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Latest Pleistocene history of pluvial Lake Franklin, northeastern Nevada, USA

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ABSTRACT

At its maximum extent during the last glacial cycle, Lake Franklin covered 1100 km^2 of the Ruby Valley of northeastern Nevada, making it one of the largest pluvial lakes between Lakes Bonneville and Lahontan. Mapping of shorelines, surveying of topographic profiles, and radiocarbon dating of gastropod shells were employed to reconstruct the latest Pleistocene history of the lake. During the first half of the Last Glacial Maximum (LGM), Lake Franklin covered ~42% of its maximum area. This extent increased to ~60% during the second half of the LGM. Some radiocarbon ages suggest that the lake briefly rose to near its highstand between 20 and 18 ka, but the best constrained rise occurred ca. 17 ka, when the lake rapidly transgressed to its highstand elevation of 1850 m. This rise was synchronous with highstands of nearby pluvial lakes, implicating a regional shift in the balance between precipitation and potential evaporation. The lake dropped to 1843 m, before rising once more to 1850 m ca. 16.0 ka. After falling and stabilizing at 1843 m again ca. 15.4 ka, the lake rapidly regressed to <1818 m (a loss in area of >70%) by 14.8 ka. This regression was synchronous with the fall of Lake Bonneville from the Provo shoreline and the regression of Lake Lahontan from the Sehoo shoreline. Radiocarbon ages and stratigraphic evidence document a final transgression in the latest Pleistocene that reached 1820 m (34% of maximum area) ca. 13.0 ka, synchronous with the Recess Peak Glaciation in the Sierra Nevada, and overlapping with the start of the Younger Dryas and minor transgressions of Lakes Bonneville, Lahontan, and Owens. The correspondence of this Lake Franklin history with other climate archives from this region underscores the value of pluvial lake deposits as sources of paleoclimate information and indicates synchronous forcing of climate changes during the last glacial-interglacial transition.

INTRODUCTION

The expansive area of internal drainage in the southwestern United States known as the Great Basin is characterized by a dramatic landscape of fault-block mountains and broad basins produced by extensional tectonics that began in the Oligocene (Stewart, 1998). Today, the Great Basin is one of the driest parts of the United States, but during glacial cycles of the Pleistocene, many of these basins contained pluvial lakes (Reheis, 1999a, 1999b). Given the topography of the region, most of these lakes were hydrologically closed. As a result, fluctuations of their water levels were driven largely by changes in the balance between precipitation and potential evaporation, known as effective moisture. Therefore, records of these lakes are important sources of terrestrial paleoclimate information (e.g., Benson et al., 2003).

The best-known and largest of these lakes, Bonneville in western Utah and Lahontan in western Nevada (Fig. 1), have been studied for more than a century. Grove Gilbert and Israel Russell were the first to reconstruct the extents of these former water bodies (Russell, 1885; Gilbert, 1890), and mapping and dating of shoreline landforms remain a common approach to studying pluvial lakes (e.g., Adams and Wesnousky, 1998; Kurth et al., 2011). Researchers seeking continuous records have also studied stable isotopes in sediment cores retrieved from areas formerly inundated by these lakes (e.g., Oviatt et al., 1999; Benson et al., 2003, 2011). Water-level fluctuations have been compared with other terrestrial and marine paleoclimate records to identify long-distance teleconnections and forcing mechanisms of climate change in the Great Basin (e.g., Oviatt, 1997; Benson et al., 1998, 2003). Additionally, attempts have been made to quantify pluvial climate conditions using general circulation models, as well as hydrologic models that simulate lake levels (e.g., Hostetler and Benson, 1990; Matsubara and Howard, 2009).

These studies have generated a wealth of information about the latest Pleistocene history of the largest pluvial lakes, but much less is known about the smaller lakes that were widespread and numerous in the Great Basin (Mifflin and Wheat, 1979). This situation represents a missed opportunity to clarify important details about the latest Pleistocene climate of this region because smaller lakes offer several advantages. For instance, lakes with smaller watersheds should have responded to climatic fluctuations with shorter lag times than the much larger Lakes Bonneville and Lahontan. The simpler hypsometry of small lake basins would have produced steadier changes of water level in response to a given shift in effective moisture, in contrast to larger lakes that occupied multiple subbasins as they filled to higher levels. Smaller lakes generally lacked inflowing rivers that delivered water from distant mountains where climatic conditions may have been notably different, making them sources of more spatially discrete climate records. Finally, smaller lakes are unlikely to have substantially altered the climate of their surrounding watersheds as Hostetler et al. (1994) demonstrated for Lake Bonneville.

Here, we examine the potential for a relatively small pluvial lake, Lake Franklin (Fig. 1), to contribute paleoclimate information relevant to the Great Basin. Lake Franklin was targeted

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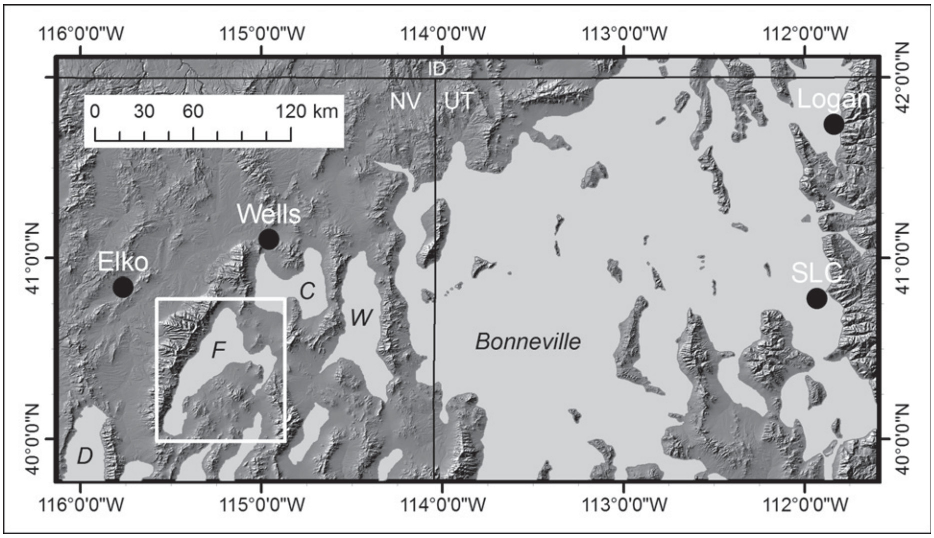

Figure 1. Location map of northeastern Nevada (NV) and northwestern Utah (UT) showing the outlines of Lakes Bonneville, Waring (W), Clover (C), Franklin (F), and Diamond (D). Outlines of other pluvial lakes are for reference only and are not discussed in the text. SLC—Salt Lake City, Utah. The white box delineates the area of Figure 2.

because it left behind a series of well-preserved and accessible beach ridges produced by wave action along the former lakeshore. Existing radiocarbon ages for some of these beach ridges (Lillquist, 1994) indicated that they contain material suitable for radiocarbon dating. Also, the close proximity of Lake Franklin to other pluvial lakes (Fig. 1) provides the opportunity to compare with other records.

Our methodology centered on documenting and dating beach ridges produced by wave action when Lake Franklin stood at different levels. This "shore-based" approach offers the advantage of working with landforms that directly record the former water level of the lake. It is, however, inevitably limited by the incomplete nature of the geomorphic record. Comprehensive application of sequence stratigraphy is also impractical for Lake Franklin due to a lack of natural exposures, which hampered our ability to identify a unique trajectory of water-level change in some time intervals. Nonetheless, careful documentation of the stratigraphy observed in hand excavations, and compilation of a large data set of radiocarbon ages support development of a hydrographic history of Lake Franklin that is sufficiently robust to permit comparison with other records.

SETTING AND PREVIOUS WORK

Lake Franklin inundated ~1100 km^2 of the Ruby Valley in northeastern Nevada with water up to 36 m deep. A shallower (<10 m) arm of the lake extended eastward into North Butte Valley (Fig. 2). Today, the floor of Ruby Valley is flat to very gently sloping, with a minimum elevation of ~1813 m. The valley is bordered to the east by the unglaciated Medicine and Maverick Springs Ranges, which have summit elevations of ~2500 m. In contrast, the Ruby Mountains, rising abruptly to maximum elevations >3400 m along the western side of the valley, exhibit spectacular alpine glacial geomorphology along much of their 130-km-long extent (Osborn and Bevis, 2001; Munroe and Laabs, 2011).

Most streams in the Lake Franklin watershed are ephemeral. The largest fluvial system is the Franklin River, which historically carried water from the northern Ruby Valley to a playa that hosts Franklin Lake (Fig. 2). Upstream diversions now deplete flow so that water is generally only present during spring snowmelt. A contrasting hydrologic setting is found on the floor of the southern Ruby Valley (Fig. 2), where ~200 springs discharge groundwater to a 55 km^2 perennial wetland known as the Ruby Marshes (Thompson, 1992).

The latest Pleistocene history of Lake Franklin has received only limited attention prior to this study. Well-preserved shoreline features recording the former presence of a lake in the Ruby Valley were noted by geologists in the nineteenth century, but they were erroneously considered evidence of a much larger regional lake (Simpson, 1876). Later expeditions realized that these shorelines reflected a lake confined to the Ruby Valley (Russell, 1885; Gilbert, 1890), which was named Lake Franklin (Sharp, 1938).

Despite this early recognition, only two prior studies have considered the history of Lake Franklin in detail. Thompson (1992) studied sediment cores from the Ruby Marshes and used the relative abundance of aquatic palynomorphs sensitive to salinity as an indicator of paleo–water depth. *Pediastrum*, in particular, became more abundant between 18,500 and 15,400 ^{14}C yr B.P., indicating more dilute water. Lillquist (1994) identified shoreline features around the Lake Franklin basin and assigned ages to beach ridges using radiocarbon dating of gastropod shells. The resulting data set suggests that Lake Franklin was at its latest Pleistocene highstand between 16,800 ± 130 and 15,070 ± 100 ^{14}C yr B.P., overlapping with the interval inferred by Thompson (1992).

These prior studies are significant because they broadly constrain the timing of the Lake Franklin highstand. However, the methods used by Thompson (1992) to infer water depth are indirect and equivocal, and the age models he developed are imprecise owing to a scarcity of material suitable for radiocarbon dating. Similarly, the lake history proposed by Lillquist (1994) is compromised by reliance on a small number of dates from uncertain stratigraphic contexts. Thus, while these studies are a valuable starting point, these limitations hinder the comparison of Lake Franklin with records of climatic changes during the last glacial-interglacial transition elsewhere in the Great Basin. The work presented here facilitates these comparisons by increasing the number of radiocarbon ages for shoreline deposits from known stratigraphic contexts, thereby establishing more precise age limits on past water-level changes of Lake Franklin.

METHODS

Field Mapping and Geographic Information System (GIS) Analysis

The most common depositional shoreline landforms constructed by Lake Franklin are linear concentrations of wave-worked sediment known as beach ridges. These ridges, which stand 1–3 m tall by 50–100 m wide, and which are continuous for (in some cases) many kilometers, were identified in the field, on U.S. Geological Survey (USGS) 1:24,000 scale topographic maps, and on aerial imagery. Maps of Ruby Valley have primary contour intervals of 40 ft (or less), with numerous intermediate contours, aiding the identification and tracing of these ridges. Soil moisture and vegetation contrasts between ridges and the linear basins filled with fine sediment on their upslope sides (known as playettes) further

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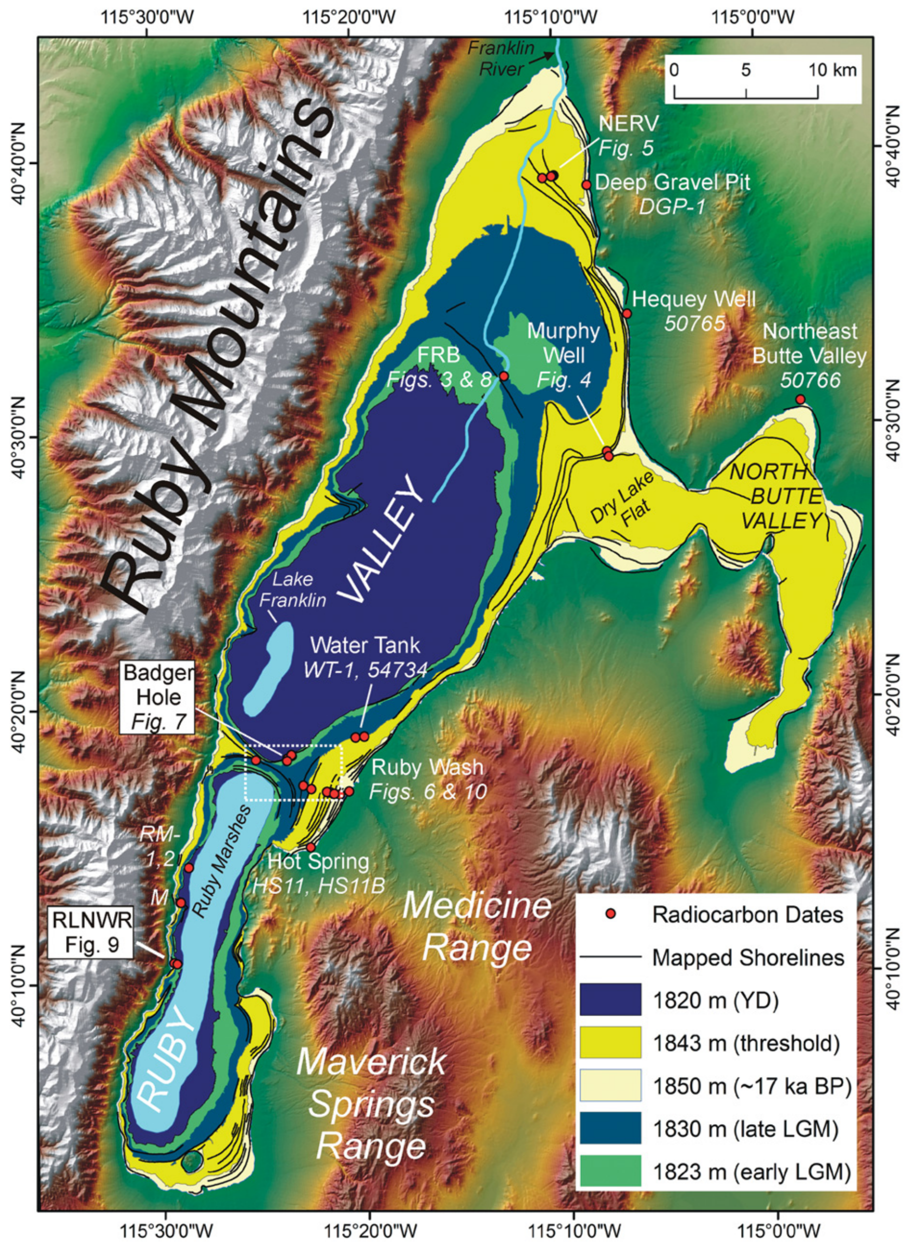

Figure 2. Detailed map of Lake Franklin, which filled the Ruby Valley and part of the North Butte Valley east of the Ruby Mountains. Solid black lines indicate mapped beach ridges and other shoreline landforms of Lake Franklin. Dots mark locations of radiocarbon-dated samples. Labels identify localities of detailed study (referenced to other figures), or specific radiocarbon dates listed in Tables 3 and 4. The dashed box delineates the area of Figure 6. Outlines show reconstructions of Lake Franklin during several key intervals of the last pluvial cycle. YD—Younger Dryas; LGM—Last Glacial Maximum; NERV—Northeast Ruby Valley; FRB—Franklin River Bridge; RLNWR—Ruby Lake National Wildlife Refuge Quarry.

enhance the visibility of ridges in aerial imagery and on the ground.

Identified beach ridges were digitized in ArcGIS 9.3 and combined with raster analysis of a 10 m digital elevation model to generate outlines of Lake Franklin at elevations corresponding to major shorelines. We assumed that a constant shoreline elevation represents a single paleo–lake level. Although differential isostatic uplift has reportedly altered the elevations of Lake Franklin shorelines, total uplift was minimal (<3 m) and was greatest in the northeastern part of the North Butte Valley (Lillquist, 1994), ~30 km away from the study sites for this project.

Study Sites

Field investigations were conducted throughout the parts of the Ruby and North Butte Valleys inundated by Lake Franklin. Extensive field reconnaissance identified eight locations offering a combination of well-preserved beach ridges, relative ease of access, and (in some cases) preexisting exposure (Fig. 2). These sites are introduced alphabetically next, with additional details presented in Table 1. (Note: all site names are informal.)

Badger Hole (BH)

The BH site is located in central Ruby Valley where a stream cut in Ruby Wash breaches a beach ridge at 1820 m (Fig. 2). Two trenches were excavated by hand into the north side of the stream cut. This site was not documented in previous studies.

Deep Gravel Pit (DGP)

The DGP site is located at the northern end of Ruby Valley (Fig. 2) where gravel was removed from a beach ridge for use in road construction. The area surrounding the excavation has been extensively disturbed, making it difficult to determine the elevation of the shoreline, but it is ~1850 m. In 2011, a small exposure at the north end of this excavation provided access to undisturbed sediment. This site was not previously dated.

Franklin River Bridge (FRB)

At the FRB site in north-central Ruby Valley, an abandoned gravel pit on the east side of the Franklin River provided exposure of a broad beach ridge with a crest elevation of ~1823 m (Figs. 2 and 3). Lillquist (1994) presented three radiocarbon ages for lacustrine sediment at this site, and this study produced two more.

Hot Spring (HS)

The HS site is located 4.5 km south of the RW site where the 1850 m beach ridge crosses a fan built by an unnamed stream draining from the Maverick Springs Range (Fig. 2). No natural exposure is present at this location, so hand excavation was required to characterize sediment forming this ridge. This site was not documented in previous studies.

Murphy Well (MW)

The MW site in the northeastern sector of Ruby Valley (Fig. 2) features a small borrow pit excavated in a beach ridge representing the 1843 m shoreline. Parallel ridges representing

TABLE 1. STUDY SITES IN THE RUBY VALLEY

Site ID	Site name	Latitude/longitude (°N/°W)	Type	No. of new ^{14}C dates	No. of previous ^{14}C dates*	Shoreline elevations (m)	Figures
BH	Badger Hole	40.30199/115.39496	Hand excavations	2	0	1820	2, 7
DGP	Deep Gravel Pit	40.64760/115.13941	Gravel pit	1	0	1850	2
FRB	Franklin River Bridge	40.52998/115.21055	Gravel pit	2	3	1823	2, 3, 8
HS	Hot Spring	40.24775/115.37717	Hand excavations	2	0	1850	2
HW	Hequey Well	40.56827/115.10890	Augered lagoon	0	1	1850	2
MW	Murphy Well	40.48303/115.12694	Gravel pit	2	1	1846, 1843, 1840	2, 4
NBV	North Butte Valley	40.51372/114.96786	Augered lagoon	0	1	1850	2
NERV	Northeast Ruby Valley	40.65273/115.16922	Road cut	6	0	1843, 1840	2, 5
RLNWR	Ruby Lake National Wildlife Refuge	40.17629/115.48714	Gravel pit	5	5	1830	2, 9
RM	Ruby Marsh	40.21547/115.48364	Streambed	3	0	–	2
RW	Ruby Wash	40.28133/115.36299	Hand excavations	12†	7	1850, 1846, 1843, 1840, 1836, 1830, 1826, 1820, 1818	2, 6, 10
WT	Water Tank	40.31460/115.33160	Augered lagoon	1	1	1830	2

*From Lillquist (1994).
†One sample (RW-4b) collected by augering.

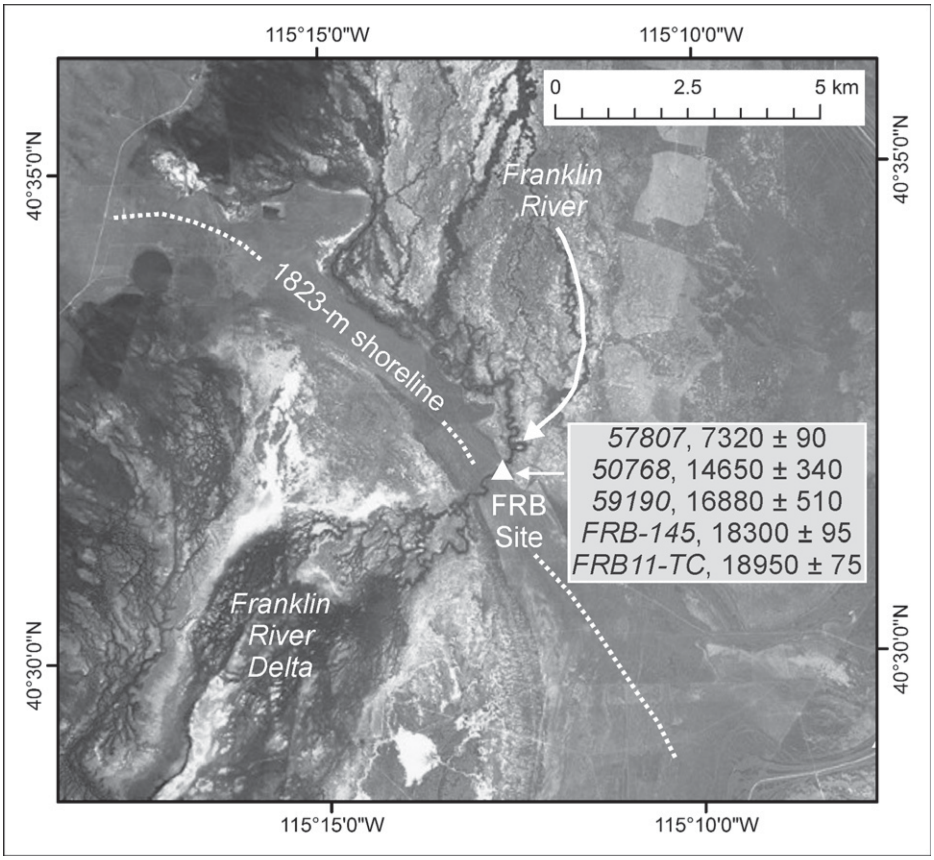

Figure 3. Satellite image showing the massive shoreline at 1823 m that arcs across the northern Ruby Valley, highlighted by a dotted white line that traces the ridge crest. The Franklin River Bridge (FRB) site is located in a borrow pit just east of where the modern Franklin River breaches this ridge en route to its delta at the north end of the Franklin Lake playa. In total, five radiocarbon dates are available for this site. Ages are presented in ^{14}C yr B.P.

the 1846 and 1840 m shorelines are also present (Fig. 4). Hand excavation was required to reach undisturbed sediment in the southeast wall of this pit, which yielded two radiocarbon ages. Lillquist (1994) reported a single radiocarbon age from this site, although we were unable to relocate this excavation.

Northeast Ruby Valley (NERV)

The NERV site at the extreme northern end of Ruby Valley includes beach ridges representing the 1843 m and 1840 m shorelines of Lake Franklin (Figs. 2 and 5). Hand excavation in slumped road cuts along Highway 229 exposed undisturbed sediment that yielded four radiocarbon ages from the 1843 m shoreline, and two more from the 1840 m shoreline.

Ruby Lake National Wildlife Refuge Quarry (RLNWR)

The RLNWR site is located along the southwestern side of Ruby Valley where an active borrow pit provides exposure into a spit at 1830 m (Fig. 2). Lillquist (1994) reported five radiocarbon ages of lacustrine sediment at this location, and this study generated five more.

Ruby Wash (RW)

The RW site in southeastern Ruby Valley features a series of beach ridges arcing across a large fan built by Ruby Wash (Fig. 2). Ten beach ridges are preserved from the highstand at 1850 m down to 1818 m, some with associated playettes (Fig. 6). Lillquist (1994) excavated pits in the crests of many of these beach ridges and presented radiocarbon ages for six of them. This study relocated and enlarged these pits, and made new excavations into the crests of previously unstudied beach ridges, which yielded 12 more radiocarbon ages.

Lillquist (1994) also reported radiocarbon ages on gastropod shells from lagoonal deposits behind beach ridges at three additional locations: the Hequey Well (HW) site behind the 1850 m beach ridge in east-central Ruby Valley, in the northeast Butte Valley (NBV) behind

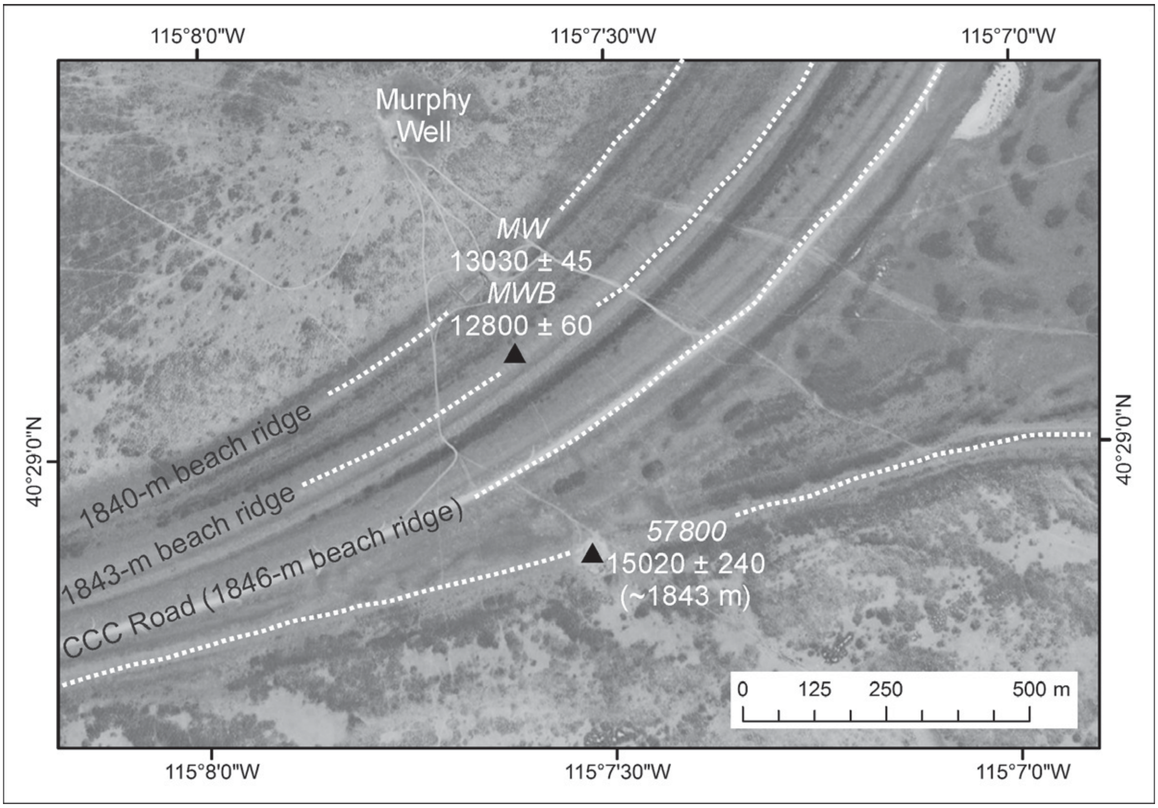

Figure 4. Aerial photo showing sample sites and shorelines in the vicinity of Murphy Well. Shoreline crests are highlighted by dotted white lines. The main road on the east side of the Ruby Valley (CCC Road) travels along the crest of the 1846 m beach ridge. Samples MW and MWB were obtained from a small borrow pit on the 1843 m beach ridge. Sample 57800 of Lillquist (1994) likely came from a pit on the opposite side of the road. Ages are presented in ^{14}C yr B.P.

the 1850 m beach ridge, and at the Water Tank (WT) site behind the 1830 m beach ridge in central Ruby Valley (Fig. 2).

Surveying

Surveying was conducted with a laser total station in the vicinity of existing USGS benchmarks. Surveying at RLNWR and MW was employed to determine the elevation of beach ridges in which samples were collected for ^{14}C dating. Long topographic profiles were also measured to capitalize on the large number of beach ridges preserved at the RW (5 km) and NERV (1 km) sites. Measurements were made at intervals ranging from <10 m when passing over ridge crests, to ~50 m when crossing playettes.

Sampling

Given the low relief of the Ruby Valley floor, and the general lack of flowing streams, natural exposures of sediments comprising beach ridges are almost nonexistent. Extensive reconnaissance revealed a small number of preexisting exposures, but in most cases, hand excavation was necessary to investigate the sedimentology and stratigraphy of beach ridges, and to obtain gastropod shells suitable for radiocarbon dating. Preliminary examination of the stratigraphy of beach ridges documented a ubiquitous layer of fine silt, 20–50 cm thick, overlying coarse sandy gravel throughout the study area. Fossil shells were absent from the silt, and sparsely present in the sandy gravel, but never at depths shallower than ~75 cm. Large (1 m^3) pits were, therefore, excavated in the crests of beach ridges to reach fossiliferous material. At the RW site, seven preexisting pits, presumably representing the field work of Lillquist (1994), were exploited and enlarged laterally into undisturbed material. Three entirely new pits were excavated on other beach ridges at the RW site, with a fourth at the HS site. In borrow pits (i.e., DGP, FRB, MW, RLNWR), and other exposures (BH, NERV), slumped material was excavated by hand until undisturbed sediment was encountered. At all sites, shells were collected by passing shovelfuls of sediment through a 1-mm-mesh screen in the field. The sedimentology and stratigraphy exposed in each excavation were also documented as a context for interpreting the ^{14}C dates.

Radiocarbon Dating

Gastropod shells were prepared for radiocarbon dating following a consistent set of procedures. Shells were soaked and lightly sonified in distilled water to loosen coatings of secondary carbonate and remove any sediment packed internally. Light scraping with a needle was necessary for more recalcitrant coatings. Shells were dried and weighed before submission to the National Ocean Sciences Accelerator Mass Spectrometry facility (NOSAMS) where acid-alkali-acid leaching was conducted prior to analysis. Because the shells were small, most samples consisted of multiple shells collected from a discrete sedimentary layer. In some cases, however, single shells were large enough to provide sufficient carbon for a radiocarbon date without combination.

The new radiocarbon results for this study were combined with those reported by Lillquist (1994) to yield an integrated set of ^{14}C ages for

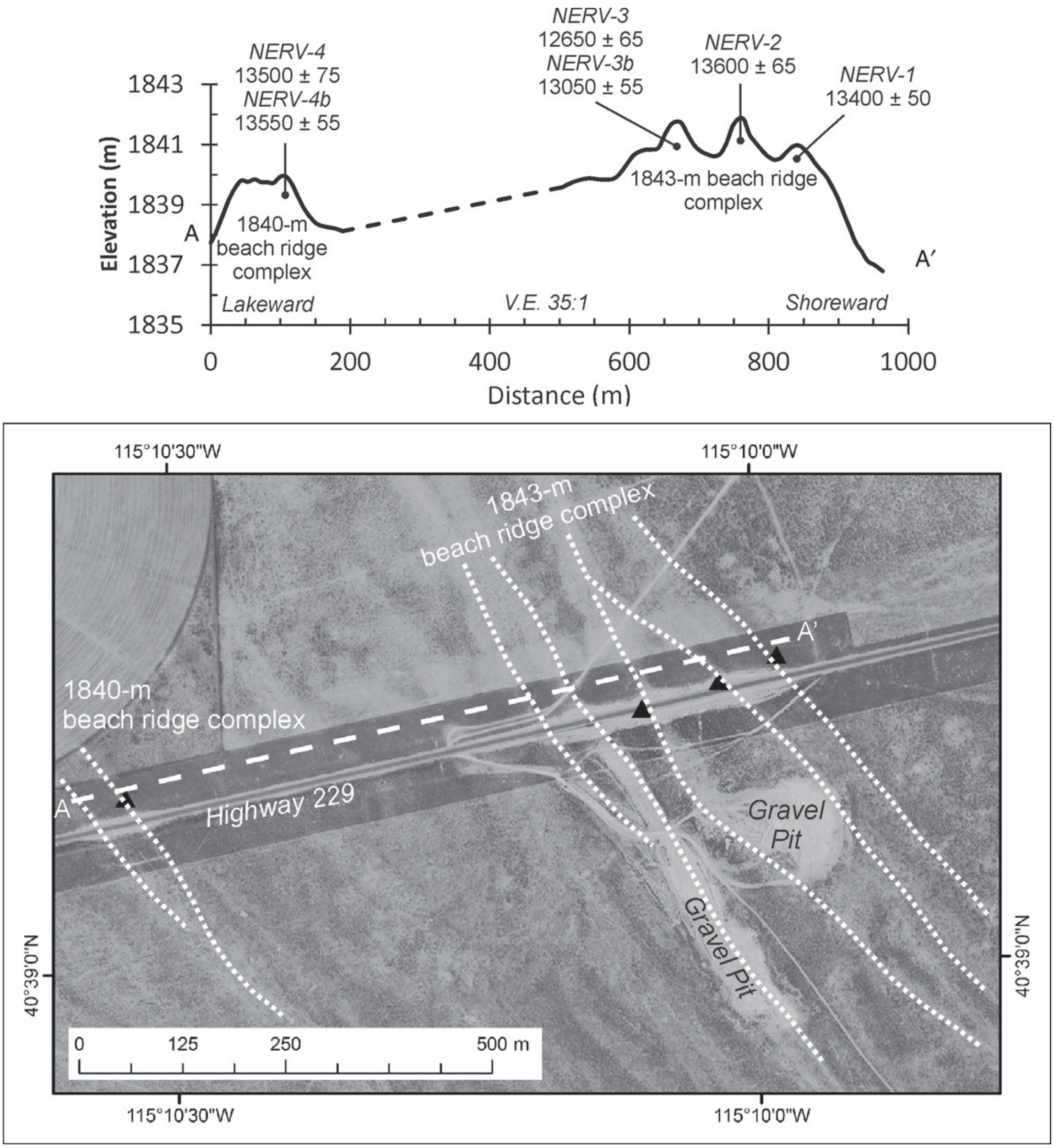

Figure 5. Lower panel shows sample sites (triangles) and beach ridges at the Northeast Ruby Valley site over an aerial photo base. White dotted lines denote crests of beach ridges. The upper panel shows a topographic survey across the 1843 m and 1840 m beach ridge complexes from A to A′. Dashed survey line represents a gently sloping section devoid of beach ridges where no data were collected. The 1843 m beach ridge complex has three distinct crests; samples NERV-1 and NERV-2 from the outer two are similar in age, while the inner crest (samples NERV-3 and NERV-3b) is significantly younger. The outer crest of the 1840 m complex (NERV-4 and NERV-4b) yielded ages similar to the outer crests of the 1843 m feature. Ages are presented in ^{14}C yr B.P. V.E. is vertical exaggeration.

Lake Franklin shorelines. All of these ages were calibrated into calendar yr B.P. using the program Calib 6.0 (Stuiver and Reimer, 1993; Reimer et al., 2009).

To evaluate the possibility that a radiocarbon reservoir effect has skewed the apparent ages of the gastropod shells (e.g., Lin et al., 1998), two shells and a live snail recovered from springs in the Ruby Marshes were submitted for radiocarbon dating. The modern spring water has an unknown residence time in bedrock aquifers and is not a perfect analog for the water that filled the Pleistocene lake. However, in the absence of a preferred alternative, this approach was employed to provide an upper limit on the potential magnitude of such an effect.

Hydrograph Construction

A history of latest Pleistocene fluctuations of Lake Franklin was produced by considering (1) the calibration range of each radiocarbon age, (2) the facies from which the dated shells were obtained, (3) the stratigraphic position of the sample relative to other radiocarbon ages,

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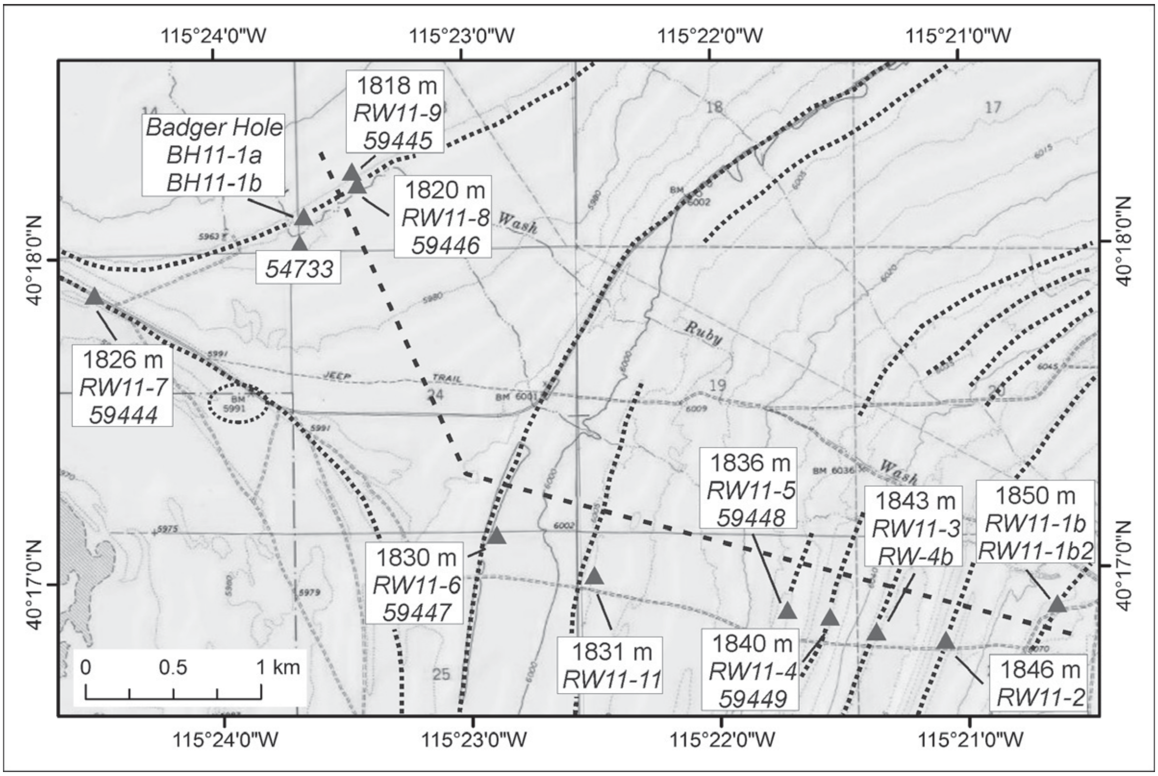

Figure 6. Detail map of the Ruby Wash and Badger Hole localities from the 1:24,000 scale U.S. Geological Survey (USGS) Franklin Lake SE quadrangle showing the locations of ^{14}C dates (triangles). Dashed black line marks the topographic survey shown in Figure 12. Dotted black lines denote beach ridge crests. Dashed oval highlights the USGS benchmark to which the survey was tied.

and (4) the elevation of the sample. By plotting the median value of the calibration range for each radiocarbon age (using the range with the highest probability for ages with multiple ranges) against elevation, and using straight line segments to connect ages obtained directly from sediment comprising beach ridges, we generated an initial overview of water-level changes through time. Ages of sediments representing lagoonal and nearshore environments were considered with reference to the ages of beach ridge sediments to clarify the sequence of shorelines in cases of overlapping calibration ranges. Elevations of ridges with strongly overlapping calibration ranges were also considered using the logic that prominent, sharp-crested ridges were likely produced during regression, whereas broad, subdued ridges may have been submerged by a later transgression. After incorporating this additional information, plotted ages were adjusted, if necessary, within their most probable calibration range to smooth out higher-frequency fluctuations suggested by the midpoints of the radiocarbon calibration ranges alone, while retaining water-level changes supported by both chronology and stratigraphy. This approach may have eliminated actual, rapid, water-level fluctuations in the interest of simplicity. However, because the calibration ranges of some of these ages are >1000 yr, small adjustments (on the order of a century) that reduced the apparent number of reversals in the hydrograph were considered preferable to a more complicated water-level history for which stratigraphic data were equivocal or not available.

RESULTS

The results of this study include reconstructions of Lake Franklin at different stages during the latest Pleistocene, over 6 km of topographic surveying across sequences of beach ridges, and 36 new ^{14}C ages that support construction of a hydrograph of water-level fluctuations during the last pluvial cycle. All but two of these ages were obtained on gastropod shells collected from preexisting or hand-excavated exposures that provided clear stratigraphic context. In this section, the dimensions of Lake Franklin are presented for several water-level elevations (Table 2), along with the sedimentology and stratigraphy of the consistent facies encountered throughout the study area. New radiocarbon ages from each study site are also reported (Table 3), along with preexisting dates from Lillquist (1994) (Table 4; note: all ages from this previous study are distinguished by five-digit sample numbers beginning with “5” or “2”). When first introduced in the text, all ages are presented in radiocarbon yr B.P. with associated uncertainty, along with the most probable calibrated age in ka. This approach is utilized in the interest of clarity and brevity, and it is not intended to overstate the precision of the calibrated ages. Full calibration ranges for all dates are presented in Tables 3 and 4, with the most probable range highlighted in bold.

Lake Franklin Reconstructions

Well-preserved beach ridges around Ruby Valley permit reconstruction of the dimensions of Lake Franklin at various elevations (Fig. 2; Table 2). The highest preserved beach ridge is at an elevation of ~1850 m, as noted by previous studies (Mifflin and Wheat, 1979; Lillquist, 1994). Mapping identified 10 consistent beach ridges representing shorelines of Lake Franklin below the highstand ridge (Table 2). On average, these ridges are separated by ~3 m vertically and correspond to changes in lake area

TABLE 2. DIMENSIONS OF LAKE FRANKLIN AT DIFFERENT WATER LEVELS

Shoreline elevation (m)	Area (km^2)	% of maximum	Maximum depth (m)
1850	1100	100	36
1846	1051	96	32
1843	1000	91	29
1840	811	74	26
1836	763	69	22
1831	674	61	17
1830	655	60	16
1826	568	52	12
1823	467	42	9
1820	377	34	6
1818	332	30	4

of 20–200 km^2. In some cases, these ridges are more prominent than the 1850 m ridge, either because they are larger (broader, or with greater relief), or because the depressions on their upslope sides have not been filled as extensively with slopewash and lagoonal sediment. A major beach ridge is present at 1846 m in the RW locality, and upslope from the dated site at MW. The next lower ridge, at 1843 m, commonly exhibits multiple crests near this elevation and is strongly developed throughout the study area. Beach ridges at 1840 m are similar in relief to the ridges at 1843 m, but are typically narrower. Beach ridges at 1836 and 1831 m are more subdued, with playettes on their upslope sides. A more prominent beach ridge at the lower end of the RW transect, and the large spit at RLNWR are part of the 1830 m shoreline. The shoreline at 1826 m is represented by a massive ridge that separates the modern Franklin Lake playa from the Ruby Marshes. Evidence of the 1823 m shoreline is confined to the FRB site, where a broad ridge arcs across the northern Ruby Valley and is breached by the Franklin River. The lowest two beach ridges, at 1820 and 1818 m, record the final shoreline-producing phase of Lake Franklin (Table 2).

Sedimentology and Stratigraphy

Excavations reveal that beach ridges are mantled by a ubiquitous layer of fine silt containing sparse granules and gravel clasts (<5% by volume). These larger fragments float within the silt matrix and are randomly arranged. Roots are generally restricted to this silt layer, the top of which exhibits a vesicular texture (Av horizon). Soil development within this silt layer is limited to modest color changes induced by oxidization and organic matter additions near the surface. The magnitude of these effects diminishes downward to a visually determined base of weathering at a depth of ~50 cm.

Hand excavations and preexisting exposures reveal that beneath the surficial silt layer, Lake Franklin beach ridges are consistently composed of sandy gravel arranged in beds from 5 to 50 cm thick. Clasts of all sizes are well rounded, and beds locally exhibit an open-work texture. Pockets of well-sorted coarse sand are also present within some sandy gravel layers. Shells are most abundant in these finer pockets.

Some deep excavations (>1 m) along the RW transect penetrated through the sandy gravel into a loose, well-sorted, coarse sand. At several sites, this unit was abundantly fossiliferous, and gravel was nonexistent. Fine bedding, including cross-stratification, was observed in some exposures of this unit.

Playettes on the upslope sides of beach ridges are underlain by massive, fine silt with infrequent granules and small gravel clasts. Similar coarse fragments are present on the back slopes of beach ridges, and stringers of coarser material are visible extending from these back slopes onto playette surfaces. Transects of auger holes reveal that the massive, fine silt forms a wedge that onlaps the coarser beach ridge sediment, reaching thicknesses in excess in 2 m near the playette center.

Study Sites

Badger Hole (BH)

Both trenches excavated at the BH site exposed ~40 cm of coarse sand with well-rounded pebbles (Fig. 7). Sample BH11–1a, collected from near the base of this sandy gravel yielded an age of 11,550 ± 50 ^{14}C yr B.P. (13.4 ka). The sand unconformably overlies an indurated silty marl ~50 cm thick. The upper ~10 cm section of the marl is weathered pinkish-red, and staining descends along fractures for another 10 cm. Beneath the marl, there is a reduced (greenish) clayey sand at least 40 cm thick. Sample BH11–1b, collected from the clayey sand, returned an age of 14,050 ± 75 ^{14}C yr B.P. (17.1 ka).

Deep Gravel Pit (DGP)

In 2011, the DGP site exposed ~2 m of well-sorted, sandy gravel. The degree of carbonate cementation in these deposits is notably greater than in other localities within the study area (Lillquist, 1994). A gastropod shell (DGP-1) collected from 30 cm below the top of this sandy gravel yielded an age of 42,300 ± 480 ^{14}C yr B.P. (45.6 ka).

Franklin River Bridge (FRB)

Excavation into the east wall of the borrow pit at FRB exposed 250 cm of sediment divisible into three main units (Fig. 8). This deposit is primarily composed of finely bedded, sandy gravel that extends from the surface to a depth of 225 cm, with a cemented layer of fine sand from 167 to 171 cm. Gastropods (FRB11-TC) from a depth of 200 cm returned an age of 18,950 ± 75 ^{14}C yr B.P. (22.5 ka), while shells from ~50 cm higher (FRB-145) yielded an age of 18,300 ± 95 ^{14}C yr B.P. (21.9 ka). Lillquist (1994) reported an age (59190) of 16,800 ± 510 ^{14}C yr B.P. (20.1 ka) from near the top of this section, as well as an age (50768) of 14,650 ± 340 ^{14}C yr B.P. (17.8 ka) from the same depth as sample FRB11-TC (200 cm).

The sandy gravel unconformably overlies clayey silt with sand interbeds at 225 cm (Fig. 8). Below 250 cm, the sediment is coarser clayey sand with sparse pebbles. A sample (57807) of marly concretions from the clayey sand yielded an age of 7320 ± 90 ^{14}C yr B.P. (8.1 ka).

Hot Spring (HS)

A hand excavation on the crest of the highstand beach ridge at the HS site revealed several decimeters of fine sandy silt overlying an abundantly fossiliferous medium- to coarse-grained pebbly sand. Gravel was less abundant in this beach ridge due to its position on the distal slope of a sandy alluvial fan. Two fossil gastropods (both Lymnaeids) were collected from a depth of 100 cm. Sample HS11 returned an age of 13,150 ± 55 ^{14}C yr B.P. (16.0 ka), and sample HS11b returned an age of 13,250 ± 55 ^{14}C yr B.P. (16.2 ka).

Murphy Well (MW)

Surveying tied to a USGS benchmark revealed that the beach ridge at the MW site has a crest elevation of 1842.1 m, making it correlative to the 1843 m shoreline at RW (Fig. 4). Hand excavation to remove slumped material from the eastern wall of the borrow pit in this ridge exposed 240 cm of undisturbed, bedded sediment. The upper 60 cm section is composed of sandy gravel dominated by rounded granules and sparse pebbles. This unit grades downward into a well-sorted, open-work gravel with carbonate coatings that extends to 100 cm. From 100 to 150 cm, the sediment is an upward-coarsening sandy gravel. The lowest unit from 150 to 240 cm features open-work fine gravel at the top, and it fines downward to sandy gravel. Carbonate coatings were absent below 150 cm.

TABLE 3. NEW RADIOCARBON AGES FOR LAKE FRANKLIN

Sample ID	Lab code	Site*	Latitude/longitude (°N/°W)	Elev. (m) map (*surveyed*)	Facies†	Method§	Material	^{14}C age (yr B.P. ± error)	δ^{13}C (‰)	Calibration (yr B.P.)	Median prob. (ka)
BH11-1b	OS-90088	BH	40.30199/115.39496	1820	N	Sn	*Pisidium* or *Sphaerium* spp.	14,050 ± 75	–1.86	**16,852–17,458 (1.000)**	17,096
BH11-1a	OS-89974	BH	40.30199/115.39496	1820 (*1820.5*)	B	Sn	Lymnaeid and *Pisidium*	11,550 ± 50	–4.68	**13,267–13,537 (0.993)**	13,387
										13,546–13,556 (0.007)	
DGP-1	OS-82632	DGP	40.64760/115.13941	1850	B	Sgp	Lymnaeid	42,300 ± 480	1.84	**44,797–46,342 (1.000)**	45,557
FRB11-TC	OS-89975	FRB	40.52998/115.21055	1823	B	Sg	Lymnaeid	18,950 ± 75	–1.51	**22,275–22,979 (0.937)**	22,544
										23,121–23,246 (0.063)	
FRB-145	OS-82638	FRB	40.52998/115.21055	1823	B	Sgp	Lymnaeid, *Pisidium, Gyraulus*	18,300 ± 95	–0.51	**21,491–22,215 (1.000)**	21,846
HS11b	OS-92041	HS	40.24775/115.37717	1850	B	Sh	Lymnaeid	13,250 ± 55	–8.73	**15,530–16,709 (1.000)**	16,231
HS11	OS-89976	HS	40.24775/115.37717	1850	B	Sh	Lymnaeid	13,150 ± 55	–7.65	**15,282–16,528 (1.000)**	15,992
MW	OS-90074	MW	40.48303/115.12694	1843 (*1842.1*)	B	Sgp	Lymnaeid, *Pisidium, Gyraulus*	13,050 ± 45	2.52	**15,188–16,373 (1.000)**	15,749
MWB	OS-92037	MW	40.48303/115.12694	1843 (*1842.1*)	B	Sgp	Lymnaeid, *Pisidium, Gyraulus*	12,800 ± 60	0.65	**14,895–15,669 (0.985)**	15,216
										15,751–15,840 (0.015)	
NERV-2	OS-90076	NERV	40.65301/115.16811	1843 (*1841.9*)	B	Sr	Lymnaeid, *Pisidium, Gyraulus*	13,600 ± 65	3.13	**16,520–16,954 (1.000)**	16,759
NERV-4b	OS-92058	NERV	40.65189/115.17561	1840 (*1839.9*)	B	Sr	Lymnaeid	13,550 ± 55	0.65	**16,469–16,913 (1.000)**	16,723
NERV-4	OS-90236	NERV	40.65189/115.17561	1840 (*1839.9*)	B	Sr	Lymnaeid	13,500 ± 75	0.00	**16,332–16,911 (1.000)**	16,672
NERV-1	OS-90075	NERV	40.65328/115.16727	1843 (*1840.9*)	B	Sr	Lymnaeid	13,400 ± 50	1.12	**16,067–16,859 (1.000)**	16,574
NERV-3b	OS-92024	NERV	40.65273/115.16922	1843 (*1841.8*)	B	Sr	Lymnaeid, *Pisidium, Vorticifex*	13,050 ± 55	0.35	**15,185–16,383 (1.000)**	15,753
NERV-3	OS-90077	NERV	40.65273/115.16922	1843 (*1841.8*)	B	Sr	*Stagnicola, Pisidium, Vorticifex*	12,650 ± 65	–0.92	14,278–14,304 (0.004)	14,961
										14,516–15,249 (0.979)	
										15,355–15,457 (0.017)	
RLNWR-L	OS-82633	RLNWR	40.17629/115.48714	1830 (*1829*)	B	Sgp	*Pisidium* and *Gyraulus*	16,750 ± 70	–3.14	19,573–19,738 (0.269)	19,910
										19,746–20,204 (0.731)	
RLWR-5	OS-90239	RLNWR	40.17877/115.49056	1830 (*1831.8*)	B	Sgp	Lymnaeid, *Pisidium, Gyraulus*	15,800 ± 60	–0.39	**18,753–19,313 (1.000)**	18,957
RLNWR-U	OS-82642	RLNWR	40.17877/115.49056	1830 (*1830*)	B	Sgp	*Pisidium* and *Gyraulus*	15,750 ± 140	–3.11	**18,651–19,345 (1.000)**	18,924
RLWR-4	OS-90238	RLNWR	40.17877/115.49056	1830 (*1831.8*)	B	Sgp	*Vorticifex*	14,450 ± 50	–0.09	**17,220–17,877 (1.000)**	17,588
RLWR-3	OS-90237	RLNWR	40.17877/115.49056	1830 (*1831.8*)	B	Sgp	Lymnaeid	14,250 ± 75	–1.46	**16,987–17,659 (1.000)**	17,334
RM-2	OS-90138	RM	40.21547/115.48364	1825	S	Cs	*Stagnicola* spp. or *Lymnaea* spp.	3220 ± 25	–8.96	**3380–3478 (1.000)**	3430
RM-1	OS-90240	RM	40.21547/115.48364	1825	S	Cs	*Stagnicola* spp. or *Lymnaea* spp.	2180 ± 30	–9.81	**2116–2314 (1.000)**	2237
Modern	Beta-311494	RM	40.21080/115.47507	1819	S	Cl	*Pyrgulopsis*	770 ± 30	–8.00	**669–733 (1.000)**	698
RW11-1b2	OS-92025	RW	40.28141/115.34487	1850 (*1848.7*)	L	Sn	Lymnaeid	19,000 ± 70	0.20	**22,317–22,997 (0.909)**	22,601
										23,104–23,263 (0.091)	
RW11-1b	OS-90241	RW	40.28141/115.34487	1850 (*1848.7*)	B	Sh	Lymnaeid	13,600 ± 45	1.72	**16,558–16,944 (1.000)**	16,764
RW-4b	OS-82634	RW	40.28026/115.35602	1843 (*1842.2*)	N	Sa	Lymnaeid	13,400 ± 75	2.48	**15,946–16,858 (1.000)**	16,554
RW11-2	OS-90242	RW	40.27964/115.35239	1846 (*1844.7*)	B	Sh	Lymnaeid, *Pisidium, Gyraulus*	13,350 ± 75	1.23	15,638–15,745 (0.021)	16,467
										15,864–16,841 (0.979)	
RW11-3	OS-90243	RW	40.28023/115.35617	1843 (*1842.2*)	B	Sh	Lymnaeid, *Pisidium, Gyraulus*	13,100 ± 75	–4.64	**15,213–16,468 (1.000)**	15,871
RW11-4	OS-90313	RW	40.28094/115.36014	1840 (*1839.6*)	N	Sh	Lymnaeid, *Pisidium, Gyraulus*	13,100 ± 60	1.59	**15,224–16,452 (1.000)**	15,870
RW11-5	OS-90314	RW	40.28133/115.36299	1836 (*1835.8*)	N	Sh	Lymnaeid, *Pisidium, Gyraulus*	13,050 ± 50	1.22	**15,187–16,378 (1.000)**	15,751
RW11-6	OS-90315	RW	40.28544/115.38239	1830 (*1828.2*)	B	Sh	Lymnaeid, *Pisidium, Gyraulus*	12,950 ± 75	–0.06	**15,070–16,251 (1.000)**	15,521
RW11-11	OS-90319	RW	40.28328/115.37589	1831 (*1829.9*)	N	Sh	Lymnaeid, *Pisidium, Gyraulus*	12,700 ± 45	0.55	**14,667–15,257 (0.94)**	15,054
										15,330–15,492 (0.06)	
RW11-7	OS-90316	RW	40.29812/115.40910	1826	B	Sh	Lymnaeid, *Pisidium, Gyraulus*	12,450 ± 65	1.60	**14,146–15,015 (1.000)**	14,551
RW11-9	OS-90318	RW	40.30424/115.39167	1818.5 (*1819*)	B	Sh	*Fossaria* spp. and family Hydrobiidae	12,100 ± 50	–4.23	**13,796–14,110 (1.000)**	13,944
RW11-8	OS-90317	RW	40.30356/115.39134	1820 (*1820.5*)	B	Sh	Lymnaeid	10,950 ± 50	–7.72	**12,646–12,974 (0.981)**	12,813
										13,025–13,056 (0.019)	
WT-1	OS-82637	WT	40.31415/115.33883	1830	L	Sa	Lymnaeid, *Pisidium, Gyraulus*	12,700 ± 55	–2.73	**14,640–15,261 (0.931)**	15,051
										15,322–15,501 (0.069)	

*Keyed to Table 1.

†B—beach; N—nearshore; L—lagoon; S—spring.

§Sgp—sieved from gravel pit exposure; Sn—sieved from natural exposure; Sh—sieved from hand excavation; Sr—sieved from road cut; Sa—sieved from auger hole; Cs—collected from stream; Cl—collected live.

TABLE 4. RADIOCARBON AGES FOR LAKE FRANKLIN IN LILLQUIST (1994)

Sample ID	Lab code	Site	Latitude/ longitude (°N/°W)	Elev. (m) map (*surveyed*)	Facies*	Material	^{14}C age (yr B.P. ± error)	Calibration (yr B.P.)	Median prob. (ka)
59190	Beta-59190	FRB	40.52998/115.21055	1823	B	*Pyrgulopsis* spp., *Vorticifex effusa*, *Pisidium* spp.	16,880 ± 510	18,955–19,172 (0.032) **19,204–21,357 (0.968)**	20,124
50768	Beta-50768	FRB	40.52998/115.21055	1823	B	*Pyrgulopsis* spp., *Vorticifex effusa*, *Pisidium* spp.	14,650 ± 340	**17,049–18,568 (1.000)**	17,823
57807	Beta-57807	FRB	40.52998/115.21055	1823	O	Calcareous concretions	7320 ± 90	**7971–8331 (1.000)**	8133
50765	Beta-50765	HW	40.56827/115.10890	1850	L	*Pyrgulopsis* spp., *Pisidium* spp.	15,070 ± 100	**18,007–18,583 (1.000)**	18,255
57800	Beta-57800	MW	40.47982/115.12546	1840 (*1842.1*)	B	*Pyrgulopsis* spp., *Vorticifex effusa*, *Pisidium* spp.	15,020 ± 240	**17,662–18,690 (1.000)**	18,234
50766	Beta-50766	NBV	40.51372/114.96786	1850	L	*Pyrgulopsis* spp., *Pisidium* spp.	16,800 ± 130	19,570–20,288 (1.000)	19,959
29022	Beta-29022	RLNWR	40.17877/115.49056	1830 (*1831.8*)	L	Marl	18,030 ± 1050	18,974–19,124 (0.007) **19,240–23,950 (0.993)**	21,509
57804	Beta-57804	RLNWR	40.17877/115.49056	1830 (*1831.8*)	L	*Pyrgulopsis* spp., *Vorticifex effusa*, *Gyraulus parvus*, *Pisidium* spp.	14,360 ± 150	**17,032–17,899 (1.000)**	17,462
29023	Beta-29023	RLNWR	40.17877/115.49056	1830 (*1831.8*)	L	Tufa	13,380 ± 110	15,620–15,878 (0.039) **15,840–16,862 (0.961)**	16,475
57805	Beta-57805	RLNWR	40.17877/115.49056	1830 (*1831.8*)	L	*Pyrgulopsis* spp., *Vorticifex effusa*	12,870 ± 140	**14,872–16,417 (1.000)**	15,437
29021	Beta-29021	RLNWR	40.17877/115.49056	1830 (*1831.8*)	L	*Amnicola* spp., *Pisidium* spp. Shells	12,030 ± 140	**13,453–14,241 (0.991)** 14,346–14,374 (0.004) 14,432–14,466 (0.005)	13,893
54733	Beta-54733	RW	40.30054/115.39525	1818.5 (*1819*)	L	*Pyrgulopsis* spp.	17,870 ± 160	20,545–20,754 (0.064) **20,762–21,780 (0.936)**	21,325
59447	Beta-59447	RW	40.28537/115.38236	1830 (*1828.2*)	N	*Pyrgulopsis* spp.?, *Pisidium* spp.?	13,330 ± 115	**15,554–16,831 (1.000)**	16,357
59448	Beta-59448	RW	40.28133/115.36299	1836 (*1835.8*)	N	*Pyrgulopsis* spp.?, *Pisidium* spp.?	13,090 ± 100	**15,188–16,489 (1.000)**	15,852
59444	Beta-59444	RW	40.29953/115.42000	1826	N	Unknown	12,930 ± 100	**15,041–16,303 (1.000)**	15,511
59449	Beta-59449	RW	40.28091/115.36013	1840 (*1839.6*)	B	*Pyrgulopsis* spp.?	12,720 ± 110	14,245–14,355 (0.016) **14,463–15,660 (0.977)** 15,772–15,830 (0.007)	15,066
59446	Beta-59446	RW	40.30356/115.39134	1820 (*1820.5*)	B	*Pyrgulopsis* spp.?, *Pisidium* spp.?	11,560 ± 110	**13,202–13,693 (1.000)**	13,414
59445	Beta-59445	RW	40.30424/115.39167	1818.5 (*1819*)	B	Unknown	11,500 ± 100	**13,152–13,598 (1.000)**	13,356
54734	Beta-54734	WT	40.31460/115.33160	1830	L	*Pyrgulopsis* spp., *Pisidium* spp.	15,550 ± 160	**18,510–19,016 (0.945)** 19,076–19,270 (0.055)	18,749

*B—beach ridge; N—nearshore; L—lagoon; O—other.

Two ages were obtained on gastropod shells from a depth of 200–240 cm in this exposure. Sample MW yielded an age of 13,050 ± 45 ^{14}C yr B.P. (15.8 ka), and sample MWB yielded an age of 12,800 ± 60 ^{14}C yr B.P. (15.2 ka). The calibration ranges of these dates overlap from 15.2 to 15.7 ka (Table 3).

Lillquist (1994) reported an age (57800) of 15,020 ± 240 ^{14}C yr B.P. (18.2 ka) from near the MW site. However, the UTM coordinates and elevation (1843.1 m) provided suggest that this age came from a slightly higher shoreline ~400 m to the south of the MW site we excavated (Fig. 4).

Northeast Ruby Valley (NERV)

Extensive road cuts along Highway 229 in northeast Ruby Valley provide access to sediment comprising beach ridges that represent the 1843 and 1840 m shorelines. All of these ridges are composed of medium- to coarse-grained sandy gravel, and cross-bedding was noted in one particularly sand-dominated layer. Sections of the sandy gravel are abundantly fossiliferous.

Surveying reveals that the 1843 m shoreline at NERV consists of three ridges, each separated by gentle swales with ~1 m of relief (Fig. 5). The entire 1843 m beach ridge complex has a width of ~300 m and a back slope that rises more than 4 m. Sample NERV-1 from 100 cm below the crest of the outer ridge returned an age of 13,400 ± 50 ^{14}C yr B.P. (16.6 ka), and sample NERV-2 from 140 cm below the middle crest was dated to 13,600 ± 65 ^{14}C yr B.P. (16.8 ka). Two samples were dated from a depth of 80 cm in the inner crest. The first (NERV-3) yielded an age of 12,650 ± 60 ^{14}C yr B.P. (15.0 ka), while the second (NERV-3b) was dated at 13,050 ± 45 ^{14}C yr B.P. (15.8 ka). The calibration ranges of these two ages overlap at 15.2 ka (Table 3).

The two crests of the 1840 m beach ridge complex reach similar elevations (1839.9 and 1839.8 m) and are separated from the 1843 m complex by a horizontal distance of 570 m (Fig. 5). Two samples from a depth of 120 cm in the outer ridge yielded overlapping ages. Sample NERV-4 returned an age of 13,500 ± 75 ^{14}C yr B.P. (16.7 ka), and sample NERV-4b was dated at 13,550 ± 55 ^{14}C yr B.P. (16.7 ka).

Ruby Lake National Wildlife Refuge Quarry (RLNWR)

The large excavation at RLNWR yielded five radiocarbon ages, which, combined with five more reported by Lillquist (1994), constrain when Lake Franklin stood at 1830 m. Two quarries are present in the spit forming the 1830 m shoreline at the RLNWR. In 2010, the north wall of the upper pit exposed ~4 m of well-rounded, stratified gravel and coarse sand (Fig.

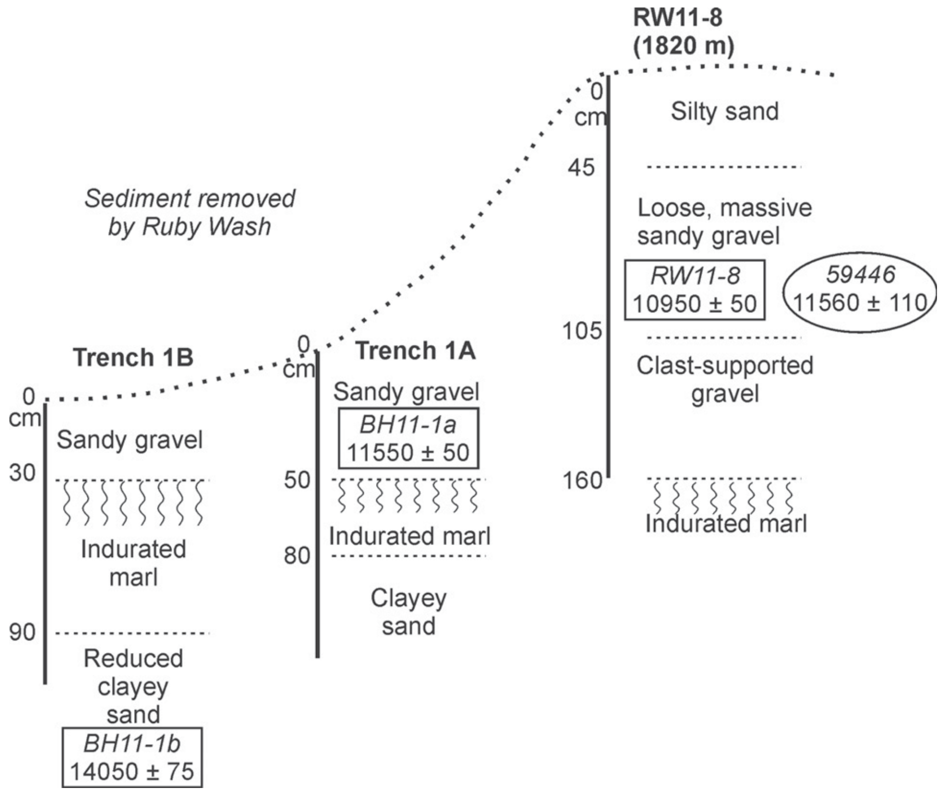

Figure 7. Stratigraphic columns for two trenches dug where Ruby Wash has breached the 1820 m beach ridge at the Badger Hole site (Fig. 2) and the pit excavated into the crest of this ridge ~400 m to the east (RW11–8, Fig. 6). The beach ridge is primarily composed of sandy gravel that overlies marl and clayey sand. Radiocarbon date BH-1b indicates that this marl accumulated before 14,000 ^{14}C yr B.P. (17 ka). The upper part of the marl is oxidized, documenting subaerial exposure before deposition of the overlying beach gravels. Radiocarbon ages (in ^{14}C yr B.P.) suggest that the ridge was built in the latest Pleistocene. Dates enclosed in rectangles are from this study; dates surrounded by ovals are calibrated from Lillquist (1994).

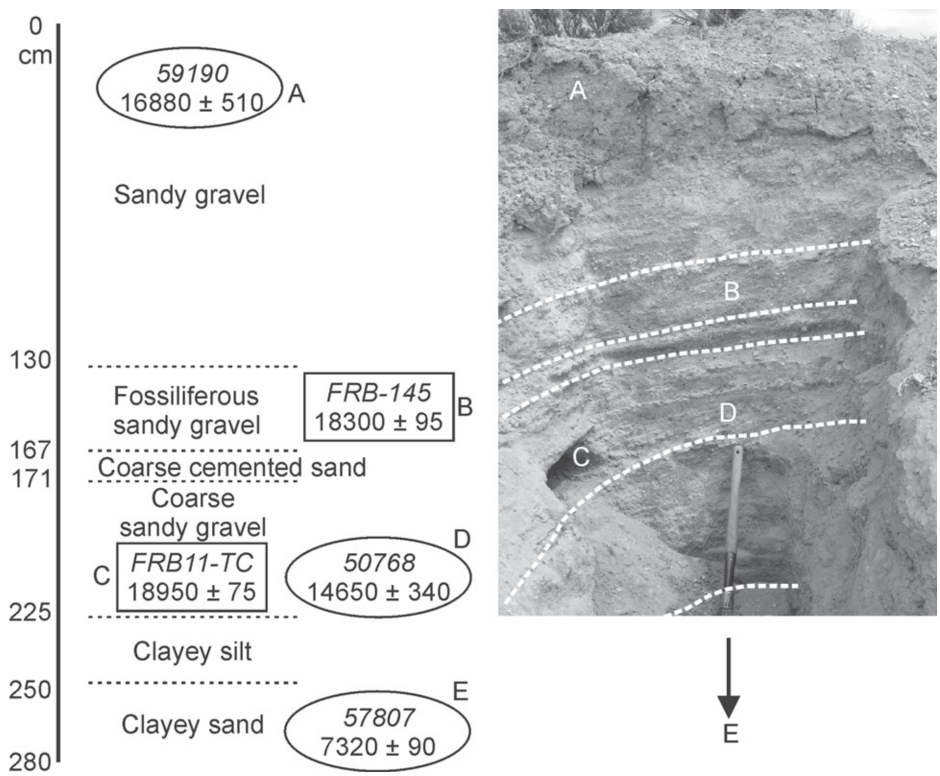

Figure 8. Annotated stratigraphic column and scaled photograph of the exposure at the eastern end of the borrow pit at the Franklin River Bridge (FRB) site (see Figs. 2 and 3). Letters A through E link the radiocarbon ages to their location in the photograph. The sandy gravel comprising the massive beach ridge at this site unconformably overlies a sticky, clayey silt layer, which overlies a slightly coarser clayey sand. The lowest age (shown in ^{14}C yr B.P.) was determined on marly concretions within the clayey sand and may reflect precipitation of carbonate from groundwater flowing from the nearby Franklin River. Three of the remaining four dates are in stratigraphic order and suggest construction of the ridge during the Last Glacial Maximum. The remaining date (50768) is notably younger, and its significance is unclear. Dates enclosed in rectangles are from this project; dates surrounded by ovals are calibrated from Lillquist (1994).

9). The sediment is moderately well indurated and locally fossiliferous. The uppermost 35 cm is composed of sandy gravel with cobbles to 10 cm in diameter. This unit is underlain by a finer, open-work gravel extending to a depth of ~100 cm below the modern ground surface, which has a surveyed elevation of 1831.8 m. Local pockets of marly sand, ~25 cm thick, were observed within this unit. In the lower part of the exposure, a unit of marly sandy gravel extends from a depth of ~100 to ~200 cm and abruptly overlies a coarse, bedded gravel (Fig. 9).

Figure 9 shows the north wall of the upper quarry along with the five new radiocarbon ages generated by this project. The lowest two ages were obtained from gastropods collected from depths of 250 cm (RLNWR-L) and 180 cm (RLNWR-U). The lower sample yielded an age of 16,750 ± 70 ^{14}C yr B.P. (19.9 ka) and the upper yielded 15,750 ± 140 ^{14}C yr B.P. (18.9 ka). Sample RLWR-5 from a pocket of marly sand at a depth of 150 cm yielded an age of 15,800 ± 60 ^{14}C yr B.P. (19.0 ka). Sample RLWR-4 from near the top of the open-work gravel yielded 14,450 ± 50 ^{14}C yr B.P. (17.6 ka), and sample RLWR-3 from the coarse layer at the surface yielded 14,250 ± 75 ^{14}C yr B.P. (17.3 ka).

The other five radiocarbon ages for RLNWR are from lagoons that existed on the landward side of the spit (Table 4). Lillquist (1994) reported an age of 14,360 ± 150 ^{14}C yr B.P. (17.5 ka) for a sample (57804) of gastropod shells from the lower quarry, which has since been graded. This result matches the younger ages for samples RLWR-3 and RLWR-4 (Table 3). Lillquist (1994) also reported an age of 12,870 ± 140 ^{14}C yr B.P. (15.4 ka) for shells (57805) from the south wall of the upper quarry. Three other ages from the upper quarry were reported by Lillquist (1994) from the unpublished work of D. Currey. A sample of marl (29022) yielded an imprecise age of 18,030 ± 1050 ^{14}C yr B.P. (21.5 ka). The wide calibration range (19.2–24.0 ka) for this sample overlaps the oldest age from the gravels (RLNWR-L). A sample of tufa (29023) returned an age of 13,380 ± 110 ^{14}C yr B.P. (16.5 ka), and a collection of shells (29021) yielded an age of 12,030 ± 140 ^{14}C yr B.P. (13.9 ka).

Ruby Wash (RW)

Ten of the eleven shorelines listed in Table 2 are represented by beach ridges at the RW locality, making this the most complete sequence of shorelines in the study area (Figs. 2 and 6). Excavations into the crests of these ridges reached sandy gravel beneath a silt cap ranging from 27 to 50 cm thick (Fig. 10). Five of these excavations penetrated through the sandy gravel into loose, sorted sand. Shells of aquatic gastropods suitable for radiocarbon dating were recovered from each of these ridges. Two samples were dated from the highstand beach ridge. Sample RW11–1b, from 110 cm below the surface in the sandy gravel, returned an age of 13,600 ± 45 ^{14}C yr B.P. (16.8 ka). A second sample (RW11–1b2) from the contact between the sandy gravel and underlying silt at the base (150 cm) of the ridge returned an age of 19,000 ± 70 ^{14}C yr B.P. (22.6 ka). Sample RW11–2 from the sandy gravel at a depth of 120 cm in the next lower beach ridge (1846 m) returned an age of 13,350 ± 75 ^{14}C yr B.P. (16.5 ka). Two samples were analyzed from within the beach ridge at 1843 m. Sample RW11–3 from the sandy gravel was dated at 13,100 ± 75 ^{14}C yr B.P. (15.9 ka), whereas sample RW-4b from the deeper loose sand was dated to 13,400 ± 75 ^{14}C yr B.P. (16.6 ka). Sediment comprising the beach ridge at 1840 m also yielded a pair of ages representing the two major facies. Sample 59449 from the sandy gravel returned an age of 12,720 ± 110 ^{14}C yr B.P. (15.0 ka), whereas sample RW11–4 from the underlying coarse sand was dated to 13,100 ± 60 ^{14}C yr B.P. (15.9 ka). A pair of ages (RW11–5 and 59448) from the loose sand beneath sediment comprising the 1836 m beach ridge are nearly identical (13,050 ± 50 ^{14}C and 13,090 ± 100 ^{14}C yr B.P., respectively), whereas the loose sand comprising the 1831 m beach ridge (RW11–11) yielded a slightly younger age of 12,700 ± 45 ^{14}C yr B.P. (15.1 ka). A sample (RW11–6) from the sandy gravel ~1 m below the surface of the 1830 m beach ridge yielded an age of 12,950 ± 75 ^{14}C yr B.P. (15.5 ka), and sample 59447 from deeper in the coarse sand was dated to 13,330 ± 115 ^{14}C (16.4 ka).

Lillquist (1994) reported an age (59444) of 12,930 ± 100 ^{14}C yr B.P. (15.5 ka) from the 1826 m ridge. Although we did not relocate this pit, his map suggests that he excavated at a point immediately downslope from the 1830 m shoreline. A separate pit excavated in the crest of the 1826 m beach ridge in this study exposed 150 cm of loose, sparsely fossiliferous sand with rare well-rounded pebbles. Sample RW11–7, from a depth of 110–125 cm in this pit, returned an age of 12,450 ± 65 ^{14}C yr B.P. (14.6 ka). The calibration ranges for these radiocarbon ages do not overlap (Tables 3 and 4).

The two lowest beach ridges yielded the youngest radiocarbon ages (Fig. 10). Samples from the sandy gravel within the 1820 m beach ridge (59446 and RW11–8) yielded ages of 11,560 ± 110 ^{14}C yr B.P. (13.4 ka) and 10,950 ± 50 ^{14}C yr B.P. (12.8 ka) respectively. Two

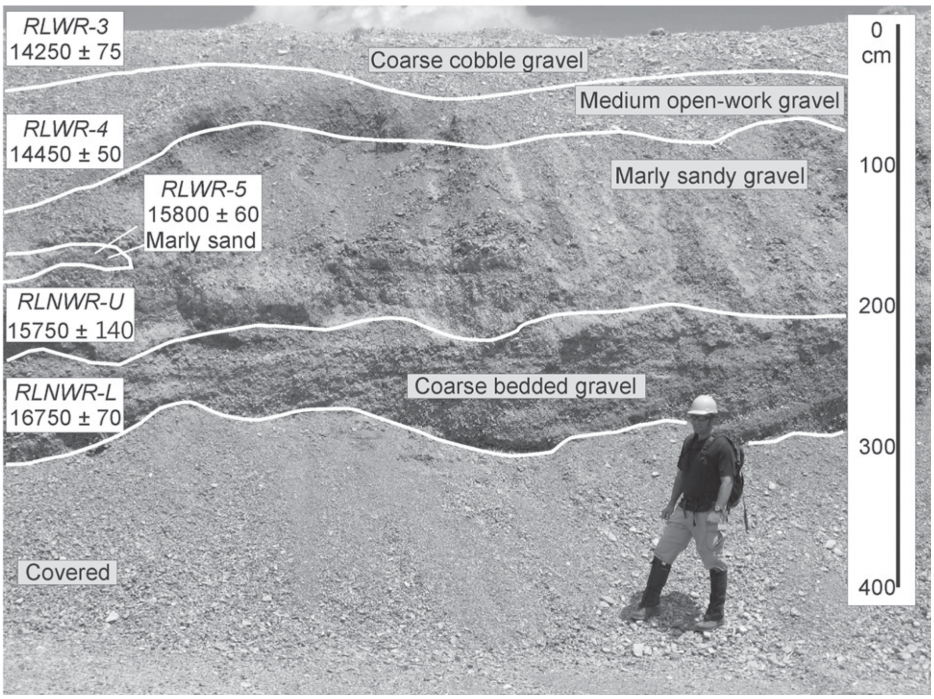

Figure 9. Annotated photograph showing the north wall of the upper quarry at the Ruby Lake National Wildlife Refuge Quarry (RLNWR) site in 2010 (Fig. 2). The wall stands ~400 cm high and exposes crudely stratified, fossiliferous, sandy gravel that comprises a spit formed when Lake Franklin stood at an elevation of 1830 m. Five radiocarbon ages obtained from this exposure (shown in ^{14}C yr B.P.) are in stratigraphic order and suggest a long period of water-level stability at this elevation.

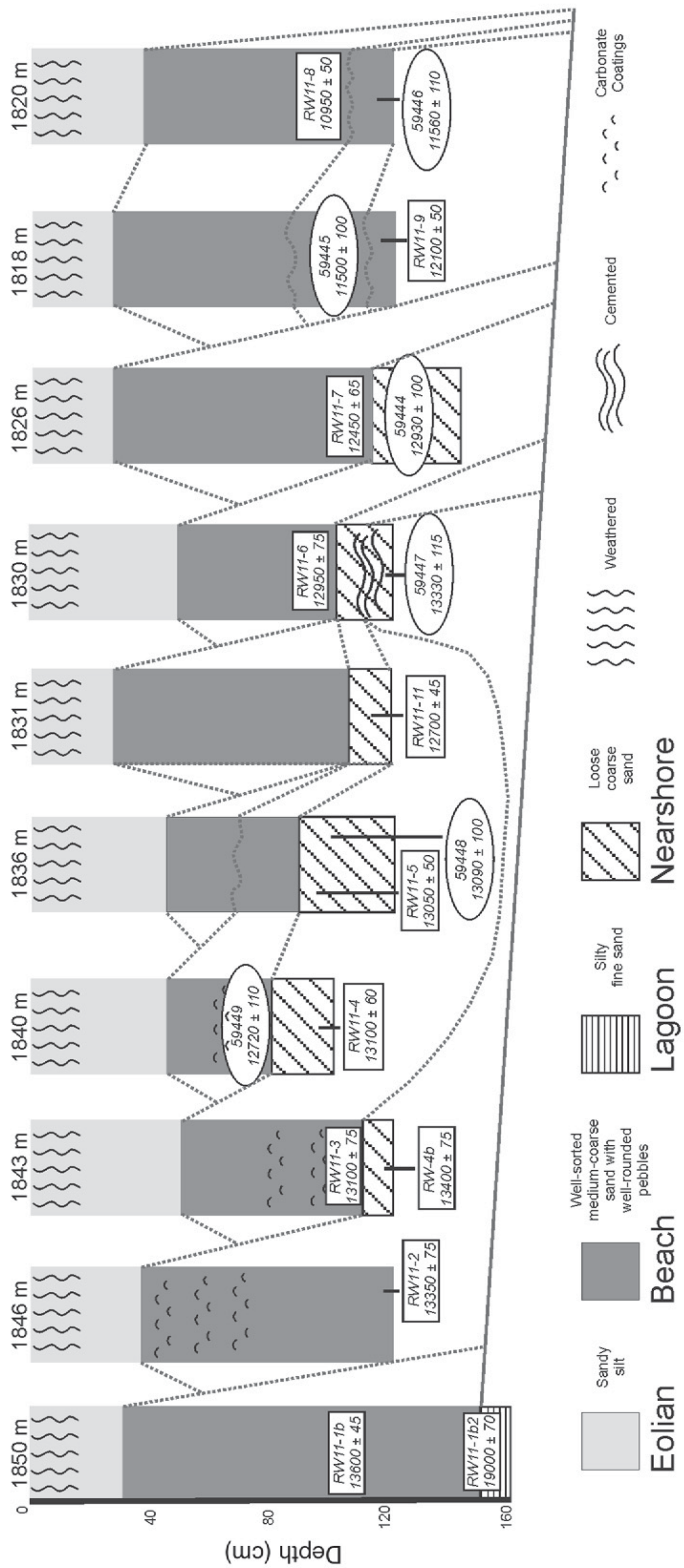

Figure 10. Stratigraphic columns for excavations into the crests of beach ridges at the RW site (Fig. 6), presented at a common scale (in cm). Radiocarbon dates are shown in ^{14}C yr B.P. Dates enclosed in rectangles are from this project; dates surrounded by ovals are calibrated from Lillquist (1994). All of the beach ridges are mantled by several decimeters of eolian silt. Beneath this layer, each ridge is composed of bedded sandy beach gravel. Five of the excavations penetrated into loose, coarse sand interpreted as a nearshore facies. Dotted lines show correlations made on the basis of the radiocarbon ages, sedimentology, and stratigraphic relationships.

samples from sandy gravel comprising the beach ridge at 1818 m (RW11–9 and 59445) yielded slightly older ages of 12,100 ^{14}C yr B.P. (13.9 ka) and 11,500 ± 100 ^{14}C yr B.P. (13.4 ka).

Other Radiocarbon Ages

Lillquist (1994) provided radiocarbon ages from several additional sites in the Ruby Valley (Fig. 2; Table 4). Two were obtained from lagoonal deposits behind the 1850 m beach ridge: sample 50766 from the NBV yielded an age of 16,800 ± 130 ^{14}C yr B.P. (20.0 ka), and sample 50765 from HW returned an age of 15,070 ± 100 ^{14}C yr B.P. (18.3 ka). Lillquist (1994) also reported an age (54734) of 15,550 ± 160 ^{14}C yr B.P. (18.8 ka) on shells obtained from lagoonal deposits behind the 1830 m ridge at the WT site (Fig. 2; Table 4). For this study, augering near the coordinates presented by Lillquist (1994) yielded shells (WT-1, Table 3) that returned a considerably younger age of 12,700 ± 55 ^{14}C yr B.P. (15.1).

Finally, Lillquist (1994) reported an age of 17,870 ± 160 ^{14}C yr B.P. (21.3 ka) for a sample (54733) collected from near the BH site (Figs. 2 and 6; Table 4). No stratigraphic context was provided, but the coordinates listed for this sample indicate it was retrieved from an area where Ruby Wash was impounded before breaching the ridge (Lillquist, 1994).

Samples Collected from Modern Springs

Two gastropod shells were collected and dated from the channel immediately below a flowing spring on the west side of the Ruby Valley (Fig. 2; Table 3). Sample RM-1 returned an age of 2180 ^{14}C yr B.P. (2.2 ka), and sample RM-2 yielded an age of 3220 ± 25 ^{14}C yr B.P. (3.4 ka). A live specimen of *Pyrgulopsis* (modern, Table 2) returned an age of 770 ± 30 ^{14}C yr B.P. (0.7 ka).

Water-Level Fluctuations

Panel A of Figure 11 presents the radiocarbon ages compiled for this study plotted against their elevations, with symbols distinguishing new dates and those reported by Lillquist (1994). Two dates are excluded for clarity: the very old age (DGP-1) for a shell from the DGP site (Table 3), and the young age (57807) for marly concretions in the lowest sedimentary unit at the FRB site (Table 4). The three ages for shells collected from springs in the Ruby Marshes are also excluded because they are not germane to past water-level fluctuations (Table 3). The data points are scattered between roughly 19,000 and 11,000 ^{14}C yr B.P., although there is a particularly dense cluster of dates between 14,000 and 13,000 ^{14}C yr B.P. at elevations from 1840 to 1850 m.

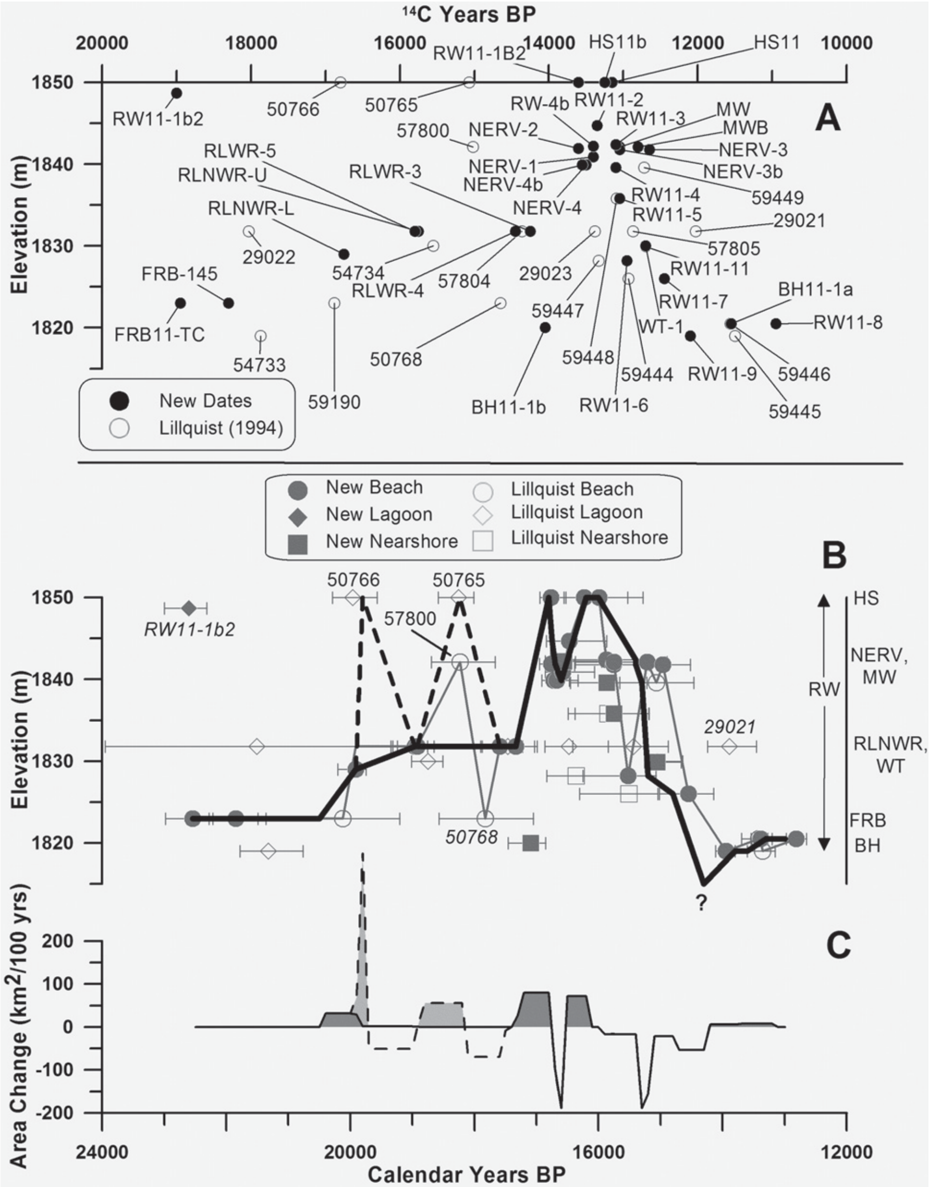

Figure 11. (A) The new radiocarbon ages for Lake Franklin and the existing ages from Lillquist (1994), in ^{14}C yr B.P., plotted against elevation. Samples DGP-1, RM-1, RM-2, and modern (Table 3), and 57087 (Table 4) are not included for clarity. (B) The ages calibrated into calendar yr B.P. with 2σ calibration ranges. Samples are grouped by facies (beach, lagoon, and nearshore) and coded for this study and for Lillquist (1994). Notations along the right side designate the study sites representing the different shoreline elevations. The thin gray line represents a preliminary hydrograph for Lake Franklin determined by connecting the midpoints of the calibration ranges for dates derived from beach ridges. The thicker black line represents a more sophisticated hydrograph taking into account stratigraphic relationships between sampled layers and the particular facies from which samples were collected. The dashed black lines denote possible alternative trajectories that are less well constrained by the available evidence. "?" indicates that the timing and elevation of this lowstand are unknown. Outlying samples mentioned in the text are labeled; samples ignored in the hydrograph are in italics. (C) The calculated rate of area change for Lake Franklin, highlighting the rapid rise to the pluvial maximum ca. 17 ka, the dramatic regression after 15.4 ka, and the minor transgression in the latest Pleistocene.

DISCUSSION

Interpretation of Radiocarbon Ages

Given the reliance of this study on radiocarbon dating, it is important to consider external factors that may impact the fidelity with which radiocarbon ages from aquatic gastropod shells record the actual age of the enclosing sediment. Some factors, such as recrystallization of aragonite to calcite after deposition, or precipitation of secondary carbonate on shell surfaces, work to yield radiocarbon ages that are younger than the enclosing sediment. In this study, however, X-ray diffraction analysis of the dated shells revealed the characteristic peaks of a dominantly aragonite composition, and the careful pretreatments, which reduced sample masses by up to 75%, were designed to minimize the potential impact of secondary carbonate.

Radiocarbon ages that are older than the enclosing sediment can arise if the dated gastropods were living in water that contained dissolved carbon derived from carbonate bedrock. Because this rock would be much older than the half-life of ^{14}C, the $^{14}C/^{12}C$ ratio in the water (and, by extension, the shells) would diverge from the reference atmospheric value. Carbonate bedrock is present in the watershed of Lake Franklin, and the numerous springs discharging at the Ruby Marshes indicate that at least some of the water that sustained Lake Franklin was likely derived from groundwater aquifers, making this a valid concern in the Ruby Valley. Yet, efforts to determine whether gastropods that lived in Lake Franklin might be subject to radiocarbon reservoir effects yielded equivocal results. The ages for the shells recovered from streams below flowing springs (RM-1 and RM-2) are unexpectedly old (Table 3), but because the shells did not contain live snails at the time of collection, it is possible that they were exhumed from older spring deposits by the modern stream. A better assessment is offered by the radiocarbon age of 770 ± 30 ^{14}C yr B.P. (0.7 ka) obtained for the live snail (modern, Table 3). This result indicates that gastropods living directly in the water discharging from Ruby Valley springs do exhibit a radiocarbon reservoir effect of several centuries in magnitude. However, this effect is certain to have been substantially diluted in a lake with the surface area and volume of Lake Franklin (Table 2), which undoubtedly received high volumes of surface runoff and precipitation onto the lake surface. Thus, no attempt is made to systematically adjust the ages reported here.

Finally, reworking of shells during construction of shoreline landforms can incorporate older shells into younger geomorphic features. This possibility is of particular note for radiocarbon ages obtained on shells collected directly from sandy gravel facies of beach ridges. Because the gastropod varieties that were dated in this study live not on high-energy beach faces, but rather in lower-energy nearshore environments, these shells were certainly reworked to a certain degree prior to deposition. However, the dated shells were almost universally intact with little evidence for extensive mechanical breakage that would be expected from a long period of reworking by wave action. Moreover, even though nearly all of the radiocarbon ages were determined on composites of multiple shells (in most cases more than six), the resulting ages have consistently small uncertainties, which would not be expected if shells were reworked from numerous sources with different ages. Overall, the condition of the shells and the narrow uncertainty ranges on the radiocarbon ages are consistent with rapid, short-distance transport of shells from the nearshore environment before incorporation into beach gravels.

Interpretation of Sedimentary Facies

Hand excavation of more than a dozen new pits, and clearing of an equal number of preexisting exposures provided a comprehensive perspective on the types of sediment present in Lake Franklin beach ridges, despite the lack of natural exposures. The surficial silt layer, found throughout the study area, is interpreted as an eolian deposit postdating formation of the beach ridges. This interpretation, which is consistent with other studies (e.g., Adams and Wesnousky, 1998; Kurth et al., 2011), is supported by the ubiquity of the silt layer, as well as the sharpness of the textural discontinuity between the silt and underlying sediment. The random coarser fragments incorporated within the silt were presumably bioturbated upward from the underlying sandy gravel.

The bedded sandy gravel with local openwork texture underlying the silt is interpreted as a beach deposit. Similar sediment has been reported from pluvial lake beach ridges elsewhere in the Great Basin (e.g., Adams and Wesnousky, 1998; Kurth et al., 2011). Variations in the grain size of this material between sites likely reflect differences in wave regime and proximity to a sediment source. Grain-size differences between beds within a given ridge are likely due to fluctuations in wave energy as the beach was constructed.

Finally, the loose, well-sorted, coarse sand encountered beneath the sandy gravel in the deeper excavations at the RW site is interpreted as nearshore sediment that accumulated during construction of a beach ridge at higher elevation. Wave action would winnow sand from the beach face and transport it downslope to accumulate in lower-energy locations beneath wave base. The abundance of shells in this material, and its high degree of sorting are consistent with deposition in this setting. These deposits may have been moderately reworked during water-level lowering, making this unit similar to the regressive facies noted in previous studies (e.g., Adams and Wesnousky, 1998).

Latest Pleistocene Water-Level Fluctuations of Lake Franklin

The results of this study support development of a detailed hydrograph of water-level fluctuations of Lake Franklin during the last pluvial cycle (Fig. 11B). This hydrograph is fundamentally based on the large data set of radiocarbon ages because the absence of extensive exposures in the study area precluded thorough application of sequence stratigraphy. This approach reduces certainty in some of the inferred water-level fluctuations and limits our ability to identify higher-frequency water-level fluctuations. However, the stratigraphic context of the dated shells, which was clearly revealed in excavations and natural exposures, was used in combination with radiocarbon ages to maximize certainty in the reconstructed hydrograph.

Two ages (50765 and 50766) of lagoonal deposits reported by Lillquist (1994) fall off the best-fit line that represents the hydrograph in Figure 11B. Because the stratigraphic context of these ages is unavailable, these ages were incorporated as possible departures from the best-fit line. Two other ages were ignored because of uncertainty regarding their stratigraphic contexts (noted in Fig. 11B).

To organize the discussion, the water-level history of Lake Franklin is divided into six time intervals: pre–Last Glacial Maximum (LGM; >24 ka), early LGM (24–21 ka), late LGM (21–17 ka), pluvial maximum (17–16 ka), late glacial regression (16–14 ka), and latest Pleistocene transgression (14–12 ka).

Pre-LGM (>24 ka)

The lone date (DGP-1) from DGP provides a tantalizing clue to the early history of Lake Franklin. The calibrated age (45.6 ka) is considerably older than any other obtained in this study and indicates that a precursor of Lake Franklin reached (at least) 1850 m during an older pluvial cycle. Support for this age is provided by the greater amount of pedogenic carbonate within the beach gravels at this site (Lillquist, 1994) relative to beach ridges yielding younger radiocarbon ages. The significance of this result is difficult to ascertain. At face value, the date suggests high water during marine isotope stage (MIS) 3. Little is known about pre–MIS 2 lakes in the Great Basin relative to the last pluvial cycle, although pre-LGM highstands apparently occurred during glacial stages (e.g., Kurth et al., 2011; Reheis, 1999a; Oviatt et al., 1999; Oviatt and McCoy, 1992). Thus, it seems unlikely that Lake Franklin would have stood near its highest level for MIS 2 during the MIS 3 interstadial. Future investigations if this borrow pit is reopened would help clarify interpretation of this result.

Early LGM (24–21 ka)

Evidence for the extent of Lake Franklin during the first half of the LGM comes primarily from the FRB site (Fig. 8). Three ages in stratigraphic order (FRB11-TC, FRB-145, and 59190) indicate that the water level stood near 1823 m from ca. 22.5 ka to 20 ka (Fig. 11B). At this elevation, Lake Franklin had a maximum depth of ~9 m and covered 43% of its highstand area (Table 2). It is not possible to determine from the field evidence whether a precursor to the beach ridge at 1826 m, which currently divides the Lake Franklin basin, existed at this time (Fig. 2). If not, then the area of Lake Franklin at 1823 m determined from the modern topography (Table 2) is an underestimate.

The span of the radiocarbon results (Fig. 8; Tables 3 and 4) indicates that water stood near the 1823 m level for ~2500 yr (Fig. 11B), which is consistent with the size (1.25 km wide and 12 km long) of the beach ridge (Fig. 3) in which the FRB site is located. This evidence suggests that climate during the early LGM in the Ruby Valley was stable and featured enhanced effective moisture, although to a much lesser degree than the intervals that followed.

The sandy gravel comprising this beach ridge sits unconformably above a clayey silt layer that resembles lagoonal sediments elsewhere in the study area (Fig. 8). The abruptness of the contact between these units suggests that the lagoon was impounded behind a transgressing beach ridge as the water level rose to 1823 m. The deeper clayey sand is interpreted to represent floodplain sediment from the Franklin River before formation of the lagoon. The Holocene age for sample 57807 (8.1 ka) is interpreted to represent a groundwater effect from the nearby Franklin River.

The age from sample RW11–1b2 at the RW site was ignored in creating the hydrograph (Fig. 11B). This sample was an assemblage of shells from the contact between the beach gravel and the underlying silt at the base of the pit excavated in the 1850 m beach ridge (Fig. 10). This radiocarbon age is considerably older than the other date from this ridge (RW11–1b), and it is nearly identical to sample FRB11-TC from

FRB at an elevation nearly 30 m lower. Although the intent was to obtain an age for the base of the beach gravel, shells from the silt may have been inadvertently dated. Nonetheless, it is notable that the silt resembles the lagoonal sediments elsewhere in the study area, and a lagoon environment in this position on the Ruby Wash alluvial fan requires a topographic obstacle, like a beach ridge, to impound water. Thus, this explanation for the older age of RW11–1b2 still requires that Lake Franklin stood near 1850 m at some unknown point before the early LGM, perhaps corresponding to the sediment exposed at DGP. Without dating shells directly from the silt, however, it is not possible to determine the age of this lagoon fill.

Late LGM (21–17 ka BP)

Evidence for the extent of Lake Franklin during the late LGM comes primarily from RLNWR, where five dates from the beach gravel indicate that Lake Franklin stood near 1830 m from ca. 20 ka to 17.3 ka (Figs. 9 and 11B; Table 3). The marl age (29022), while imprecise, overlaps with the lower two ages from this site, supporting the interpretation of a water level near 1830 m in the late LGM. Another age (54734) from the WT site (Fig. 2) also overlaps considerably with sample RLWR-5 (Tables 3 and 4). Together, these ages suggest that the water level in Lake Franklin stayed near 1830 m for nearly 3000 yr, implying a relatively stable climate. At 1830 m, Lake Franklin covered 60% of its highstand area (Table 2). The change in lake area from 1823 to 1830 m was ~140% at an average rate of ~30 km^2/century (Fig. 11C), indicating that effective moisture increased considerably from the early LGM to the late LGM.

As noted already, a few ages suggest the possibility that Lake Franklin rose to near its ultimate highstand briefly during the late LGM. Sample 50766 from a lagoon behind the 1850 m beach ridge at NBV (Fig. 2) calibrates to 20.0 ka (Lillquist, 1994), raising the possibility that water temporarily rose to 1850 m during the transition from the early to late LGM (Fig. 11B). However, no information is provided about the stratigraphic context of this sample. This ambiguity, combined with the lack of conclusive evidence for transgression and regression within the exposure at RLNWR, makes interpretation of a high-water phase ca. 20 ka tenuous. Two other ages suggest a second transgression toward the end of this interval. Sample 57800 from the 1843 m ridge near MW (Fig. 4) has a calibrated age of 18.2 ka (Table 4). A second sample (50765) from a lagoon behind the highstand shoreline at site HW (Fig. 2) yielded the same age, suggesting that water was as high as 1843 m, and possibly up to 1850 m, ca. 18.2 ka. Once again, however, the lack of detail about the stratigraphic setting of these samples undermines confidence in this transgression. Furthermore, the exact location from which sample 57800 was collected is unclear. If it was obtained from the UTM coordinates provided by Lillquist (1994), as shown in Figure 4, it actually came from a beach ridge produced not by Lake Franklin, but by a lake in an adjacent closed depression known as Dry Lake Flat (Fig. 2). Although these two lakes were connected when Lake Franklin rose above 1843 m, they were independent at lower water elevations. Thus, sample 57800 indicates a time when water in Dry Lake Flat stood at 1843 m, but Lake Franklin could have been lower. Overall, it appears that the best interpretation is that Lake Franklin stood at ~1830 m through a stable late LGM, building the large shoreline spit at RLNWR. If water level did rise to 1843 m (or 1850 m) ca. 18.2 ka, then it is worth noting that the lake was back down to 1830 m (a loss of 450 km^2) by ca. 17.5 (samples RLWR-3 and RLWR-4).

Sample 50768 was ignored in creating the hydrograph (Fig. 11B) because it is out of chronologic order when compared with the other four ages from the FRB locality, all of which are considerably older (Fig. 8). The reason for the young age of this sample is unclear; however, it was a result of a standard analysis of ^{14}C and has a relatively large uncertainty. Thus, it is possible that some of the shells in this collection were incompletely cleaned before analysis.

Pluvial Maximum (17–16 ka)

The pluvial maximum of Lake Franklin featured a rapid rise from 1830 m to 1850 m ca. 17.0 ka (Fig. 11B). This rise, which involved an increase in lake area of 168% (Table 2), may have occurred in just a few centuries between ca. 17.3 ka and 16.8 ka, given the ages for samples RLWR-3 and RW11–1b (Table 3). This major change in the dimensions of Lake Franklin, at a rate of ~80 km^2/century (Fig. 11C), signals a significant increase in effective moisture following the end of the LGM. At its highstand elevation, Lake Franklin had a maximum depth of ~36 m and covered 1100 km^2, placing it in the top 10% of all western U.S. pluvial lakes when ranked by maximum area during the last pluvial cycle. (Fig. 2; Table 2). Nonetheless, the lake was still an order of magnitude smaller than Lakes Bonneville and Lahontan.

No shoreline landforms or wave-worked sediments were recognized above the 1850 m beach ridge. Although this is negative evidence, it nonetheless suggests that the 1850 m highstand marks an all-time maximum lake level for Lake Franklin. This is in contrast to other basins in the region, where littoral sediments and shoreline landforms have been mapped above the latest Pleistocene highstand (e.g., Reheis, 1999a; Kurth et al., 2011).

Beach ridges representing the pluvial maximum and subsequent regression of Lake Franklin are particularly well preserved at the RW site, and 16 radiocarbon ages for these ridges, along with other dates from BH and HS, permit the sequence of water-level changes during this interval to be deciphered. For the dates from RW, an important distinction is made between the samples collected directly from beach sediment, and those collected from the loose, coarse sand at depth interpreted as a nearshore facies related to a beach ridge at higher elevation. Figure 10 illustrates possible correlations between the stratigraphic units encountered in the 10 excavations at site RW. Figure 12 combines these ages with others representing the pluvial maximum and subsequent regression from the other sites. All of these dates are plotted with a schematic subsurface stratigraphy projected below the 5-km-long topographic survey from the 1850 m beach ridge at the head of Ruby Wash down to the 1818 m beach ridge.

The age of the highstand of Lake Franklin at 1850 m is directly constrained by three radiocarbon ages from two localities: RW11–1b from the head of Ruby Wash, and HS11 and HS11-b from the HS site (Figs. 11B and 12). The two HS dates overlap strongly, but their calibration ranges are distinct from sample RW11–1b (Table 3). Moreover, samples (RW11–2, NERV-1, NERV-2, NERV-4, NERV-4b) from beach ridges at slightly lower elevations (1846 m and 1843 m) fall in between the two sets of highstand ages (Table 3). This situation suggests that Lake Franklin first reached an elevation of 1850 m ca. 16.8 ka, dropped slightly (Figs. 11B and 11C) to build a complex of lower beach ridges over a span of two centuries, and then rose back to 1850 m (Fig. 12). This interpretation is supported by dates from nearshore sediment encountered beneath the 1843 m (RW-4b) and 1830 m (59447) beach ridges at RW, and a date on tufa from the RLNWR quarry (29023) indicating that water stood above 1830 m ca. 16.5 ka (Fig. 12). The lake then rapidly transgressed back to 1850 m by ca. 16.0 ka, and may have been stable at this elevation for a few centuries, given the overlapping calibration ranges for samples HS11 and HS11-B (Figs. 11B, 11C, and 12).

Late Glacial Regression (16–14 ka)

Available radiocarbon evidence indicates that after 16 ka, Lake Franklin returned to an elevation of 1843 m to finish constructing one of the most prominent beach ridges in the Ruby

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Valley (Figs. 11B, 11C, and 12). Five samples (RW11–3, MW and MWB, and NERV-3 and NERV-3b) from three localities have calibration ranges that overlap at 15.4 ka (Table 3). In addition, nearshore sediment with the same age was encountered at sites RW11–4 and RW11–5 (Fig. 12). The compound nature of landforms representing this shoreline, clearly documented by two separate clusters of radiocarbon ages (NERV-1 and NERV-2 from ca. 16.6 ka, and RW11–3, MW, MWB, NERV-3, and NERV-3b from ca. 15.4 ka), indicates that Lake Franklin stabilized at this elevation more than once. This interpretation is consistent with the massive size of the 1843 m beach ridge throughout the Ruby Valley, and the presence of multiple crests on this shoreline, for instance at NERV (Fig. 5). A possible explanation for this convergence is that the sill separating Ruby Valley from Dry Lake Flat and Northern Butte Valley is at an elevation of 1840–1843 m (Fig. 2). Thus, transgression of Lake Franklin above this elevation requires flooding of an additional ~100 km^2 with shallow water. This substantial increase in potential evaporation may have limited transgressions above ~1843 m to the wettest times of the last pluvial cycle.

After this second interval of stability at 1843 m, the lake regressed to build the 1840 m beach ridge at RW ca. 15.3 ka (Figs. 11B and 12). This change occurred quite rapidly, at an average rate of nearly −200 km^2/century (Fig. 11C). Sample RW11–11, from nearshore sediment encountered at depth in the pit excavated in the 1831 m shoreline, represents this regression. Sample RW11–6, from the beach sediment within the 1830 m beach ridge, indicates that the level of the lake dropped from 1840 to 1830 m by ca. 15.2 ka, corresponding to a loss of ~150 km^2 (Table 2). Sample 59444 is interpreted as nearshore sediment recording the construction of the 1830 m beach ridge, and two samples from lagoonal deposits behind ridges representing this shoreline (WT-1 from the WT site, and 57805 from RLNWR) also have the same age.

By ca. 14.8 ka, Lake Franklin dropped to 1826 m, as represented by sample RW11–7. At this elevation, Lake Franklin split into two separate water bodies, one centered over the Franklin Lake playa in northern Ruby Valley, and the other centered over the Ruby Marshes (Fig. 2). The combined area of the two lakes at this stage was approximately half that of the pluvial maximum (Table 2).

Sample 29021 falls off the hydrograph during this regression (Fig. 11B). This sample, which was a standard radiocarbon age obtained on a

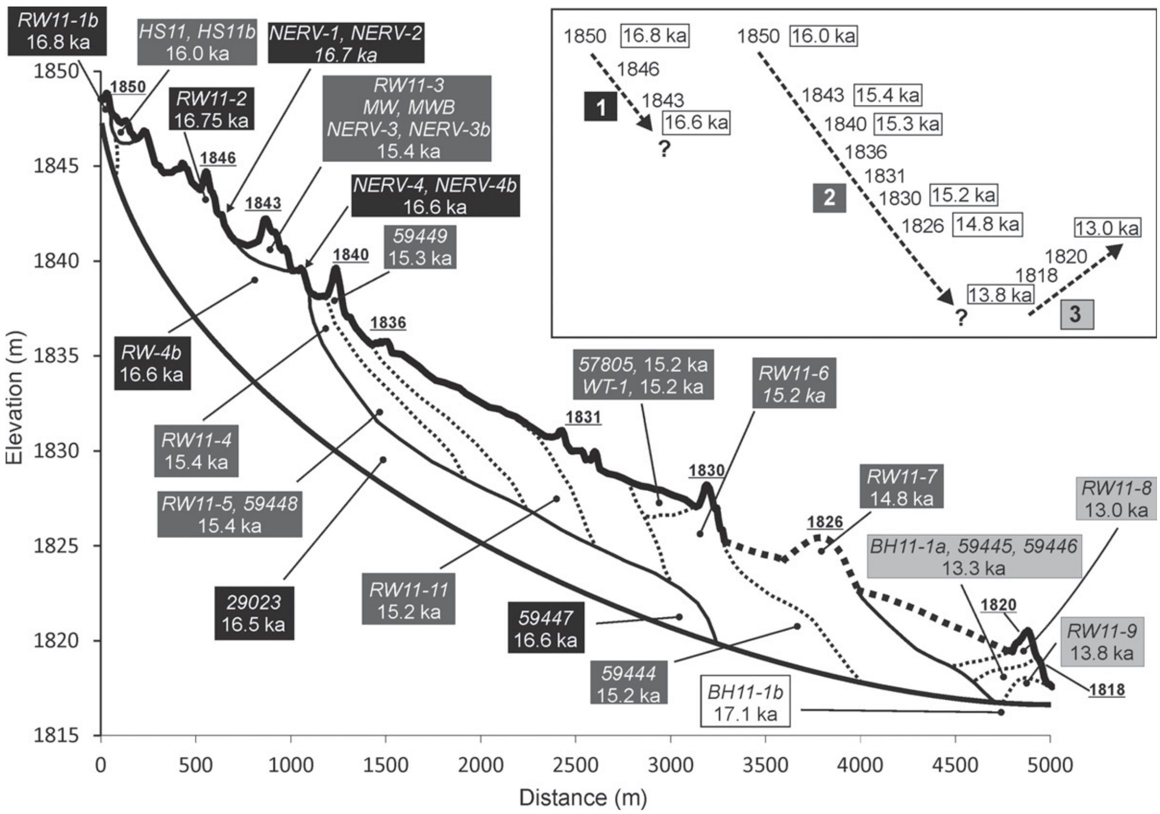

Figure 12. Composite stratigraphy for beach ridges representing the pluvial maximum, late glacial regression, and latest Pleistocene transgression of Lake Franklin. Inferred subsurface relationships are projected below a 5-km-long topographic survey from the 1850 m shoreline at the head of Ruby Wash, down to the 1818 m shoreline (Fig. 6). Dotted parts of this profile are interpolated. Unit thicknesses are exaggerated for clarity. Solid lines represent boundaries between three transgression-regression sequences. Dates are presented in calibrated yr B.P. Dates shown above the profile are for samples collected from beach ridges, or from lagoons behind beach ridges. Those below the profile are from nearshore facies. Sample BH11–1b represents a stage of Lake Franklin predating the first rise to 1850 m. Black with white lettering represents the first regression from the 1850 m shoreline (after 16.8 ka). White lettering over dark gray represents the second regression (after 16.0 ka). Black lettering over light gray represents the latest Pleistocene transgression (after ca. 14 ka). The sequence of these events is shown schematically in the inset, with shorelines denoted by their elevations in meters.

collection of shells from lagoonal sediment behind the 1830 m spit at RLNWR, yielded an age similar to those collected directly from beach gravel at the 1818 and 1820 m beach ridges. Because no stratigraphic information was provided for 29021, it is difficult to interpret these similar ages at different elevations. It is possible that this sample returned an artificially young radiocarbon age because of incomplete pretreatment of shells before dating. The very large number of small gastropod shells necessary to yield a standard radiocarbon age makes this possibility more likely.

Latest Pleistocene Transgression (14–12 ka)

The final phase of Lake Franklin documented in this study is a late transgression represented by the lower beach ridges at RW and BH (Figs. 11B and 12). Although this is the least expansive reconstructed phase of Lake Franklin, the lake still covered an area of at least ~350 km^2 (33% of its highstand extent) at the peak of this transgression (Table 2), indicating that effective moisture remained elevated above modern values.

Shell samples collected from the beach gravel comprising the 1818 m ridge suggest that the ridge was built between 13.8 and 13.3 ka (Table 2). The younger of these results (59445) overlaps with the older ages (BH11–1a and 59446) obtained from the higher 1820 m ridge, but it fails to overlap with the youngest age (RW11–8) from this shoreline (ca. 13.0 ka). This relationship suggests that the 1818 m ridge was built before the beach ridge at 1820 m, requiring a rise in water level (Figs. 11B and 12). Evidence for a transgression also comes from the cross section of the 1820 m ridge at BH, where the beach sediment is clearly visible resting unconformably on a layer of marly, clayey sand (Fig. 7). The upper part of this fine sediment is oxidized, implying significant subaerial exposure. Thus, it appears that after constructing the 1826 m ridge at 14.8 ka, Lake Franklin fell to below 1818 m for ~1000 yr before transgressing again to (at least) 1820 m by ca. 13 ka (Figs. 11B and 12).

Water-level fluctuations into the Holocene, and the final demise of Lake Franklin, are not constrained by the data reported here. No shorelines below 1818 m were identified, suggesting that lower lake stages were either too short-lived, or too shallow, to generate preservable beach ridges.

Comparison with Other Regional Records

The large number of radiocarbon ages for shoreline landforms of Lake Franklin permits comparison with other relevant paleoclimate records. During the early LGM (24–21 ka), when Lake Franklin stood at 1823 m, mountain glaciers and ice sheets globally were in extended positions (Clark et al., 2009) in response to reduced solar insolation during the Northern Hemisphere summer, amplified cooling due to ice-albedo feedbacks, and lowered levels of atmospheric greenhouse gasses. Regionally, ^{36}Cl dating reveals that moraines corresponding to the Tioga 2 glaciation in the Sierra Nevada, 500 km southwest of Lake Franklin, were deposited between 25 and 20 ka (Phillips et al., 1996). A radiocarbon-dated rock flour record from Bear Lake in northern Utah indicates that the Bear River Glacier in the western Uinta Mountains, 400 km east of Lake Franklin, reached its latest Pleistocene maximum extent ca. 24 ka (Laabs et al., 2007; Rosenbaum and Heil, 2009). Surface-exposure dating of moraine boulders with ^{10}Be suggests that alpine glaciers in the northern and eastern Uinta Mountains were at their terminal positions by 22–20 ka (Laabs et al., 2009), synchronous with glaciers in the Wallowa Mountains 500 km to the north (Licciardi et al., 2004). In addition, ^{3}He ages from moraine boulders on the Fish Lake Plateau, 350 km southeast of Lake Franklin, indicate a local glacial maximum at 21.1 ka (Marchetti et al., 2011). Together, these similarities indicate that the earliest reconstructed phase of Lake Franklin corresponds to a climate that was suitable for glacier growth.

Other pluvial lakes in this region had moderately high, or rising, water levels during the early LGM. For instance, Lake Diamond, 50 km southwest of Lake Franklin (Fig. 1), was apparently near its overflowing level by 26.5 ka, based on radiocarbon dating of tufa (Tackman, 1993). Lake Bonneville, which fell slightly during the Stansbury Oscillation ca. 25 ka, was rising again after 25 ka (Oviatt, 1997). The record of Lake Estancia in central New Mexico, 1000 km southeast of Lake Franklin, exhibits multiple highstands during the early LGM (Allen and Anderson, 2000). In the southwestern Great Basin, numerous lakes were high during this interval, including Owens (Bacon et al., 2006), Panamint (Jayko et al., 2008), and Thompson (Orme, 2008). Within the Lake Franklin basin, the abundance of *Pediastrum* began to increase at 24.5 ka, indicating a transition from saline to dilute water conditions (Thompson, 1992). Collectively, these records illustrate that pluvial lakes throughout the Great Basin were responding to increases in effective moisture during the early LGM, although at least in the northern Great Basin, effective moisture had yet to reach levels that were required for highstand conditions.

During the late LGM interval (21–17 ka), Lake Franklin expanded as effective moisture continued to increase in the northern Great Basin. Well-constrained glacier records from the surrounding region indicate maximum ice extents at this time, including the Tioga 3 glaciation in the Sierra Nevada (Phillips et al., 2009) and glacier advances in central Colorado to the east (Brugger, 2007) and southern California to the southwest (Owen et al., 2003). Results from the Ruby Mountains adjacent to Lake Franklin also indicate a glacial maximum immediately prior to 19 ka (Laabs et al., 2011a). Many pluvial lakes that were high during the early LGM remained high through this interval, and Lake Bonneville continued to rise toward its overflowing level (Oviatt, 1997). Abundances of *Pediastrum* in cores from the Ruby Marshes reached peak levels ca. 20 ka, indicating freshwater conditions (Thompson, 1992). Together, these connections are consistent with increasingly cold and/or wet conditions across this region during the late LGM.

Some of the more tenuous oscillations in the Lake Franklin hydrograph during this interval also find intriguing support from regional paleoclimate records. Most notably, the possible rise of Lake Franklin to 1843 m (or 1850 m) ca. 18.2 ka overlaps with a pronounced cold interval seen in a speleothem record from Pinnacle Cave in southern Nevada (Lachniet et al., 2011). This connection suggests the possibility that Lake Franklin briefly rose to near its highstand elevation in response to a short episode of cooler temperatures that reduced evaporation rates. Similarly, if Lake Franklin rose ca. 18.2 ka, then the subsequent drop back to 1830 m by 17.6 ka overlaps in time with a pronounced desiccation event in Lake Estancia (Allen and Anderson, 2000). This event, referred to as the "Big Dry," may have been of regional extent across the Great Basin, although evidence from Lakes Bonneville and Lahontan is equivocal (Broecker et al., 2009).

The pluvial maximum of Lake Franklin (17–16 ka) exhibits strong correspondence with other well-dated pluvial lake records from the Great Basin. Nearby Lakes Clover and Waring (Fig. 1) reached highstands at the same time as Lake Franklin (Munroe and Laabs, 2012). Lake Newark (Kurth et al., 2011) and Lake Jakes (García and Stokes, 2006) were also at their highstands ca. 16.9 ka. Lake Diamond remained high until at least 16.6 ka (Tackman, 1993). Lake Bonneville overflowed from 18.5 to 15.0 ka (Oviatt, 1997; Benson et al., 2011), and Lake Lahontan was near its highstand after ca. 16.5 ka (Adams and Wesnousky, 1998). This regional signal indicates that pluvial lakes throughout the Great Basin were driven to (in many cases) unprecedented highstands by an abrupt increase in effective moisture that began ca. 17 ka. The timing of this convergence of highstands is synchronous with the age of Heinrich Event 1 in the North Atlantic region (Bond et al., 1992; Hemming, 2004), suggesting that atmospheric teleconnections related to cooling of the North Atlantic induced increased precipitation in the southwestern United States (Asmerom et al., 2010; Munroe and Laabs, 2012).

Regression of Lake Franklin after 15.4 ka matches the conversion of Lake Bonneville to a closed basin below the Provo shoreline (Godsey et al., 2011), the rapid drop of Lake Lahontan from the Sehoo highstand after 15.8 ka (Adams and Wesnousky, 1998; Benson et al., 2012), and the onset of deglaciation in the Wasatch Mountains at 15.7 ± 1.3 ka (Laabs et al., 2011b). On a broader scale, this interval corresponds with the Bølling-Allerød (Greenland Interstadial 1) warming in the North Atlantic (Lowe et al., 2008). Speleothem records from the southwestern United States register this warming as an abrupt increase in $\delta^{18}O$ values (Asmerom et al., 2010; Wagner et al., 2010), corresponding to drier conditions. Overall, it appears that final regression of pluvial lakes was driven by a regional decrease in effective moisture.

The latest Pleistocene transgression (14–12 ka) to (at least) 1820 m represents a temporary reversal in this increasing aridity. This event appears to have had a regional footprint. For instance, other pluvial lakes in the northern Great Basin exhibited modest transgressions at this time, including Lake Bonneville (Oviatt, 1997; Oviatt et al., 2005), Lahontan (Benson et al., 2012), and Owens (Orme and Orme, 2008). Glaciers in the Sierra Nevada readvanced ca. 13.4 ka (Phillips et al., 2009), and cool conditions persisted into the Younger Dryas interval (MacDonald et al., 2008). This transgression may reflect cooling and/or increased precipitation resulting from changes in atmospheric circulation induced by the Younger Dryas event in the North Atlantic. This stadial, which was apparently driven by glacial lake outburst flooding (Carlson et al., 2007), was similar to Heinrich Event 1 in that North Atlantic Deep Water formation was inhibited, which halted the Atlantic Meridional Overturning Circulation (McManus et al., 2004), leading to extreme cooling of the North Atlantic region (Denton et al., 2005). Because speleothem records have demonstrated that cool conditions in the southwestern United States correspond with stadial conditions in the North Atlantic (Asmerom et al., 2010), it is reasonable to infer a causal link between the Younger Dryas event and the transgression of Lake Franklin back to 1820 m. However, given the available age control, the latest Pleistocene transgression of Lake Franklin began before the Younger Dryas interval (ca. 13.8 ka vs. 12.9 ka) and must have been initiated by a mechanism other than the cooling of the North Atlantic. Perhaps Lake Franklin began to rise in response to the cooling responsible for the Recess Peak advance of glaciers in the Sierra Nevada. Atmospheric teleconnections related to the Younger Dryas event may have subsequently enhanced effective moisture in Ruby Valley, sustaining the lake at the 1820 m level after the initial perturbation had diminished.

CONCLUSIONS

The results of this investigation permit construction of a well-dated hydrograph for a previously understudied pluvial lake in northeastern Nevada. This hydrograph is fundamentally based on radiocarbon dating of gastropod shells because a lack of extensive exposures precludes comprehensive application of sequence stratigraphy. This approach limits our ability to define a unique trajectory of water-level change during some time intervals. However, careful consideration of the sedimentology and stratigraphic setting of the layers from which shells were collected, in conjunction with surveyed elevations of beach ridges, increases certainty in the reconstructed water-level fluctuations.

The location of Lake Franklin, midway between Lakes Bonneville and Lahontan, and its extent relative to other lakes in the Great Basin during the last pluvial cycle offer potential for comparison with other regional paleoclimate records. Results indicate that during the first half of the LGM (24–21 ka), Lake Franklin covered roughly 43% of its maximum extent. Water level was stable for ~2500 yr, averaging 1823 m and constructing a massive beach ridge where the Franklin River delivered sediment from the glaciated Ruby Mountains.

During the second half of the LGM (21–17 ka), Lake Franklin expanded to cover 60% of its highstand area. The level of the lake was again stable (or with oscillations around a consistent mean elevation) at 1830 m for nearly 3000 yr. A few radiocarbon ages suggest short-lived lake-level rises during this time. However, because the stratigraphic contexts of these dates are equivocal, these oscillations are less well constrained.

The pluvial maximum of Lake Franklin (17–16 ka) began with an abrupt rise to a highstand elevation of 1850 m ca. 17.0 ka. This rise was synchronous with highstands in numerous surrounding pluvial lakes, as well as with Heinrich Event 1 in the North Atlantic, suggesting a causal linkage involving an atmospheric teleconnection. At this point, Lake Franklin covered an area of ~1100 km^2, ranking it in the top 10% of all U.S. pluvial lakes during the last pluvial cycle. The pluvial maximum contained a minor oscillation spanning no more than a few centuries, in which lake level dropped and shoreline landforms were constructed at 1846 and 1843 m, before a second rise to 1850 m.

After reaching its highstand elevation a second time, Lake Franklin regressed to 1843 m and built one of the most prominent shoreline features throughout Ruby Valley ca. 15.4 ka. After 15.4 ka, Lake Franklin fell rapidly to an elevation of 1826 m by 14.8 ka, in concert with the regression of Lake Bonneville from the Provo shoreline after 15.0 ka, and the fall of Lake Lahontan from the Sehoo shoreline after 15.8 ka. The nadir of this regression is unknown; however, the presence of a weathered surface recording subaerial exposure indicates that it reached an elevation below 1818 m, and a surface area of <25% of the highstand lake extent.

Lake Franklin rose one final time during a latest Pleistocene transgression ca. 13.8 ka, which overlapped in time with the Recess Peak advance of glaciers in the Sierra Nevada and the Younger Dryas event in the North Atlantic. The simultaneous occurrence of modest transgressions in other pluvial lakes indicates a regional driver for this late water-level rise.

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