized as a major soil forming process for late Pleistocene soils in the western US and in other arid regions elsewhere ((Yaalon and Ganor, 1973; McFadden et al., 1986, 1992, 1998; McFadden and Weldon, 1987; Reheis et al., 1995). Our studies of soil development on Sehoo barriers indicate that eolian additions and the processes by which colian material is introduced into the profiles control soil development on these features.

Plants and the typically coarse gravel of Lahontan barriers initially act as surface roughness elements which trap dust that is blown onto the surface. Commonly, the bases of plants are surrounded by ‘silt collars’ which are several centimeters thick and extend 10 to 20 cm outward from the bases of the desert shrubs. The mean residence time for dust on a surface is probably controlled by the effective roughness and the rate at which dust is supplied. Through time, with the introduction of more dust and the development of Av horizons armored by desert pavements, surfaces are effectively smoothed and the trapping efficiency most likely reduced (Wells et al., 1985; Gerson and Amit, 1987).

When the rate of dust influx exceeds some threshold value, it begins to accumulate in sheets on barrier surfaces. Loess caps are usually discontinuous and many have a scalloped or eroded appearance. A well-developed stone pavement overlying a typical Sehoo (Av/Bw/Bk) profile projects uninterruptedly beneath a 40 cm thick loess cap on a high barrier on the east side of the Black Rock Desert (Fig. 1). We interpret the loess to be a Holocene deposit because it accumulated and was partially eroded after the Sehoo profile was fully-developed. Even though loess caps are most common on the east or downwind sides of large playas such as the Carson Sink and Black Rock Deserts, we did not observe that soil development systematically varied according to the extent of upwind playa as did Chadwick and Davis (1990).

Once the dust is deposited onto the surface of the barriers, it is introduced into the profiles by a number of processes including water percolation, gravity, and bioturbation by plants and animals. Silt and clay, and probably to a lesser extent fine sand, can be moved into the profile directly by infiltrating water after rainstorms or during snow melt. Wright and Foss (1968) demonstrated that silt will move readily through medium sand columns with relatively small quantities of water. Given that the parent material for virtually all of the profiles examined consists of coarse sand to gravel to cobbles and sometimes boulders, the silt and clay at depth in the profiles (Tables 1–3) most likely was moved by percolating water.

Silt and clay in many cases has moved below the depth of bioturbation into the zone where the original bedding of the beach gravels is evident. Original bedding is apparent within 10 to 20 cm of the surface of the Jessup playette barrier for most profiles, yet silt and clay accumulation plots show that in particular, silt has been translocated to much greater depths in most cases (Fig. 5). We attribute most of the deep translocation to water percolation.

Silt caps consisting of loose fine sediment in conical piles atop large gravel and cobble clasts also demonstrate that in some cases the fine earth material is merely falling through the interstices between clasts and accumulating on top of other clasts. The silt caps probably form when the soil is in a relatively dry state because it appears that they accumulate grain by grain due to their conical shape.

Bioturbation also plays an important role in mixing dust into beach barriers. Rodent holes and ‘badger piles’ are common on the surfaces of barriers and have the effect of mixing dust on the surface with the beach gravel at depth. Burrowing also appears to be the major process which destroys original bedding in the beach gravels. Fig. 4 is a cross section through the Jessup playette barrier which shows the effects of burrowing on a beach barrier. The gravel and coarse sand is thoroughly mixed with dust in the upper part of the profiles. The shallow depth of bioturbation near profile 1 (Fig. 4) was probably limited by the well-sorted but coarse (< 25 cm) clasts in this part of the barrier. In contrast, mixing to a depth of greater than one meter is particularly evident near profile 3 where abundant krotovinas are present and original bedding is lacking (Fig. 4). Plants also play a direct as well as an indirect role in mixing surface dust because dust preferentially accumulates around the bases of bushes and rodents preferentially burrow near the bases of bushes.

Soil development in the older soils probably began much as it did with the younger Sehoo profiles, namely by the introduction of eolian sediment into the coarse clastic deposits. Through time, a proportion of the fine sediment probably weathered to clay minerals. This process is evidenced in several of the paleosol profiles where clay appears to increase at the expense of silt (Fig. 9). The transition from a permeable soil environment favoring the accumulation of eolian dust to a less permeable environment favoring chemical weathering and the formation of clay may constitute an intrinsic pedologic threshold (McFadden and Weldon, 1987).

It is not surprising that the best-developed paleosols (Grimes Canyon and Quinn River Valley) are located immediately beneath Sehoo highstand deposits. These two profiles were exposed to soil forming processes for the longest periods of time, with the possible exceptions of the two pre-Sehoo profiles at the Thorne Bar. If the Grimes Canyon and Quinn River Valley profiles date from the last Eetza highstand ($\sim$130 ka), then they were exposed to soil forming processes for approximately 115,000 years. If they date from the middle Eetza highstand ($\sim$280 ka), then the soils are approximately 270,000 years old.

5. Conclusions

Based on surficial characteristics, morphologic preservation, and soil development, the highest preserved shoreline features around the perimeter of Lake Lahontan, except for the Walker Lake subbasin, were produced during the Sehoo highstand. Isolated outcrops and degraded lacustrine landforms are found in the Walker Lake subbasin at elevations up to 70 m above the late Pleistocene lake limit.

Although the soil parameters used in this study do not effectively differentiate the older landforms from the Sehoo beach barriers, their lack of lateral continuity, development of drainage networks, and generally degraded appearance in the field and on aerial photographs serve to separate them from the younger features in the subbasin. Similar old lacustrine landforms were not observed in the other subbasins of Lake Lahontan. Thus, the nearly continuous highstand shoreline in the Lahontan basin is an isochronous surface which formed at about 13 ka.

The occurrence of an isochronous surface throughout the Lahontan basin allows the examination of variability in soil forming processes over a broad area. Soil development is largely the result of the introduction of eolian fines into the generally clast-supported coarse beach gravel of the barriers. Spatial variability observed in multiple Sehoo profiles on single barriers and in the same vicinity is generally small, can not be readily attributed to prevailing wind directions, and most likely reflects local variations in the effectiveness of water percolation, gravity, and bioturbation in moving the fines into the profiles. Spatial variability noted on Sehoo profiles throughout the basin is of the same magnitude as that observed in a localized area. In striking contrast to the Sehoo soils, buried paleosols in the basin show a much higher degree of development and greater spatial variability. Although the older soils may be developed on deposits representing different lake cycles and, hence, not be the same age, all of the older soils are characterized by thicker profiles, higher structural grades, harder consistencies, and more pedogenic clay. Based on this study, the elevation of the high shoreline of Lake Lahontan should serve as an accurate and passive displacement marker with which to measure vertical deformation in the basin over the last 13,000 years.

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Appendix A. Site Descriptions (All sites are in UTM Zone 11)

Coyote Hills site (D-28; 1326.0 m)

Location: Kings River Valley (N4607400, E400000) (Fig. 1)

Many well-developed and preserved constructional shorelines were built in and amongst the Coyote Hills by waves from the south. The site consists of a south-facing highstand pocket barrier (site D-28) built across a reentrant along the shore and encloses a back-barrier depression. The undissected barrier is about 150 m long and has a crestal width of about 5 m. Surface characteristics include a poorly-developed pavement made up of coarse (< 10 cm) beach gravel primarily of felsic and intermediate volcanic rocks covered by dense cheat grass and tumble mustard. Soil characteristics (D-28; Table 3 and Fig. 7) indicate a poorly developed soil.

Quinn River Valley site (OM-10; 1325.5 m)

Location: Quinn River Valley (N4583000, E432700) (Fig. 1)

This site consists of an artificially dissected small pocket barrier now exposed in cross section. Most of the surface of the barrier has been removed or modified, so observations mainly pertain to the deposit and associated soils. The subangular to subrounded beach gravels are very coarse with a few clasts ranging to 40 cm, but with a median gravel size of 5 to 10 cm. Clasts are composed of sedimentary and metasedimentary rocks. This site is important because the deposits of two lake cycles are displayed here. Younger beach gravels with a poorly developed surface soil (site OM-10; Table 3 and Fig. 7) overlie an extremely well-developed soil developed in slightly finer-grained beach gravels (Table 4 and Fig. 9). At this site, the Sehoo lake transgressed about 2 m higher than an older lake cycle.

The Government Springs site (HRC-1; 1332.7 m)

Location: Black Rock Desert (N4543500, E319100) (Fig. 1)

The site consists of an undissected looped barrier that encloses a small playette. The surface of the barrier is covered by a well-varnished, well developed pavement of angular to subrounded clasts of massive basalt, vesicular basalt, and andesite. Surface clasts range in size to about 15 cm with a median size of about 1 to 5 cm. At a depth below about 28 cm, the median clast size increases to about 10 to 15 cm. The soil developed on this surface is relatively thin and displays weak development (Table 3 and Fig. 7).

The Eugene Mountains site (EM-33; 1329.1 m)

Location: Eugene Mountains (N4528800, E408300) (Fig. 1)

An undissected pocket barrier about 500 m long and 15 to 20 m broad encloses a large ponded area of fine-grained sediments. The surface has a discontinuous (0 to 5 cm thick) silt and fine sand cap with a moderately developed cryptogamic crust. Most of the desert brush on the barrier is spatially associated with the silt cap. In places where the silt cap is not present, there is a well-developed interlocking pavement composed of subangular to subrounded platy stones ranging in size from 1 to 10 cm with a median size of 2 to 5 cm. Lithologies include sedimentary and metasedimentary rocks. The soil pit, slightly lakeward of the crest of the barrier in a place where the silt cap was absent, shows only weak soil development (Table 3 and Fig. 7).

Prince Royal gravel pit (EM-26N; 1328.9 m)

Location: Piedmont of the Humboldt Range near Imlay (N4499600, E400500) (Fig. 1)

Site EM-26N is a cuspate barrier complex whose highest northern and southern barrier ridges represent the Lahontan. Surface and soil descriptions refer to the northern ridge which was measured at an elevation of 1328.9 m. The surface of the barrier is a stony cryptogamic crust. About 20% of the surface is covered by well-rounded beach gravel to about 5 cm in diameter and is composed of sedimentary and metasedimentary rocks. The preserved form of the barrier exhibits little to no erosion. Vegetation consists of shadscale, saltbrush, rabbit brush, other shrubs, and cheat grass. At depth, the deposit alternates between clast-supported well-rounded beach gravel and coarse sandy matrix-supported beach gravel. Soils data for EM-26N are presented in Table 3 and Fig. 7. Only the upper 5 cm of the Avk horizon contains stones with the lower 12 cm being relatively stone-free. The undersides of clasts within the 2Ck horizon have thin to thick carbonate coatings with the larger clasts having sand and small pebbles cemented to them. Discontinuous carbonate coatings on clasts were observed to extend at least 3 m below the surface. However, coatings on clasts deep in the exposure were observed on all sides of the clasts, not just the undersides. Some of these coatings appear to have been mechanically abraded and not a product of solution-reprecipitation processes.

The Trego site (G-18; 1333.5 m)

Location: Southern Black Rock Desert (N4509900, E320700) (Fig. 1)

This description pertains to the highest north-facing ridge in a large cuspate barrier complex. The ridge was constructed of very well-sorted granitic gruss $<$ 2 mm in diameter by waves traveling south across the Black Rock. There is no pavement or varnish and vegetation consists of low desert shrubs with low grasses growing around the bases of the bushes. The surface of the ridge is broken into weak coarse polygons, but columnar structure in the soil pit was difficult to discern. Soil data for site G-18 is presented in Table 1 and Fig. 7. Soil development is characterized as weak, even though there is a thin zone of clay accumulation from 19 to 25 cm depth (2Btk horizon), as indicated by an increase in clay content (Fig. 7), an increase to a moderate structural grade (Table 3), and the presence of a few thin clay films on the coarse sand grains.

Winnemucca Dry Lake site (KP-16; 1338.1 m)

Location: North end of Winnemucca Dry Lake (N4471200, E301400) (Fig. 1)

This site consists of an arcuate, broad-crested barrier more than 1 km in length that is dissected near its west end by a large drainage, but otherwise little modified. Vegetation consists mostly of widely-spaced sagebrush and greasewood. The surface of the high barrier is covered by a loose crust about 2 cm thick and separated by polygonal cracks. Polygons measure about 10 to 15 cm across. Parent material consists of well-sorted coarse sand to fine pebble gravel (~ 1 to 7 mm). There is no varnish present. Davis (1987) interpreted the barrier to be Eetza in age and cited a cambic soil horizon as evidence of its antiquity. Our examination of the soil developed on this surface indicates that it is poorly developed and more typical of a Sehoo age profile (Table 3 and Fig. 7). The excellent preservation and surficial characteristics of this site also suggest it dates from Sehoo time.

Grimes Canyon site (CS-11b; 1335.2 m)

Location: Northeastern Carson Sink (N4414600, E396900) (Fig. 1)

The Grimes Canyon progradational barrier complex is a spectacular example of a large and well-developed shoreline complex at the highstand level (Adams and Fontaine, 1996). Three distinct barrier ridges each about 500 m long but at about the same elevation were built across the mouth of a small reentrant along the shore by littoral drift from the southwest. The drainage occupying Grimes Canyon has dissected the complex to a depth of about 20 m. Several other small ephemeral gullies have also dissected the complex. Portions of the surface are covered by a discontinuous silt and fine sand mantle that has a well-developed cryptogamic crust. The < 20 cm thick eolian mantle tends to be localized in the swales between the barrier crests and closely associated with greasewood and shadscale desert shrubs. Where it is not covered by silt, the surface has a tight, well-developed pavement consisting of angular to well-rounded clasts. The angular clasts, however, tend to be derived from fractured rounded clasts or have undergone much post-depositional solution pitting. Surface clasts have a maximum size of 20 cm, a median size of about 2 to 10 cm, and are composed of metasedimentary rocks, volcanics, and rare granitics. Carbonate clasts are distinctive because of the high degree of solution weathering on their upturned surfaces. Varnish development ranges from absent to moderate depending on lithologies with dense, fine-grained metasedimentary rocks having the best developed varnish.

A natural exposure on the backside of the complex reveals a coarse clast-supported well-rounded beach deposit cemented by carbonate. Thin discontinuous carbonate coatings on clasts extend to greater than 5 m depth. They do not appear pedogenic because of the random orientation of the carbonate rinds. The soil developed on the upper surface of the complex is considered weak (Table 3 and Fig. 7). Based on soil development and preservation, the upper surface of the Grimes Canyon progradational barrier complex most likely dates from the Sehoo lake cycle. However, the interior of the complex displays an extremely well-developed paleosol in beach gravels about 7 to 9 m below the crest of the complex (Table 4 and Fig. 9).

Northern Desert Mountains site (F-9; 1334.0 m)

Location: North Flank of the Desert Mountains (N4345600, E343500) (Fig. 1)

Site F-9 is a very well-developed relatively sharp-crested pocket barrier about 500 m long built across a reentrant along the shore. It is dissected in two places by ephemeral washes separating the barrier into three sections. The barrier is composed almost exclusively of subangular to subrounded rhyolitic gravel and cobbles whereas the locally sourced fan material encroaching on the backside of the barrier is composed of intermediate to basic volcanics. The rhyolitic beach material was probably moved into the embayment by littoral drift from the east. Clasts near the base of the barrier exposed in the bottom of the gully are cobble to boulder size but fine upward to the crest where clasts average 2 to 5 cm. All of the barrier is clast supported but, in places, has a matrix of coarse pebbly sand.

The surface of the barrier has a moderately developed pavement with little to no varnish development. Soil developed on the crest of the barrier is characterized as relatively weak because of absent to weak soil structure, loose to soft consistency, and the relative thinness of the profile (Table 3 and Fig. 7). The clast-supported beach material has little matrix below about 32 cm except for a thin (4 cm) sandy layer at 40 cm depth, but a significant proportion of the fine earth fraction present consists of silt (Fig. 7). Thin discontinuous carbonate coatings are present on the undersides of clasts to a depth greater than 100 cm. Based on the preservation, surficial characteristics, and soil development we conclude that this barrier dates from the Sehoo highstand which is in direct contrast to the studies of Morrison (1964) who concluded that the high shoreline in this area dates from the Eetza highstand.

Walker River Narrows site (F-29; 1332.0 m)

Location: East side of Reservation Hill (N4320800, E337900) (Fig. 1)

A well-developed spit complex (~ 700 m long), built from south to north, is perfectly preserved except for a large gully about 25 m deep which dissects the uppermost spit near its proximal end. Site F-29 is located immediately north of the gully on the broad (~ 10 m) crest of the uppermost spit. Vegetation consists of shadscale, other desert shrubs, and bunch grasses. The surface is covered by a moderate to well-developed pavement consisting of subangular to rounded clasts with a median size of 1 to 5 cm. Varnish is absent to weak. Lithologies include ash flow tuffs, intermediate volcanics, metasediments, and felsic intrusives. The interior of the spit consists of finely-bedded (2–10 cm) fine to coarse sand and gravel (20–35%) with occasional clasts to 10 cm.

Soil developed on the crest of the spit is quite thin and has an abrupt lower boundary with unaltered parent material (Fig. 7). However, this soil is unusual because of its clear evidence for clay translocation, but relative lack of silt in the Bt horizon (Table 3). The Av horizon is fairly typical for Sehoo profiles, but most B horizons in Sehoo soils have a much higher ratio of silt to clay. The Bt horizon has few thin clay films which form bridges between sand grains and give the horizon a redder hue than is typical. The clay occurs in discrete horizontal bands 1 to 3 cm thick which are generally associated with well-sorted sand layers. The quantity of clay and thickness of the Bt horizon meet the requirements for an argillic horizon (Soil Survey Staff, 1994) and are very similar to profile 2 from lower barrier 11 (Fig. 6) in the Jessup embayment which also possesses an argillic horizon. Because the soil characteristics fall within the range of those observed for dated Sehoo profiles and the morphology of the spit is still well-preserved, we interpret the surface and its soil to date from the Sehoo highstand, in contrast to Morrison and Davis (1984) conclusion that this was a Churchill profile developed on Eetza deposits.

Thorne Bar Complex (WL-5c; ~ 1332.0 m)

Location: Southeast side of Walker Lake (N4281300 E357100) (Fig. 1)

The geomorphology of the Thorne Bar complex, located in the southeastern Walker Lake Basin (Fig. 1), is described in the section on pre-Sehoo paleosols. The uppermost barrier ridge in the continuous sequence of shorelines lies at an elevation of about 1332 m (Fig. 10). This shoreline level can be traced continuously around the complex and encloses a small playette on its northern side. The barrier enclosing the playette is designated WL-5c. The sandy surface of the barrier has a well-developed but loose pavement consisting of a mixture of sedimentary and volcanic rocks. Vegetation includes greasewood and shadscale shrubs. Sediment exposed in the soil pit consists of interstratified beach gravel and coarse sand below 20 cm depth. Gravel clasts have a maximum size of about 7 cm with a median size of 1 to 4 cm.

Soil developed on this surface is thin and has an abrupt lower boundary (Table 3 and Fig. 7). The Btjk horizon has evidence of clay translocation in the form of common thin clay bridges between sand grains and few thin coatings on clasts. The amount of clay is probably responsible for the moderate structural grade and slightly hard and sticky consistency in the B horizon (Table 3). Based on the similarity in preservation of the barrier and soil development to that observed on dated Sehoo features, we interpret it to date from the Sehoo highstand. The higher and less well-preserved lacustrine landforms above this level are interpreted to date from an older lake cycle(s).

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