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Lake levels and sedimentary environments during deposition of the Trego Hot Springs and Wono tephras in the Lake Lahontan basin, Nevada, USA

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ABSTRACT

The Wono and Trego Hot Springs (THS) tephras are widespread in the Lahontan basin and have been identified in a variety of sedimentary environments at different elevations. Davis (1983) reported lake level to be at about 1256 m when the THS tephra was deposited, an interpretation questioned by Benson et al. (1997) who interpreted lake level to be ≤1177 m at that time. This is a significant difference in lake size with important implications for interpreting the climate that prevailed at that time. Based on new interpretations of depositional settings of the THS bed at multiple sites, the larger lake size is correct. Additional sites containing the Wono tephra indicate that it was deposited when lake level was at about 1217 m in the western subbasins and at about 1205 m in the Carson Sink. Sedimentary features associated with progressively deeper paleowater depths follow a predictable pattern that is modulated by proximity to sediment sources and local slope. Fine to coarse sands with wave-formed features are commonly associated with relatively shallow water. Silty clay or clay dominates in paleowater depths >25 m, with thin laminae of sand and ostracods at sites located adjacent to or downslope from steep mountain fronts.

Introduction

During its late Pleistocene highstand, Lake Lahontan was the second largest pluvial lake in the Great Basin of the western United States. At around 13,000 ^{14}C yr BP, Lake Lahontan had a surface area of about 23,000 km^2 and a volume of about 2100 km^3 (Benson and Mifflin, 1986). For most of the period from 30 to 10 ka, however, Lahontan was at lower levels and separated into several distinct lakes that fluctuated somewhat independently. Therefore, there is not a single lake-level curve for the Lahontan basin but a family of curves that occasionally coalesced when lake levels were high (Davis, 1982). A major research goal in the Lahontan basin has been to better define this family of curves to help delineate the effects of climate fluctuations and to more accurately specify the varying load imposed by Lake Lahontan for isostatic rebound modeling (e.g., Bills et al., 2007).

Documenting lake-level curves for Lahontan has involved dating of tufa and shells associated with various shoreline levels (Broecker and Orr, 1958; Broecker and Kaufman, 1965; Benson, 1978, 1981, 1991, 1993; Benson and Thompson, 1987; Benson et al., 1995), dating of organic material associated with different lake levels (Born, 1972; Thompson et al., 1986; Adams and Wesnousky, 1998; Adams, 2003, 2007; Briggs et al., 2005), and using the elevations and distributions of tephra beds to infer former shoreline levels (Davis, 1983; Benson et al., 1997).

In the 1970s and 1980s, Jonathon Davis constructed a tephrochronologic framework for the Lahontan basin and adjacent regions by documenting the characteristics, ages, occurrences, and environmental settings of multiple tephra beds spanning the late Quaternary (Davis, 1978; 1982; 1983; 1985; 1987a). This detailed work has substantially contributed to a broader tephrochronologic framework that covers much of the western United States (Sarna-Wojcicki et al., 1983, 1991, 2005; Sarna-Wojcicki and Davis, 1991; Reheis et al., 2002). Ideally, each tephra bed represents an instant in time so that widespread and disparate outcrops can be perfectly correlated across a variety of depositional environments. This framework has proved invaluable to subsequent researchers working to reconstruct the history of paleoenvironmental fluctuations and other aspects of landscape dynamics in this region (e.g., Negrini et al., 1984, 1987, 1988; Negrini and Davis, 1992; Bell and dePolo, 1999; Reheis et al., 2002, 2003; Bell and House, 2007).

The main purpose of this paper is to use the numerous outcrops of the Trego Hot Springs (THS) and Wono tephras found in the Lahontan basin to examine the relationships between sedimentary features and paleowater depth. Key to this task is Davis' (1983) interpretation that lake level in the western subbasins of Lahontan was between 1256 and 1260 m when the THS tephra was deposited. Other outcrops of the THS at lower elevations allow estimates of paleowater depth to be associated with various sedimentary features. Similarly, the identification of lake level at the time that the Wono tephra was deposited allows a second stratigraphic marker to be used in a similar fashion.

Previous work

Tephra beds have long been noted in the deposits of Lake Lahontan (Russell, 1885; Morrison, 1964), and as petrographic, geochemical,

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and geochronologic techniques have advanced, so too has the utility of tephras grown for tying together isolated outcrops. Davis (1978) published a comprehensive monograph on the Quaternary tephrochronology of the Lahontan basin that describes the physical and chemical characteristics, distributions, depositional settings, and ages of 20 distinct tephra beds that span the age range from greater than 750,000 yr to a few hundred years old. Most of these beds were newly documented from outcrops within the Lahontan basin except the Mazama and Bishop tephras that had been previously documented elsewhere.

Davis (1983) defined lake level in the western subbasins of Lahontan to be rising through an elevation between 1256 and 1260 m during deposition of the THS bed based on two exposures of the tephra along Squaw Creek at the north end of the Smoke Creek Desert (Fig. 1). At the northern (upstream) amphitheater, the tephra is contained within poorly stratified, extensively burrowed, sandy fluvial deposits at an elevation of about 1260 m (Davis, 1983). This relatively thin (1.5 m) fluvial unit overlies a well-developed paleosol (Churchill geosol of Morrison, 1964, 1991) and in turn is capped by a thick (10–12 m) package of well-bedded sand and silt that Davis

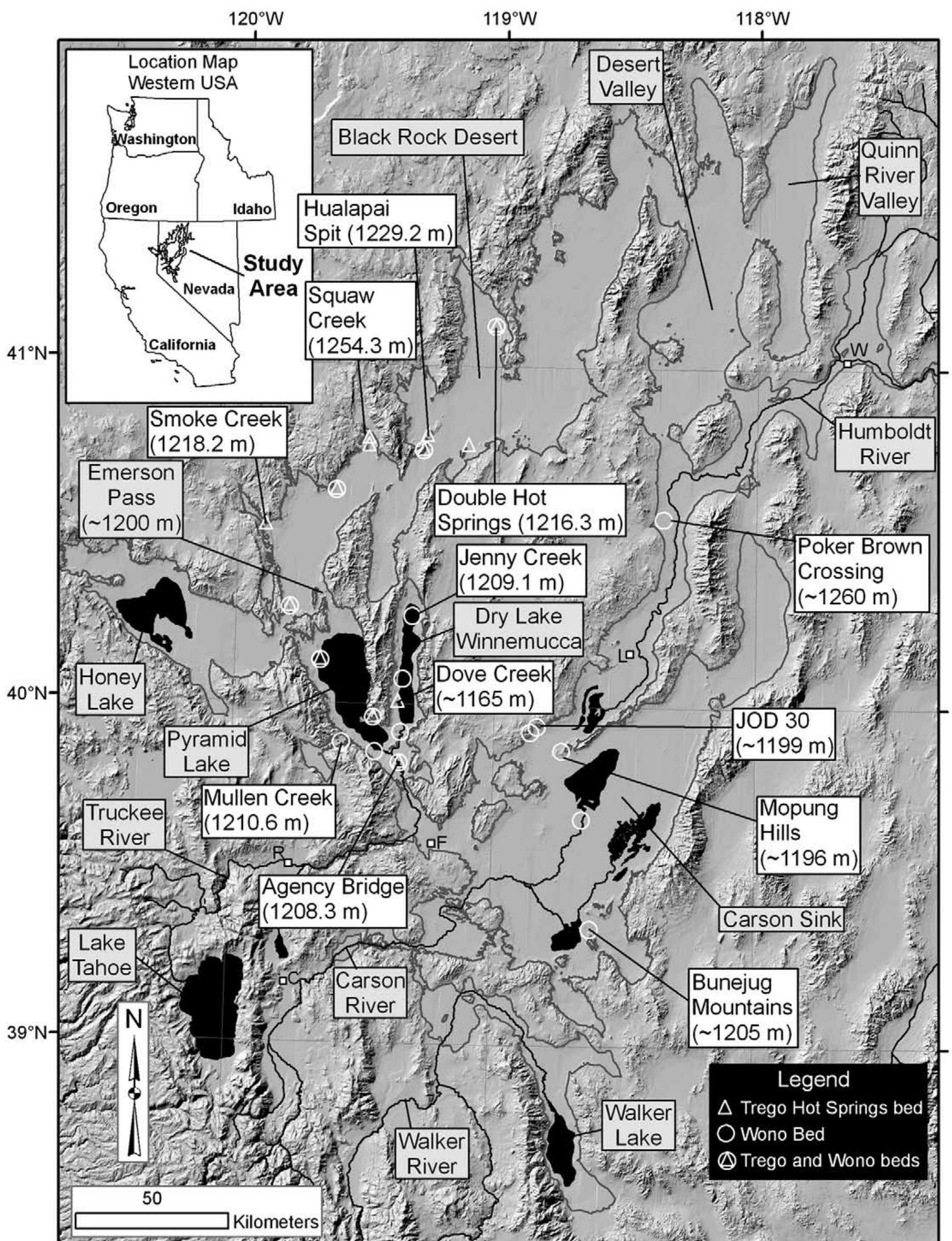

Figure 1. Map showing study sites (white boxes) where the Trego Hot Springs and Wono tephras are found as well as other tephra sites as described in Davis (1978; 1982; 1985; 1987a, b), Benson et al. (1997), and Bell et al. (2005). The thin gray line represents the last major highstand of Lake Lahontan at about 1335 m. Place names mentioned in text are shown in gray-shaded boxes. Cities are denoted by small white boxes with adjacent letters: R, Reno; C, Carson City; F, Fernley; L, Lovelock; and W, Winnemucca.

(1983) interpreted to be deltaic sediments. At the southern (downstream) amphitheater, the THS bed is contained within the base of a thick deltaic/lacustrine package at an elevation of about 1256 m. These interpretations led Davis (1983) to conclude that lake level must have been between 1256 and 1260 m at the time the THS tephra was deposited. Davis (1985; 1987a) also described a series of exposures in the Black Rock and Smoke Creek deserts where the THS and Wono beds are exposed in lacustrine beds at various elevations from about 1160 m to about 1230 m.

Subsequent to Davis' (1978, 1982, 1983, 1985, 1987a) studies, Benson et al. (1997) reexamined the Squaw Creek exposures and interpreted that the THS bed in the downstream exposure was associated with an approximately 1.5-m-thick fluvial/eolian unit capped by a buried soil, although they did note deltaic sediments both underlying and overlying the THS bed. Their interpretation was that the unit that contained the THS bed was not part of underlying and overlying delta complex(es) and was not graded to a high lake level. Benson et al. (1997) concluded that Lake Lahontan was much smaller than Davis's (1983) interpretation at the time the THS bed was deposited, probably at or close to the size of Pyramid Lake in historic time (Fig. 1). The conclusions of Benson et al. (1997) were based in part on heavy δO^{18} values associated with the THS bed in a core (PLC92B) from the north end of Pyramid Lake.

Davis (1983) assigned an age of about 23,400 ^{14}C yr BP to the THS bed and an age of about 24,800 ^{14}C yr BP to the Wono bed, based on two separate stratigraphic exposures at Pyramid Lake that contain the THS and Wono beds and a few associated radiocarbon ages. Benson et al. (1997) subsequently revised these age estimates to $23{,}200 \pm 300$ and $27{,}300 \pm 300$ ^{14}C yr BP for the THS and Wono beds, respectively, based on an age-depth plot constructed from bulk organic radiocarbon ages from core PLC92B. Also, based on heavy δO^{18} values adjacent to the Wono tephra in the core and interpretation of the depositional settings of various outcrops around Pyramid Lake, Benson et al. (1997) interpreted lake level at Wono time to be at 1207 m, the spill point from Pyramid Lake to the Smoke Creek–Black Rock subbasin (Fig. 1).

Study sites

The following study sites highlight the diverse depositional settings of the THS and Wono beds in the Lahontan basin and their implications for lake-level reconstructions. Due to length restrictions, not all THS and Wono outcrops known in the Lahontan basin are described herein (Fig. 1). For other descriptions of THS and Wono sites, see Davis (1978; 1982; 1985; 1987a,b), Benson et al. (1997), and Bell et al. (2005).

In this paper, the western subbasins include Pyramid Lake, dry Lake Winnemucca, Honey Lake, Smoke Creek Desert, Black Rock Desert, Desert Valley, and Quinn River Valley (Fig. 1). The Humboldt-Carson Sink (hereafter referred to as the Carson Sink) and Walker Lake constitute the other major subbasins of Lahontan. The Wono bed has been found throughout the Carson Sink and western subbasins whereas the THS bed has only been found in the western subbasins.

When discussing deltas in this paper, the parts of a delta are referenced to the original model of Gilbert (1885) where topsets correspond to fluvially dominated, sandy to gravelly sediments on top of the delta, relatively steep foresets correspond to the delta front, and relatively flat bottomsets correspond to the pro-delta area. In the Lahontan basin, deltas are recognized in a variety of sizes ranging from relatively large ones deposited by the Truckee (Born, 1972), Carson, and Walker (Adams, 2007) rivers to relatively small ones deposited by Squaw, Smoke, and Mullen creeks. Consequently, the amplitude of foresets (delta front) and the depth of water in which bottomsets (pro-delta) were deposited are also relative, ranging from less than a couple of meters to tens of meters.

Tephra identifications for this study were from the tephrochronology laboratory at Washington State University or were taken from Davis (1978; 1985; 1987a). Sedimentary symbols and terminology used in this paper are modified from Gierlowski-Kordesch and Kelts (2000) and Tucker (2003), as used in Adams (2007). The elevations of the Squaw Creek, Smoke Creek, Double Hot Springs, Agency Bridge, Hualapai spit, Jenny Creek, and Mullen Creek sites were surveyed with either a total station referenced to local benchmarks or a high-precision GPS system; all other elevations are approximate.

Squaw Creek

The two alternative interpretations of the depositional setting of the THS bed in the lower Squaw Creek outcrop are that it was either deposited on a delta graded to a transgressing lake surface between 1256 and 1260 m (Davis, 1983) or that the THS bed was deposited in a small, flashy stream with a heavily vegetated, marshy floodplain, which was not graded to a relatively high lake level (Benson et al., 1997). To evaluate these two very different models, a detailed analysis of the lower amphitheater was undertaken (Fig. 2). It is recognized, however, that these exposures have probably changed over the 25+ yr that they have been studied due to continued erosion by Squaw Creek.

The main disagreement that Benson et al. (1997) have with Davis's (1983) interpretation of the lower amphitheater concerns a <1.5-m-thick group of thin to medium beds near but not at the base of the 15-m-high and 50-m-long exposure that contains the THS bed (Fig. 2). Benson et al. (1997) interpret this as a package of fluvial sediments with interbedded eolian deposits and a buried soil that is not part of the deltaic complex but is underlain and overlain by deltaic deposits. In the stratigraphic column (Fig. 2), this interval corresponds to units 3 through 7.

Like Benson et al. (1997), I also interpret the lower part of the sequence to represent a deltaic environment with steeply dipping deltaic foresets (unit 1) overlain by fluviodeltaic topset sands (unit 2). Where we disagree, however, is on the sedimentary environments represented by units 3 through 7 (Fig. 2). Benson et al. (1997) describe unit 3 as consisting of "nearly 1 m of thin lenticular beds of sand and pebbly sand interbedded with gray sandy clays, all heavily disrupted by sediment-filled root casts. The sand beds typically display planar laminations, imbricate pebble layers and, rarely, decimeter-scale tabular sets". Although there are small root casts within this interval, bioturbation is minimal. In parts of the outcrop, the sandy cross sets are interbedded with thin, lenticular beds of mud that are associated with abundant limonite staining. Unit 3 also has abundant channel structures, evidence of soft-sediment deformation in the form of convolute bedding, and is conformable with underlying and overlying units across the width of the outcrop (~50 m). Benson et al. (1997) interpret unit 3 "…indicating a change from large streams that deposited Gilbert-type deltas to small flashy streams that cut across heavily vegetated, marshy floodplains". In contrast, I interpret unit 3 to also be part of the delta-top facies, which is consistent with evidence for vegetation.

Benson et al. (1997) also interpret a sandy mud (unit 4) to display soil-forming processes directly below the THS bed and a silty, eolian unit overprinted by a buried soil directly above the tephra. The tephra bed itself (unit 5) is faintly laminated, slightly bioturbated, and has a few limonite-stained root casts. The bed thickens downstream and is involved in soft-sediment deformation, both in terms of disrupted bedding and sand dikes. Benson et al. (1997) interpreted "Large sediment-filled cylinders … to be the casts of tree trunks that grew prior to deposition of the THS". According to their explanation, these features represent the casts of tree trunks that were growing on a flood plain prior to deposition of the THS, and then somehow the wood was removed and replaced with sandy sediment after deposition of the THS, all within a package of unconsolidated sediment. In terms of process, this explanation seems highly unlikely. Instead, these features are probably sand dikes that were injected from below

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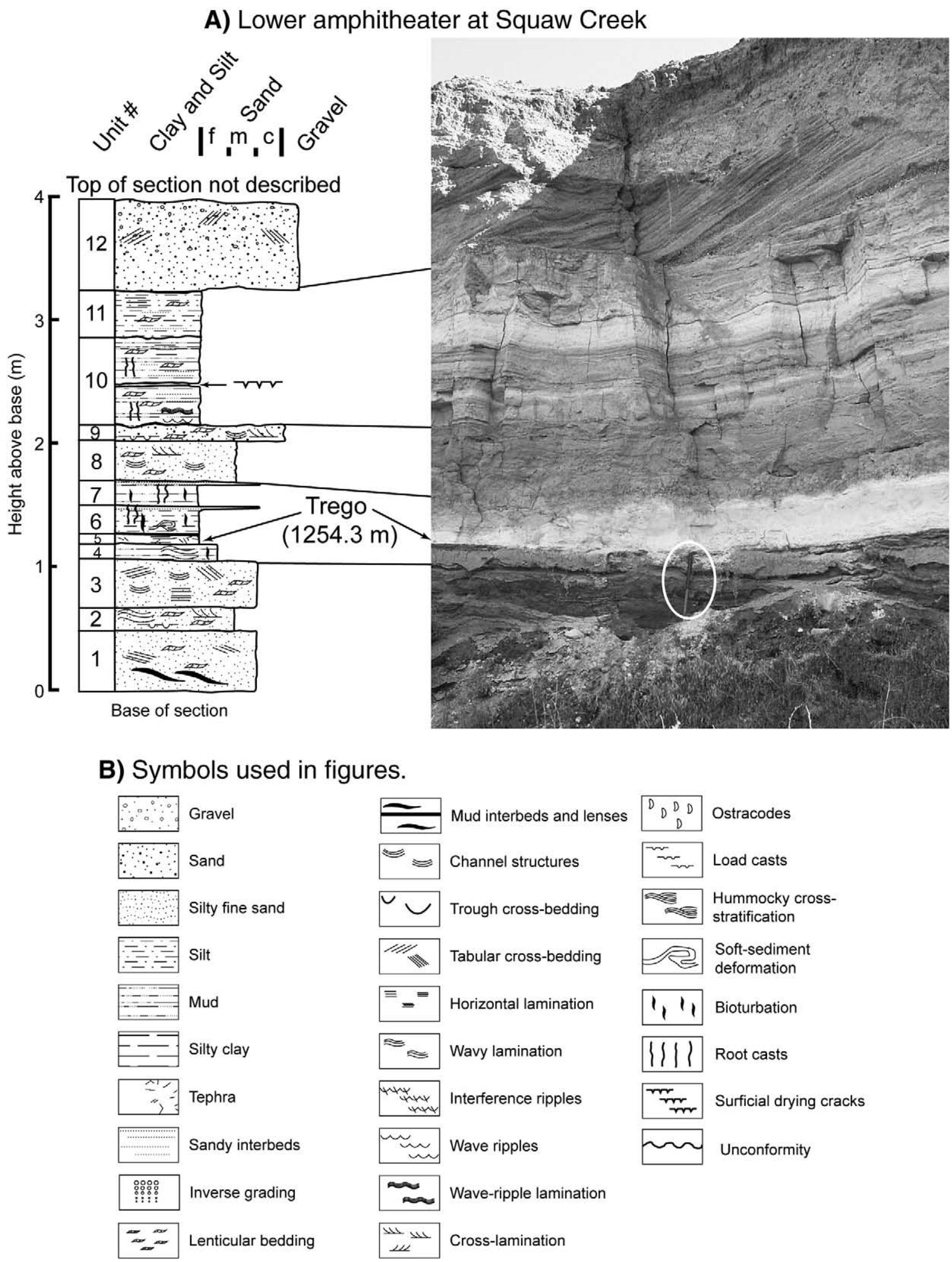

Figure 2. (A) Stratigraphic column and photograph of the lower (downstream) amphitheater at Squaw Creek. Circled pick is about 65 cm tall. (B) Sedimentary symbols used in figures in this paper (after Gierlowski-Kordesch and Kelts, 2000; Tucker, 2003; and Adams, 2007).

or fluidization features, as there is abundant evidence for other soft-sediment deformation features (e.g., convolute bedding) in the lower part of this sequence.

A silty zone (unit 6) overlying the THS bed has a diffuse lower contact and is light in color, which probably reflects abundant glass shards within the unit (Fig. 2). At the place where the section was described (Fig. 2), the silty zone was about 30–40 cm thick but it thins upstream to just a few centimeters. Instead of interpreting unit 6 as eolian (Benson et al., 1997), it is interpreted here to have been deposited in shallow water on the surface of a delta, reflecting the flush of mixed tephra and fine-grained sediment after a regional airfall event. The preferential transport of tephra shards is probably facilitated by their relatively low density and their commonly platy shape, both of which would act to lower their settling velocity and enhance their transport. Thick tephra beds with zones of dirty tephra conformably and gradationally overlying them are common in other deltaic and shallow lacustrine settings as at Mullen Creek, Double Hot Springs, Mopung Hills (see below), and along the lower Walker River (Adams, 2007).

What Benson et al. (1997) interpret as a buried soil overprinted on unit 6, I interpret as a distinct muddy layer (unit 7) similar to unit 4, which immediately underlies the THS bed (Fig. 2). Although there are abundant small, oxidized root casts within this thin mud, no other evidence for soil development was seen. Particle size analysis shows that the lower part of unit 7 has more clay than the upper part of the unit (12.7% vs. 7%) and what Benson et al. (1997) interpret as "polygonal columnar parting" are herein interpreted simply as shrinkage cracks from the abundant silt and clay in this unit. Benson et al. (1997) interpret the sedimentary sequence above unit 7 to again represent a delta setting, which is reasonable because there is abundant evidence of shallow water deposits that include oscillatory ripples, wave-ripple laminations, and beach back sets (unit 12).

In summary, the main difference between the interpretation of Benson et al. (1997) and that reported in Davis (1983) and corroborated herein is that Benson et al. (1997) break out a thin package (<1.5 m thick) of sediments within a delta sequence that they interpret as not being part of the delta (Fig. 2; units 3–7). Although there is evidence of shallow water or subaerial exposure in the form of root casts and slight bioturbation within units 3–7, these features are not inconsistent with a vegetated delta-top setting. The observation that this package is also conformable across the width of the outcrop (~50 m) with the underlying and overlying delta packages also strongly suggests that it is part of the overall sequence. In this type of depositional setting, incision through unconsolidated sediments is rapid and pervasive when base level is lowered (e.g., Born and Ritter, 1970; Adams, 2007), but there is no evidence of a major unconformity.

Benson et al. (1997) agree that the lower part of the sequence represents delta sediments, but they do not speculate on its age. There are no published lake-level curves (0–45 ka) that place lake level anywhere near this elevation (~1254 m) until the THS bed was deposited. According to what is known about the lake-level history of Lahontan, prior to THS time lake level had not attained this elevation since Marine Isotope Stage 6 (Morrison, 1991). No soil or other evidence of antiquity separates the lowermost part of the section from the overlying units 3–7. The most parsimonious explanation is that this entire package, including the THS bed, represents a fluctuating deltaic environment in a lake that transgressed to an elevation of at least 1277 m, the elevation of the top of the outcrop, and that contains the THS bed near its base. Therefore, the THS bed deposited in this setting at 1254.3 m (surveyed elevation) closely approximates lake level when the tephra was deposited, as originally interpreted by Davis (1983).

Hualapai spit

Davis (1987a) described the THS bed cropping out on the backside of a gravel spit that sits on a divide between the Black Rock Desert and Hualapai Flat (Fig. 1). The tephra rests directly on moderately steeply dipping tabular sets of subrounded to subangular beach gravel but was difficult to describe because the outcrop is in an active gravel pit where the pit slope is slightly greater than the dip of the beds. Finer grained beds of silt and sand cap the tephra, which is at an elevation of about 1229 m. The gravel in the spit was likely deposited when lake level was

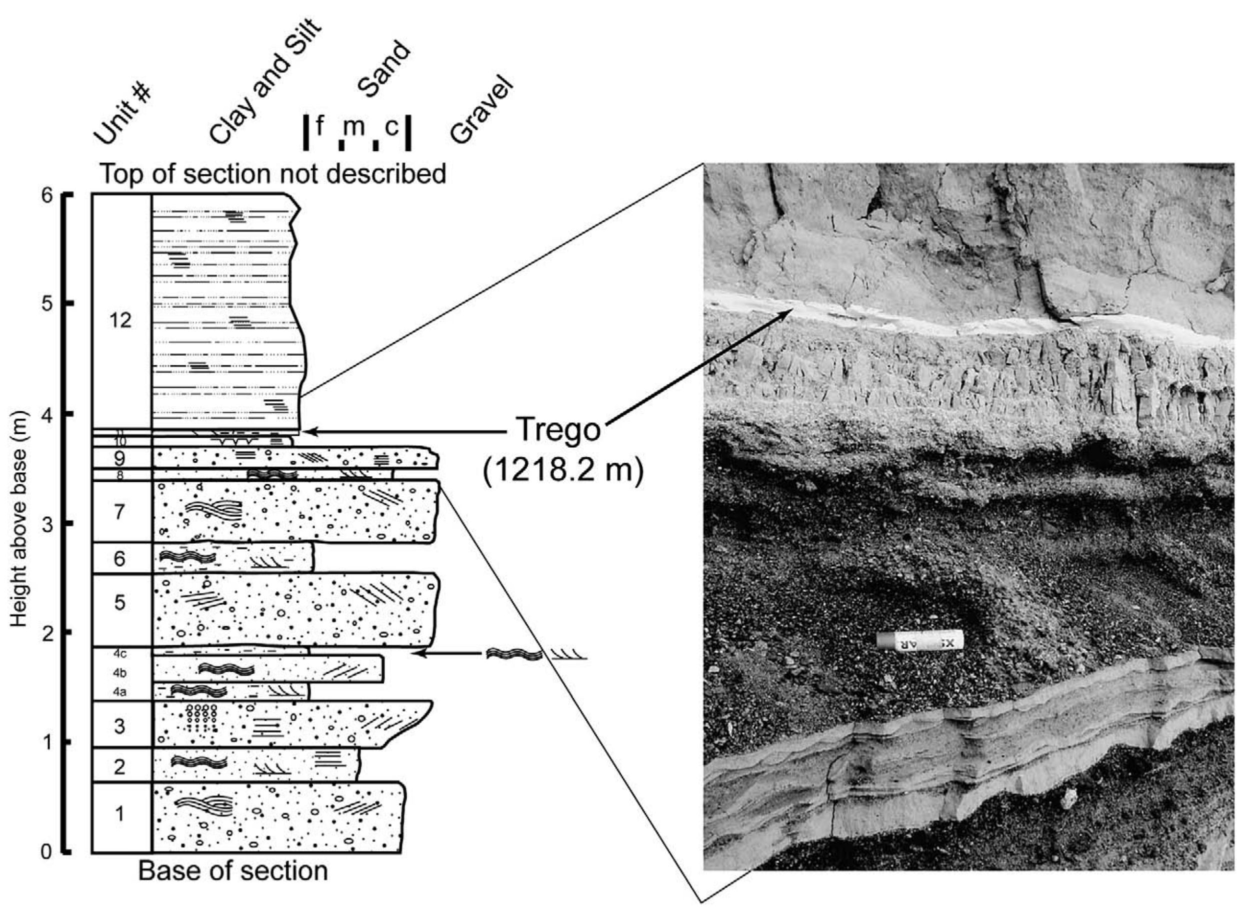

Figure 3. Stratigraphic column and photograph showing the sedimentary setting of the THS bed at Smoke Creek. Lip balm case in photo is 6.5 cm long.

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at or near the crest of the spit (1241 m) and the THS bed and overlying silt and sand beds were deposited after the lake had risen above this elevation. If Lake Lahontan was at an elevation of about 1254 m when the THS bed was deposited, then this spit was more of a shoal at that time and the tephra was deposited in about 25 m of water.

Smoke Creek

An approximately 10-m vertical cutbank along Smoke Creek (Fig. 1) exposes the THS bed in lacustrine deposits at an elevation of 1218.2 m (Fig. 3). In the lower part of the exposure, the sediments

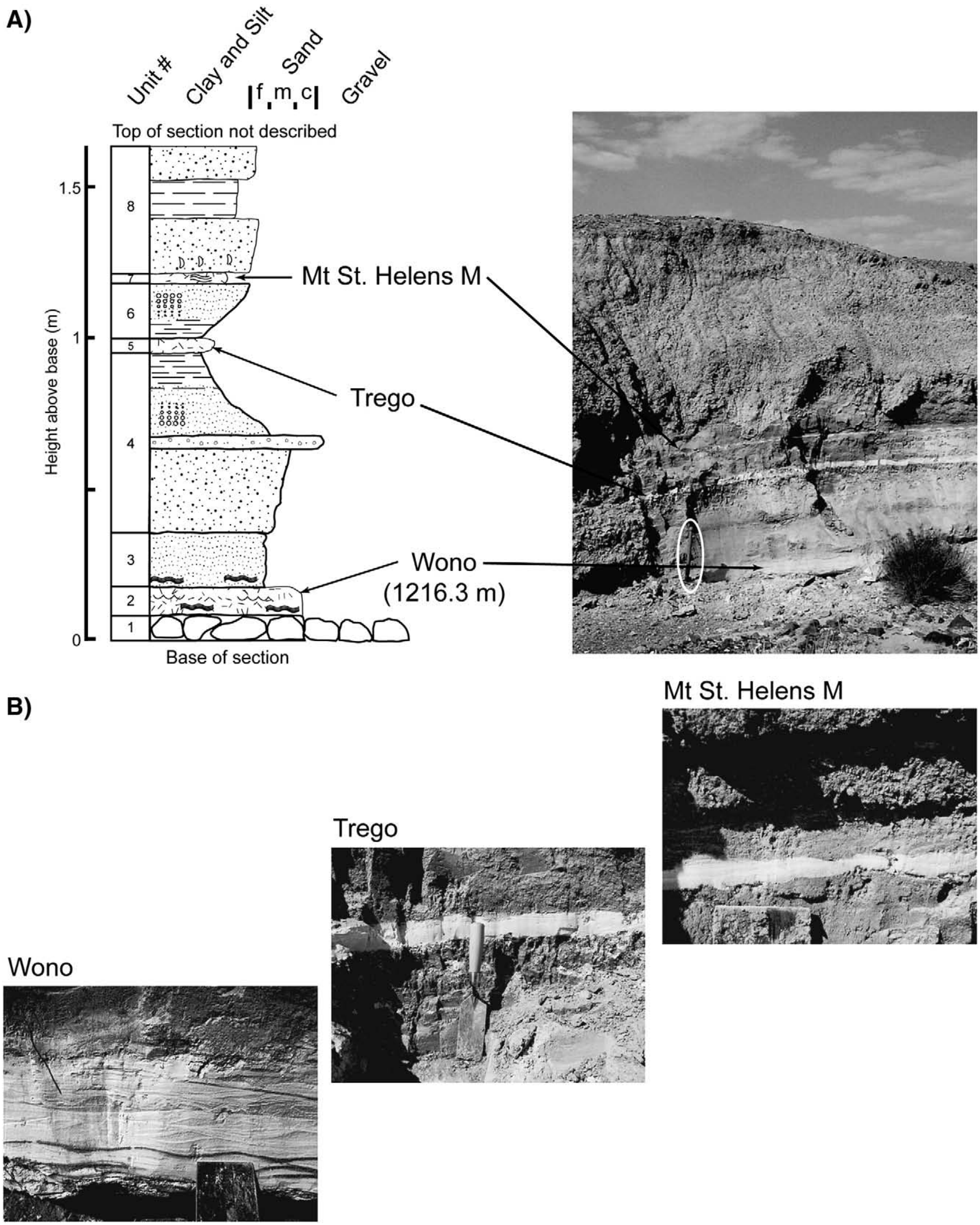

Figure 4. (A) Stratigraphic column and photograph showing the sedimentary setting of the Wono, THS, and Mt St. Helens beds at the Double Hot Springs site. Circled shovel is about 45 cm tall. (B) Close-up photographs of the Wono, THS, and Mt St. Helens beds. Note the wave-ripple laminations in the Wono bed. Trowel is about 25 cm tall and 5 cm wide.

primarily consist of tabular to wedge-shaped, fine gravel beds interbedded with thin, fine to coarse sand layers, all of which display abundant wave-formed features that include wave ripples, wave-ripple laminations, hummocky cross-stratification (HCS), and tabular beach sets (Fig. 3).

The uppermost gravel bed (unit 9) abruptly grades upward into a clay with thin laminae of medium to coarse sand and ostracod tests and distinctive shrinkage cracks that form small columns (Fig. 3). In places, the THS bed lies directly on top of the clay unit (unit 10) but in some parts of the outcrop deposition of silt began just before deposition of the tephra. Therefore, the tephra nearly, but not quite, marks a change in sedimentation to mostly silt, which composes the upper part of the section (Fig. 3). The THS bed at this location was clearly deposited in deep water below storm wave base and likely was deposited in about 36 m of water, based on the difference in elevation between the tephra beds at Squaw and Smoke creeks.

Double Hot Springs

The Double Hot Springs site (1216.3 m) was first described by Davis (1985) who noted a section containing the Wono, THS, and Mt St. Helens M (~18.6 ka; Riedel, 2007) tephras (Fig. 4). In the 1985 publication, however, Davis was not able to correlate the middle tephra but later identified it as the THS bed (Davis, 1987a). This 4-m-high section is exposed in the banks of a wash cutting through the footwall of the adjacent Black Rock fault (Dodge, 1982; Sawyer and Adams, 1998).

The base of the Double Hot Springs section is composed of tufa-covered cobbles and boulders (unit 1), which are overlain by the much finer grained section containing the tephras (Fig. 4). The Wono bed (unit 3) is about 20 cm thick and displays abundant wave-ripple laminations, wave ripples, and pinch-swell structures (Fig. 4). The overlying fine to medium sand (unit 4) also has wave-formed structures near its base and a thin (<5 cm) interbed of medium sand to rounded fine gravel, above which the unit fines upward into silty clay when the THS bed was deposited (Fig. 4). Another 5 cm of silty clay was deposited immediately after the THS bed, before the sediments coarsen upward to fine to medium sand and the Mt St. Helens M bed was deposited. Subtle wavy laminations, wave ripples, and flaser bedding are associated with this tephra, which indicates that it was deposited above wave base. Overlying the Mt. St. Helens bed, fine to medium sands with a few pebbles grade upward into interbedded sand and silty clay layers.

All of the tephras and their enclosing sediments are conformable, and the associated sedimentary features at Double Hot Springs clearly reflect deposition in a lake. Whereas the Wono and Mt. St. Helens beds were deposited in nearshore environments above wave base, the THS bed was deposited in a deeper lake (~38 m), below wave base where silty clay and clay were deposited (Fig. 4).

Agency Bridge

The Agency Bridge section is exposed along the lower Truckee River (Fig. 1) and was first described by Russell (1885), who noted a tephra interbedded with lacustrine beds. Davis (1978) identified this tephra as the Wono bed and also noted the THS bed about 60 cm above the Wono (Fig. 5). Benson et al. (1997) describe the Wono here as occurring "within a wave-sorted sand composed of reworked ostracods, snails, and charophytes", with which I agree. Benson et al. (1997) interpret a silt bed overlying the Wono as eolian, whereas I interpret it as a bed of reworked tephra similar to the silty bed overlying the THS bed at Squaw Creek.

Benson et al. (1997) conclude that the Wono at the Agency Bridge site was deposited in just a few meters of water as Pyramid Lake was spilling over Emerson Pass into the Smoke Creek Desert (Fig. 1). Benson et al. (1997) cite the elevation of Emerson Pass to be about 1207 m, but a post-Lahontan alluvial fan has likely raised the elevation of this sill since the last major lake cycle. Based on the elevation of a large, well-developed beach ridge complex at the north end of dry Lake Winnemucca (1202 m; Adams et al., 2008), the functional spillover elevation of Emerson Pass during the last lake cycle was probably closer to 1200 m. The elevation of the Wono bed at Agency Bridge

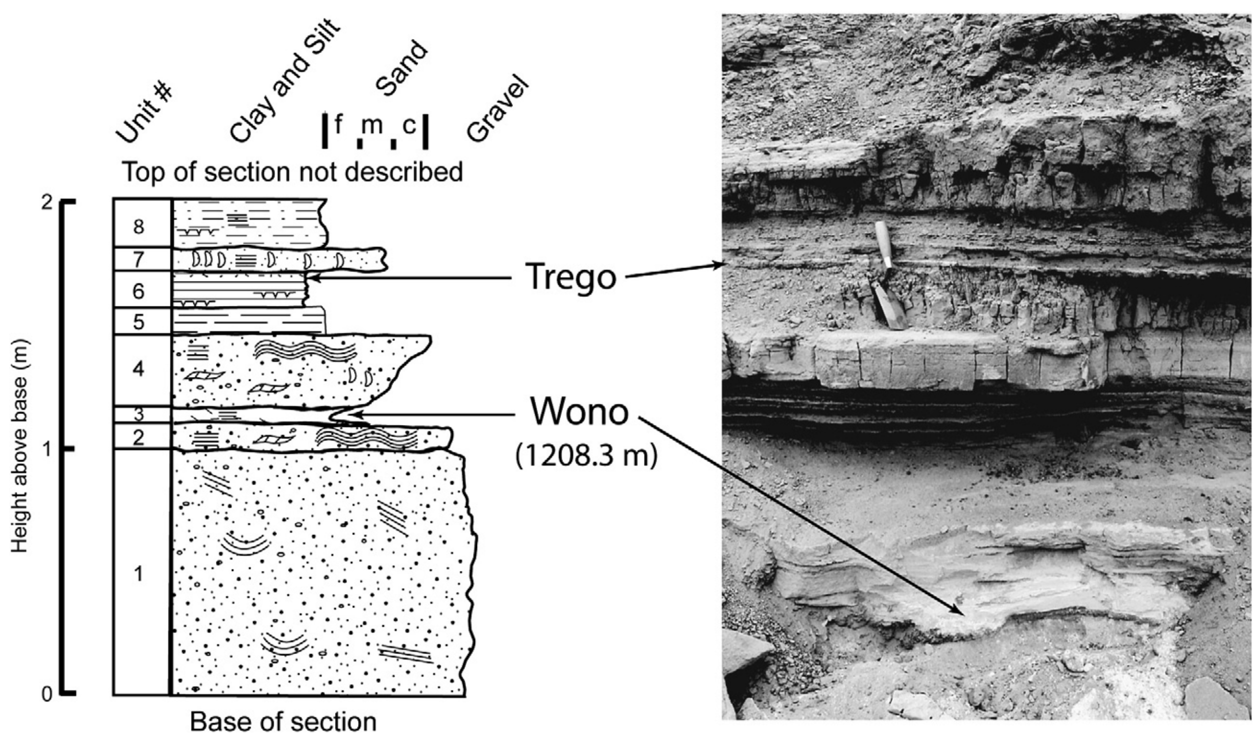

Figure 5. Stratigraphic column and photograph of the Wono and THS beds at the Agency Bridge site. Trowel is about 25 cm tall.

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(1208.3 m) compared to the elevation of Emerson Pass (~1200 m) indicates that all of the western subbasins, except for possibly Honey Lake Valley, were integrated at Wono time. This interpretation is confirmed by the elevation of the Wono bed (1216.3 m) in shallow lacustrine deposits at the Double Hot Springs locality.

At Agency Bridge, the THS bed (~1209 m), which was listed by Benson et al. (1997) in their Table 1 but was not noted in their outcrop description, is located near the top of a silty clay that contains thin, discontinuous laminae composed of fine sand and ostracod tests (unit 6). Abundant post-depositional shrinkage cracks give this unit a distinctive appearance (Fig. 5). A few small pebbles in the sediments surrounding the THS bed are interpreted to be drop stones. Overlying the THS bed, the 15-cm-thick unit 7 is composed almost entirely of ostracod tests, which reflects primarily biogenic sedimentation. The THS bed here is interpreted to have been deposited in about 45 m of water.

Table 1
Site locations, elevations, and sedimentary features associated with the THS and Wono tephras.

Site	Location[a]		Elevation (m) (Water depth)[b]	Tephra[c]	Sedimentary features[d]
	Easting	Northing			
Western subbasins					
Squaw Creek (Davis, 1983, 1987a,b; Benson et al., 1997; this study) (Fig. 2)	288310	4518271	1254.3 (0)	T	O: Reworked tephra in silty matrix; oxidized root casts; inverse grading; lenticular bedding; cross laminations. THS: Horizontal laminations; slight bioturbation; oxidized root casts; soft-sediment deformation; sand dikes. U: Coarse sand to pebbly sand interbedded with thin lenticular beds of mud; channel structures; root casts; limonite staining; convolute bedding; conformable with overlying THS bed.
Hualapai spit (Davis, 1987a,b; this study)	308688	4517156	1229.2 (~27)	T	O: Moderately dipping thin silt and sand beds. THS: Thin laminations; moderately dipping. U: Subangular to subrounded moderately dipping beach gravel (≤10 cm).
Smoke Creek (this study) (Fig. 3)	256392	4487954	1218.2 (~36)	T	O: Horizontal thin to medium silt beds. THS: Pure glass shards, ~1 cm thick. U: Clay, with prominent shrinkage cracks; laminae of medium to coarse sand and ostracods; interbedded fine to coarse sand and fine gravel with wave-ripple laminations and HCS.
Double Hot Springs (Davis, 1985; this study) (Fig. 4)	330357	4546106	1216.3 (~38; <1?)	T,W	O: Interbedded fine to medium sand and silty clay layers with abundant ostracods and occasional fish vertebrae; wavy laminations at base. Mt St. Helens: Relatively pure; wavy laminations; wave ripples; flaser bedding. Between: Fine to medium sand grading downward to silty clay with shrinkage cracks. THS: Relatively pure with faint laminations. Between: Silty clay grading downward to medium and fine sand with a single bed of medium sand to fine rounded gravel; wave-ripple laminations at base. W: Reworked; wave ripples; wave-ripple laminations; pinch-swell structures. U: Medium to coarse sand with a few pebbles lying on tufa-covered cobbles and small boulders.
Agency Bridge (Russell, 1885; Davis, 1978; this study) (Fig. 5)	298939	4409261	1208.3 (~46; ~9)	T,W	O: Fine to medium sand composed almost entirely of ostracods tests and a few pebbles; thinly bedded. THS: Thin bed near the top of silty clay unit with abundant shrinkage cracks and minor laminae composed of fine sand and ostracods. Between: Silt bed overlying coarse sand to fine gravel; horizontal and wave-ripple laminations; ostracods. W: Thinly laminated, grading upward to silty zone with abundant glass shards. U: Horizontal, thin-bedded coarse sand to fine gravel; wave-ripple laminations.
Dove Creek (this study)	297394	4437905	~1165 (~91)	T	O: Thin-bedded clay with a few thin laminae of fine to medium sand and silt; ostracods; shrinkage cracks disrupt bedding. T: Thin (~5 mm), pure bed. U: Same as overlying.
Mullen Creek (this study)	281317	4420367	1210.6 (~6)	W	O: Thinly interbedded silt and fine sand with wave-ripple laminations grading upward to fine sand, W: Thick (~90 cm); pure; horizontal laminations; soft-sediment deformation in lower part of unit. U: Medium to coarse sand.
Jenny Creek (this study) (Fig. 6)	301577	4465211	1209.1 (~8)	W	O: Well-sorted, silty fine sand with occasional faint laminations; slight bioturbation. W: Medium (7–10 cm) graded bed with wavy, thin laminations. U: Faint, medium-bedded pebbly coarse sand with lens-shaped beds of medium sand.
Carson Sink					
Bunejug Mountains (this study) (Fig. 7)	359462	4359057	~1205 (0)	W	O: Sandy subrounded to subangular gravel (10–15 cm) in moderately dipping (~8°) thin (5–15 cm) beds. W: Pure bed ~10 cm thick. U: Same as overlying.
JOD 30 (Davis, 1978; this study)	348066	4421639	~1199 (~5)	W	O: Fine sandy silt grading upward to fine to medium sand. W: Thinly laminated pure tephra ~12 cm thick. U: Thin-bedded fine to medium sand.
Mopung Hills (this study)	349047	4415866	~1196 (~8)	W	O: Thinly interbedded fine sand and silt-sized glass shards grading upward to thinly bedded fine to medium sand. W: Thinly laminated pure tephra ~5–7 cm thick. U: Thinly bedded fine to medium sand.

[a] All locations are in UTM Zone 11, NAD83.
[b] Water depth is calculated by assuming lake surface elevations of 1254.3 and 1217 m at THS and Wono times, respectively.
[c] T = Trego Hot Springs bed; W = Wono bed.
[d] Sedimentary features associated with tephra beds (THS and W) and beds immediately underlying (U) and overlying (O) tephras.

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Dove Creek

Another low-elevation outcrop (~1165 m) of the THS bed is found on the west side of dry Lake Winnemucca, below the historic highstand of this lake that reached about 1175 m in 1882. This location is on the distal part of what was a fan delta complex emanating from Dove Creek. The base of this section contains one or more tephra beds that define isoclinal and recumbent folds reflective of slumping and soft-sediment deformation. Overlying this unit and separated by an unconformity, the THS bed is contained within conformable and undeformed laminated to thinly bedded clays with bedding defined by thin laminae of fine to medium sand and ostracod tests. Based on the Squaw Creek exposures, the THS bed here was deposited in about 90 m of water. The sandy laminae here may be explained by sediment gravity flows moving down the fan delta slope, triggered by storms or wave activity.

Mullen Creek

Mullen Creek drains Warm Springs Valley and flows into the west side of Pyramid Lake (Fig. 1). In its lower reaches, Mullen Creek is incised into a Pleistocene deltaic complex that contains the Wono bed at an elevation of 1210.6 m. Here the horizontal Wono bed is unusually thick (~1 m), but there is evidence for soft-sediment deformation in the lower part of the bed. The upper part of the bed has faint horizontal laminations that grade upward into a silt and fine sand unit with wave-ripple laminations. The Wono bed here is interpreted as having been deposited in about 7 m of water in a pro-delta setting.

Jenny Creek

Jenny Creek flows into the north end of dry Lake Winnemucca and has dissected a series of beach ridges that extend from the playa at 1152 m up to the late Pleistocene highstand of about 1338 m (Fig. 1; Adams et al., 2008). The Wono bed is exposed for a distance of about 100 m in the left cutbank of Jenny Creek at an elevation of 1209.1 m, below the 1218-m beach ridge. The Wono bed here is underlain by a pebbly coarse sand with faint thin bedding and is overlain by a slightly bioturbated, well-sorted silty fine sand grading upward into a well-sorted fine sand (Fig. 6). All of these units are interpreted to have been deposited in a nearshore position in relatively shallow water, probably in about 8 m of water.

Figure 6. Photograph of the Wono bed at the Jenny Creek site (1209.1 m). Circled trowel resting on top of the Wono is about 25 cm tall.

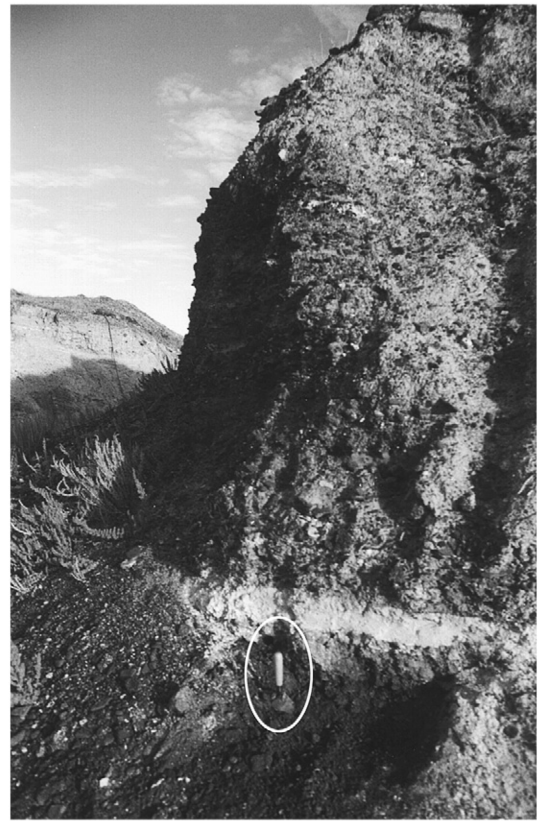

Figure 7. Photograph of the Wono bed at the Bunejug Mountains site in the Carson Sink. Circled trowel is about 25 cm tall.

Carson Sink

The Wono tephra is found in several places in the Carson Sink, all of which are in lacustrine settings below an elevation of about 1205 m (Fig. 1). The most telling of these outcrops is in a spit at the north end of the Bunejug Mountains, where the Wono is interbedded with a thick package of thin- to medium-bedded coarse beach gravels (Fig. 7) that dip to the east, away from the former lake. These relationships are interpreted to mean that the Wono was deposited in beach backsets on the margins of a lake at an elevation of about 1205 m.

On the northwest side of the Carson Sink, Davis (1978) described the Wono cropping out at two locations along Interstate 80 (Fig. 1), separated by several kilometers. At the more northerly of these sites (JOD 30), the thinly laminated Wono bed is 10–15 cm thick overall and is interbedded with fine to medium sand at an elevation of about 1199 m. Again, there is a thin (5–7 cm) silty zone above the tephra that contains abundant glass shards. A few kilometers to the southwest at JOD 31, the 15-cm-thick Wono bed lies at an elevation of about 1192 m and is encased in greenish clays (Davis, 1978). The Wono tephra at both JOD 30 and JOD 31 is interpreted as having been deposited in relatively shallow nearshore settings, probably in depths of about 6 and 13 m, respectively.

At the south end of the Mopung Hills (Fig. 1), the Wono is contained within thinly bedded, well-sorted, fine to medium sand that grades upward into silt and clay beds at an elevation of about 1196 m. The tephra itself is about 5–7 cm thick, thinly laminated and grades upward into a thin bed of mixed tephra and fine to medium sand. The

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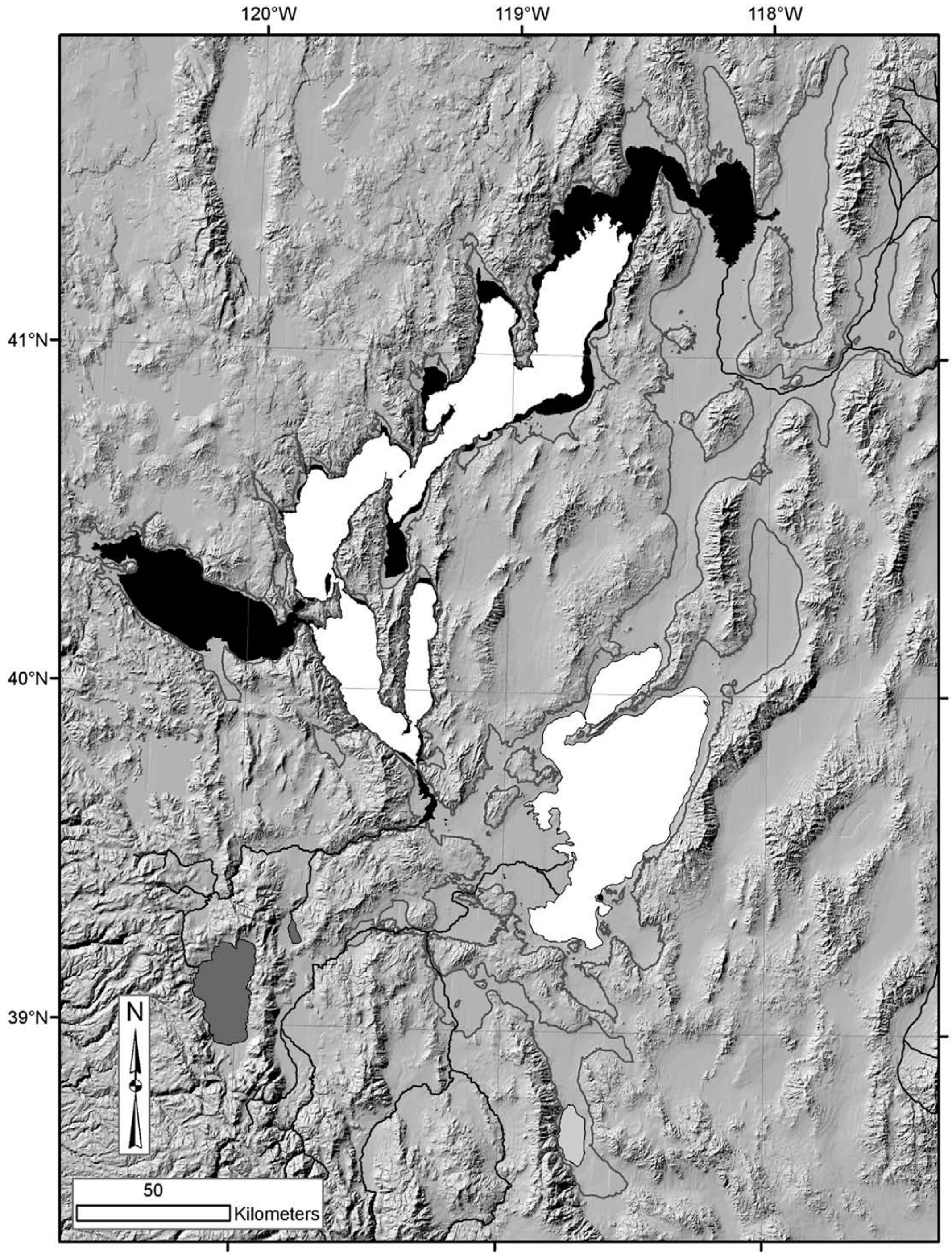

Figure 8. Map of lake levels in the Lahontan basin as they appeared in Wono time (white; Western subbasins = 1217 m; Carson Sink = 1205 m) and Trego Hot Springs time (black; western subbasins = 1254 m). The THS bed has not been found in the Carson Sink, so lake levels at THS time are not shown there. For these configurations, the Humboldt River is shown flowing into the western subbasins (Davis, 1990; Benson and Peterman, 1996; Adams et al., 1999) and the Walker River is shown as a tributary to the Carson River (Benson and Thompson, 1987; Bradbury et al., 1989; Adams et al., 1999). Thin gray line represents the last major highstand of Lake Lahontan at about 1335 m. See Figure 1 for place names.

Wono at this site is interpreted to have been deposited in a nearshore position in about 9 m of water.

Discussion

Lake levels at Wono and THS times

In the Lahontan basin, the THS and Wono beds are found in a variety of sedimentary environments at a range of elevations (Fig. 1; Table 1). In terms of lake-level history, one of the more important locations is Squaw Creek where the THS bed is found in stream alluvium at about 1260 m and in a shallow deltaic setting at 1254.3 m. The THS bed is also found in pro-delta settings ranging in elevation from about 1210 to 1220 m (Agency Bridge and Smoke Creek) and offshore settings ranging in elevation from 1165 to 1229 m (Dove Creek, Double Hot Springs, and Hualapai spit). Taken together, these sites clearly support the interpretation of a very large lake in the western subbasins at the time that the THS bed was deposited (~23.2 ka), probably with a surface elevation of around 1254 m (Fig. 8). A lake at this elevation would integrate the western subbasins

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of Lahontan and cover approximately 6800 km^2 and have a volume of about 350 km^3 (Benson and Mifflin, 1986).

Similarly, the elevational distribution of the Wono bed and the variety of depositional settings within which it is found also provide important clues for lake levels at Wono time (~27.3 ka). In the western subbasins, the Wono is found in pro-delta settings at 1208.3 and 1210.6 m (Agency Bridge and Mullen Creek, respectively) and in nearshore settings at 1209.1 m and at about 1216 m (Jenny Creek and Double Hot Springs, respectively). Cumulatively, the interpretations from these sites suggest that lake level at Wono time in the western subbasins was probably between 1216 and 1220 m, perhaps around 1217 m.

In the Carson Sink, separated from the western subbasins by the Fernley sill (~1265–1270 m), the Wono occurs in beach gravels at an elevation of about 1205 m, indicating lake level at Wono time (Fig. 7). This interpretation is confirmed by outcrops of Wono in nearshore settings at elevations ranging from about 1196 to 1199 m (Mopung Hills and JOD 30, respectively). The Wono is also found in alluvium at Poker Brown Crossing at about 1260 m (Davis, 1982), but this does not provide a very precise upper limit on lake levels.

The interpretation of lake levels from the elevations and depositional environments of the THS and Wono beds does not agree with the interpretation of lake-level trends from the δO^{18} record from a core (PLC92B) at Pyramid Lake. The δO^{18} value of the inorganic carbonate fraction of sediments in closed lake basins is influenced by a number of factors that include temperature, isotopic composition of the lake water, and evaporation (Leng and Marshall, 2004; Jones et al., 2005). Although fluctuations in δO^{18} values have been interpreted as reflecting changes in hydrologic conditions, absolute changes in lake surface area, elevation, and volume cannot be accurately predicted from isotopic fluctuations (Benson et al., 2002; Yuan et al., 2004).

Between 30 and 20 ka, δO^{18} values in core PLC92B fluctuated between about 26‰ and 32‰ (Benson et al., 1997). More specifically, at Wono and THS times, the relatively high δO^{18} values of 28.7‰ and 30‰, respectively, indicated to Benson et al. (1997) that lake levels were probably low at these times, about 1207 m at Wono time and ≤1177 m at THS time, with lakes confined to the Pyramid Lake and Winnemucca Lake subbasins. Based on interpretations of sedimentary environments of the Wono and THS tephras from multiple sites, lake level was probably about 10 m deeper at Wono time and about 80 m deeper at THS time, representing fully integrated lakes in the western subbasins (Fig. 8). Similar unexplained differences between the oxygen isotope record from a core (Yuan et al., 2006) and lake-level history derived from outcrop studies were noted at Walker Lake by Adams (2007).

Sedimentary features and paleowater depth

This study affords the opportunity to relate sedimentary features to specific water depths because known lake levels at the times of Wono and THS deposition directly correspond to known water depths at sites where these tephras are found (Fig. 1). Lake level at Wono time was at about 1217 m in the western subbasins and at about 1205 m in the Carson Sink. At THS time, lake level was at about 1254 m in the western subbasins but is unknown in the Carson Sink because the THS tephra has not been found there. These lake surface elevations allow documentation of sedimentary features associated with paleowater depths ranging from 0 to about 100 m (Table 1) in a variety of settings.

Four of the sites in this study are associated with deltaic complexes that include Squaw Creek, Smoke Creek, Agency Bridge, and Mullen Creek (Fig. 1). Paleowater depth estimates for these sites range from 0 to about 47 m and are supported by sedimentary features directly associated with the tephra beds (Table 1). The THS bed at Squaw Creek is interpreted to have been deposited as deltaic topsets in water from 0 to 1 m deep and has horizontal laminations, oxidized root casts, slight bioturbation, and soft-sediment deformation features including sand dikes.

At Mullen Creek, the Wono bed (~90 cm thick) was deposited in about 6 m of water and was probably thickened by preferential transport of low-density glass shards down Mullen Creek and off the delta front, although there is evidence of slumping in the lower part of the unit. A similarly thick (~1 m) tephra bed in a shallow delta setting along the lower Walker River can be directly traced into deltaic topsets where the tephra is only about 5 cm thick (Adams, 2007), demonstrating that tephra shards are commonly concentrated in this type of environment. Wave-rippled sand directly overlying the Wono bed at Mullen Creek indicates that this site was above wave base at the time of deposition.

At both the Smoke Creek and Agency Bridge sites, the THS bed was deposited in relatively deep water in pro-delta settings. Based on present topography, the THS bed at the Smoke Creek site was deposited about 1 km offshore in about 36 m of water and the THS bed at Agency Bridge was probably deposited about 7–8 km in front of the Truckee River delta in about 47 m of water. The THS bed at both sites is relatively thin (1–3 cm) and is interbedded with clay or silty clay with thin laminae composed of sand and ostracods. Both of these sites, however, are also located at the bases of relatively steep mountain fronts that may have occasionally contributed sediment in the form of sediment gravity flows due to runoff events or wave activity in the near shore. The Wono bed at the Agency Bridge site was deposited in about 9 m of water and is moderately thick (5–7 cm) and grades upward into a silt zone with abundant glass shards. Wave-ripple laminations directly above and below the Wono bed indicate that it was deposited above wave base.

The tephras at the Hualapai spit, Double Hot Springs, Dove Creek, Jenny Creek, Bunejug Mountains, JOD 30, and Mopung Hills sites (Fig. 1) were all deposited far away from the influence of inflowing streams and represent deposition in environments ranging from a beach (Bunejug Mountains) to deep offshore. In the shallow (<10 m) settings, sediment associated with the Wono tephra is generally thin- to medium-bedded fine to coarse sands with common wave ripples and wave-ripple laminations (Table 1). As paleowater depth increases to about 25 m (Hualapai spit), sediments transition to fine sand and silt. In paleowater depths of about 90 m (Dove Creek), sediments consist of thin-bedded clay with a few thin laminae of silt, fine to medium sand, and ostracods (Table 1). Again, this latter site is at the base of a steep mountain front, which may have been the source of the coarser sediments in the deposit.

Conclusions

The results of this study demonstrate that Davis (1983) was correct in his original interpretation that lake level was at about 1254 m in the western subbasins of Lahontan when the THS tephra (23.2 ka) was deposited, and not ≤1177 m as interpreted by Benson et al. (1997). This is a significant difference in lake size and has important implications for interpreting the climate that prevailed at that time. Based on additional sites, lake level was at about 1217 m in the western subbasins and at about 1205 m in the Carson Sink when the Wono tephra (27.3 ka) was deposited. A variety of depositional environments have been documented, which point to decreasing grain size and fewer distinctive sedimentary features with increasing paleowater depth, and which may provide useful guidance when interpreting isolated lacustrine outcrops.

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