Implications and Hydrographs for Two Pre-Bonneville Pluvial Lakes and Double Geosols from 14 OSL-IRSL Ages in Cache Valley, NE Bonneville Basin

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ABSTRACT

In the northeastern Great Basin, USA, thirteen new optically stimulated luminescence (OSL) ages and one infrared stimulated luminescence (IRSL) age show that two deep pluvial lakes preceded the Bonneville lake cycle in Cache Valley during marine oxygen-isotope stages (MIS) 6 (123-191 ka) and 4 (56-71 ka), respectively. Our new data define quantitative hydrographs of the Little Valley and Cutler Dam lake cycles in both Cache Valley and the main Bonneville basin. In western Cache Valley, excavation of a faulted, east-plunging spit has sequentially exposed these deposits and overlying MIS 3 Fielding humid-over-arid double geosols that end westward at a strand of the east-dipping Dayton-Oxford normal-fault zone. Lithologically identical double paleosols in eastern Cache Valley overlie a variety of deposits, including dated Little Valley lake beds, and persist above the Bonneville shoreline.

Six new ages show that the Little Valley lake cycle in Cache Valley began before 169 ka and ended after 143 ka, and its highest shoreline was above 1493 m. The >25 kyr duration of this pluvial lake cycle rivals the combined durations of the two subsequent lake cycles, during MIS 4 and MIS 2. The Cutler Dam lake rose at least to ~1450 m by ~67 ka in Cache Valley. In the type area in the main Bonneville basin, west of Cutler Narrows, four averaged IRSL dates from Cutler Dam lake beds show that the lake level there had dropped to ~1340 m by ~59 ka. The Little Valley lake rose at least 40 to 50 m above the local Provo shoreline whereas the Cutler Dam lake missed reaching the Provo shoreline by ~13 m.

Beneath central Cache Valley, southeast of the study area, there are two laterally extensive, confining layers of silty clay with an intervening sandy gravel layer, all overlying thick gravelly sediment. Both confining layers enclose additional thin and discontinuous gravel layers with adjacent oxidized clays. These alternating coarse and fine sediments are probably correlative with the exposed MIS 6 to MIS 1 deposits and, possibly, older lake cycles.

INTRODUCTION

Cache Valley is a narrow, elongate north-trending graben that straddles the Utah-Idaho border (Williams, 1948, 1958, 1962; Evans and Oaks, 1996; Janecke and Evans, 1999; Oaks, 2000; Janecke and others, 2003; Carney and Janecke, 2005). It is separated from the main Bonneville basin by a bedrock-cored horst upthrown between the Wasatch (west) and West Cache (east) fault zones. Cutler Narrows connects the two basins (Figure 1B). The Bear River fully entered Cache Valley through Oneida Narrows (Figure 1A) ~45 to 55 ka (Pederson and others, 2016) due to diversion by volcanic eruptions in Gem Valley in SE Idaho (Bright, 1963, 1967; Link and others, 1999; Janecke and Oaks, 2014; Utley, 2017).

PREVIOUS WORK

Pre-Bonneville Lakes in Cache Valley

The last three lake cycles of the Eastern Great Basin coincide with even-numbered marine-isotope stages (MIS) (Lisiecki and Raymo, 2005). These are the Little Valley (~123 to 191 ka, MIS 6), Cutler Dam (~ 56 to 71 ka, MIS 4), and Bonneville (~14 to 29 ka, MIS 2) lake cycles (Scott, 1988; Scott and others, 1982, 1983; McCoy, 1981, 1987; Oviatt and McCoy, 1988, 1992; Oviatt and others, 1987, 1992; Kaufman and others, 2001; Hart and others, 2004). Well- developed interglacial paleosols separate some but not all of the lake beds. A dated and formally defined paleosol is called a geosol.

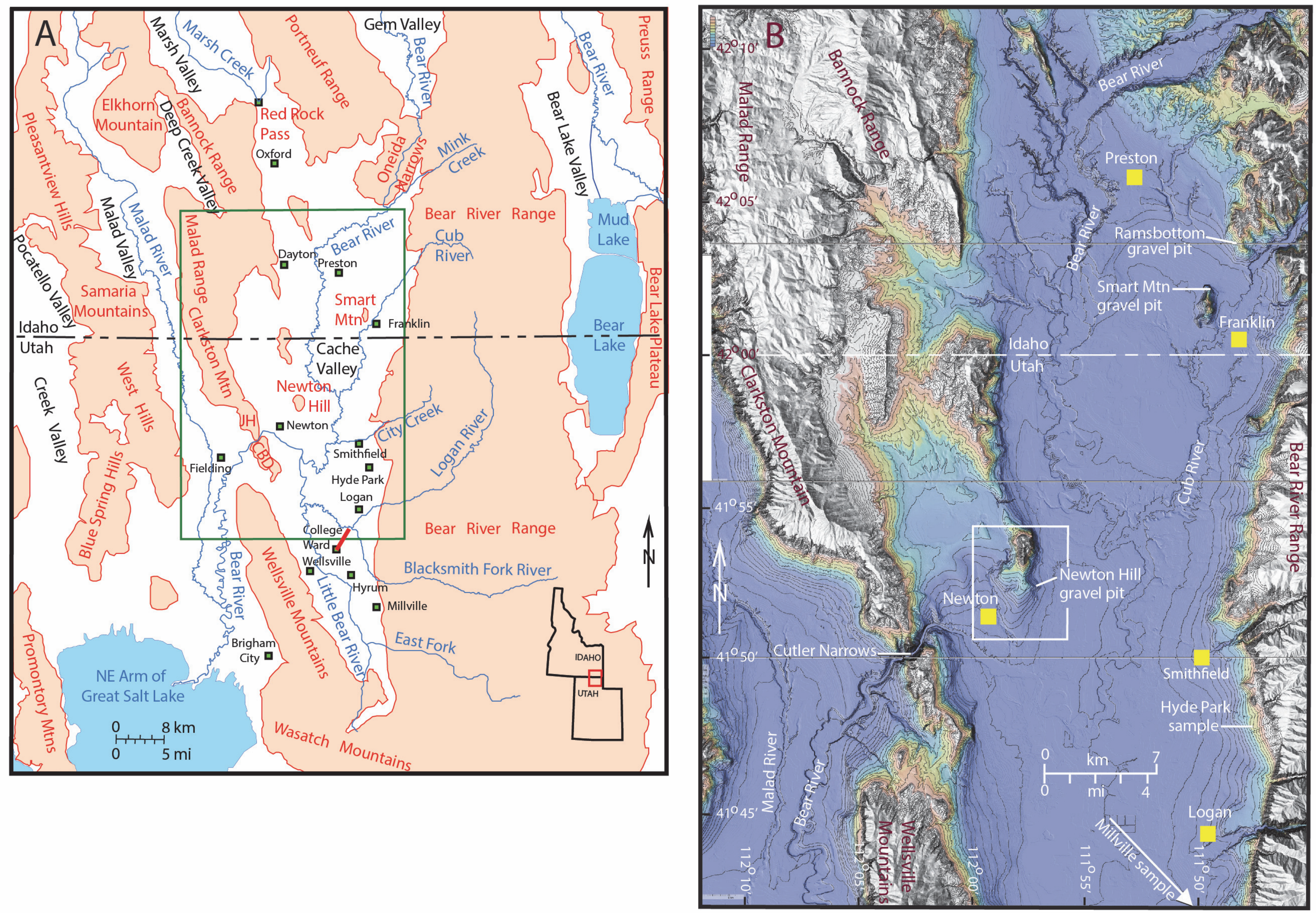

Figure 1. *A) Major features of the greater Cache Valley region, N-central Utah and SE Idaho. Green box outlines area in Figure 1 B. Red line NE from College Ward, south central Cache Valley, shows location of Figure 6. JH = Junction Hills; CBD = Cache Butte Divide. B) Landscape of Cache Valley area showing sites of pre- Bonneville deposits dated with AAR, OSL, and IRSL. Type area of Cutler Dam unit is along Bear River, SW of Cutler Narrows. Bonneville shoreline is lowest white; Provo shoreline is between blue and green shading. White box outlines area in Figure 2.*

Bright (1963, 1967) and McCoy (1981) identified lacustrine gravels below a paleosol beneath gravels of Lake Bonneville at the Ramsbottom gravel pit in Idaho, NE Cache Valley (Figure 1B). From that site and nearby Smart Mountain, Idaho, Scott and others (1982, 1983) derived amino-acid racemization (AAR) data from snail shells in the older lake beds beneath the paleosol that were correlative with AAR data from the Little Valley lake cycle in the main Bonneville basin.

Highest Altitudes of Pre-Bonneville Lakes

Oviatt and others (1987), Oviatt and McCoy (1988, 1992), and Kaufman and others (2001) concluded that the Cutler Dam unit, in exposures up to 15 m thick SW of Cutler Narrows, was deposited in marshy to shallow lacustrine conditions with ostracods indicative of fluctuating brackish conditions. The highest outcrop is at ~1340 m. The highest probable Little Valley gravels in the main Bonneville basin, which were not dated, are about half-way between the local Bonneville and Provo shorelines (Scott and others, 1982, 1983).

Incision of Cutler Narrows

The Bear River flows SW through Cutler Narrows, the deep and narrow canyon of the Bear River across the narrowest part of the Cache Butte Divide (Figure 1B). This canyon is cut into hard Paleozoic bedrock, is up to 392 m deep, and coincides with the highest bedrock along the Cache Butte Divide (Maw, 1968). Its bedrock channel is 1.8 km long.

Nearshore gravels of the Cutler Dam lake cycle in Cache Valley are ~110 m higher than somewhat younger marshy deposits in the main Bonneville basin. From that, Oaks and others (2019, 2020) concluded that most of the bedrock excavation of the lower part of Cutler Narrows, from an elevation between the highest levels attained by Cutler Dam and Little Valley pluvial lakes down to the present level near 1314 m, coincided with eastward flow during the Bonneville flood, ~17.4 ka (Marrero, 2009).

From their analysis of digital-elevation models (DEMs), Nelson (2012) and Chen and Maloof (2017) proposed that the Stansbury oscillation (~26 to 24 ka in Oviatt, 2015), may have reached into lower parts of Cache Valley through Cutler Narrows, across an area of ~300 km^2. If so, Cutler Narrows was already deeply incised to below the Stansbury level before Lake Bonneville existed, allowing Lake Bonneville to oscillate as a 5-10 m deep lake in lower Cache Valley.

METHODS

Introduction

Our study emphasizes a Staker-Parson gravel pit that we call the Newton Hill pit, in west-central Cache Valley (Figures 1, 2). Our emphasis is primarily on pre-Bonneville lakes, so the literature on Lake Bonneville is cited only where pertinent. All altitudes are above mean sea level. Those within the Newton Hill pit are tied to an altitude at a nearby section corner and based on electronic distance meter (EDM) and hand-level surveys. Altitudes of the original surface there and altitudes elsewhere are based on U.S Geological Survey 7.5-minute topographic maps, GPS readings, Caltopo Lidar, and Google Earth Pro. We report present altitudes without correction for post-Bonneville rebound or tectonics because Bonneville rebound is <10-20 m in our study area in Cache Valley and rebound of pre-Bonneville deposits cannot be computed without better pre-Bonneville hydrographs.

Age Control

We obtained 12 OSL (optically stimulated luminescence of quartz) and IRSL (infrared stimulated luminescence of feldspar) ages from the Newton Hill pit, one from the SE part of Hyde Park, Utah, and one from Muley Hill in Millville, Utah. The latter two are in the east side of Cache Valley (Figures 1A, 1B; Table 1). A metal tube was pounded horizontally into the sediment except at Muley Hill, where matrix sand was collected from gravel beds using double black plastic bags under red light at night. Surrounding sediment was obtained to establish both background data and moisture content for each sample. Lab analyses at the Utah State University OSL lab by Michelle Nelson were done under the supervision of Tammy Rittenour, with standard procedures outlined in the notes of Appendix 1.

Recalibration and new standards for OSL dating changed the OSL and IRSL dates reported earlier by us (Oaks and others, 2014, 2019, 2020). One previous pluvial lake bed dated at ~96 ka (N = 1; the Newton Hill beds), instead formed during the earlier Little Valley Lake cycle (sample USU-1083; Table 1; Appendix 1).

Construction of Map and Geologic Cross Sections

The evolving exposures of the pit walls were surveyed with a Leica model TC600 laser total station in

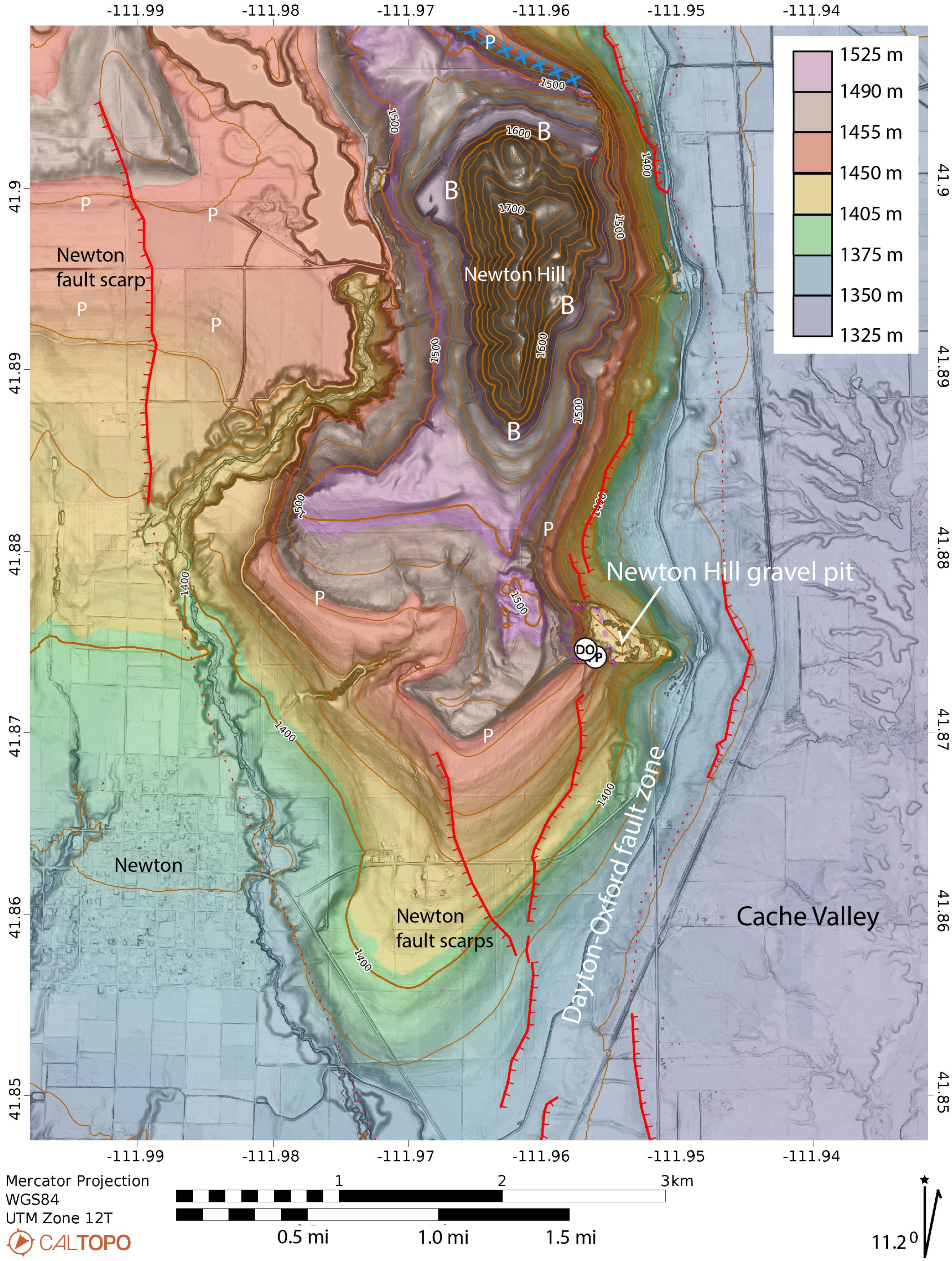

Figure 2. Digital-elevation model of LIDAR data of the Newton Hill area. A western strand of the Dayton-Oxford fault zone intersects the pit (DO). Farther west, several Newton fault scarps are left unlabeled to show their clear topographic expression. B = Bonneville shoreline, P = Provo shoreline. Contour interval 20 m. Blue is lower, brighter colors higher.

Table 1. *OSL & IRSL sample information and ages for Staker-Parson gravel pit (SE flank of Newton Hill), SE Hyde Park, and NE Millville, Cache County, Utah. See Appendix 1 for details for these samples.*

USU-Sample Number	Age in ka and Method	Hand-Level from EDM Control in Feet	EDM Altitude in Feet	Sample Altitude in Meters	Stratigraphic Unit	Location 1983 NAD	Comments; ~65 m W correction from 1983 GPS data to 1927 North American datum for USGS topographic maps in 1960s	Date and Collectors
859	15.42 ± 1.39 OSL	N.D. Map ~4790	4737 Depth ~53	1444	Late Qlbp	~ N 41° 52.614' ~W 111° 57.426'	NW edge of pit; silt & sand beds dip E; below ~4800' Qlbp highest shore	9-15-2010 TR & MN
3243 NE Millville, Utah	20.98 ± 3.04 OSL	GPS ~5083 Map ~5085 Google ~5087	N.D. Depth 3'	~1550	Early Qlbb	N 41° 41.2048' W 111° 48.2467'	3' below crest of Muley Hill, Millville, Utah; dissected older delta between Provo and Bonneville lake stands	11-19-2019 RO & TC & TR
1082	21.35 ± 3.48 OSL	~4665 Map ~4775	<4672 Depth ~115	~1422	Early Qlbb	N 41° 52.5244' W 111° 57.3198'	Center of pit; laminated silty sand over Qlv gravel; 10' above USU-1083	12-2-2011 RO & TE
854	21.72 ± 2.78 OSL	~4748 Map ~4785	N.D. Depth ~37	~1447	Early Qlbb	N 41° 52.4478' W 111° 57.3978'	Temporary road near S-center edge of pit; silty sand & clay above Qfg geosol, below Qlbp gravel	9-7-2010 TR & RO
855	39.28 ± 3.72 OSL	~4739 Map ~4810	N.D. Depth ~71	~1444	Qfg	N 41° 52.478' W 111° 57.393'	S-center of pit; red colluvium: sandy gravelly mud at top of loess geosol	9-7-2010 TR & RO
1084	53.51 ± 6.44 OSL	N.D. Map ~4875	4865 Depth ~10	1483	Qfg? Qcd?	N 41° 52.5045' W 111° 57.5009'	High W pit margin; white reworked ash and fine sand in NNW-SSE channel, under E-dipping gravel & soil, over 4° W-dipping Qlv gravel	12-5-2011 RO
856	66.82 ± 5.94 OSL	~4729 Map ~4810	N.D. Depth ~81	~1441	Qcd	N 41° 52.479' W 111° 57.388'	S-center of pit; gravel below Qfg red paleosol base; 9.8' below USU-855	9-7-2010 TR & RO
858	67.70 ± 6.46 OSL	~4709 Map ~4790	N.D. Depth ~81	~1435	Qcd	N 41° 52.473' W 111° 57.382'	S-center of pit; very fine to medium sand below gravel, ~25 ft below Qfg geosol base	9-15-2010 TR & MN
2895 SE Hyde Park, Utah	142.8 ± 13.1 OSL	N.D. Map ~4865 Google ~4898	N.D. Depth 9.25	~1493	Qlv	N 41° 47.8341' W 111° 47.8214'	N-S vertical wall; fine to coarse sand within pale green marl below Qfg white caliche geosol below Qlbb lag gravel under fine to very fine sand with snails	7-27-2018 RO
1083	144.3 ± 14.5 OSL	~4655 Map ~4780	<4673 Depth ~125	~1419	Qlv	N 41° 52.5243' W 111° 57.3310'	Center of pit; gravel 8.4' below base of Qlbb sand of USU-1082	12-2-2011 RO & TE
3202	150.0 ± 25.9 OSL	~4690' Map ~4885	N.D. Depth ~195	~1430	Qlv	N 41° 52.5570' W 111° 57.4022'	W-center of pit; pebbly sand 3.0' below base of Qfg red geosol, with thin Qcd between	10-28-2019 RO
2490	155.6 ± 21.4 IRSL	~4735 Map ~4840	N.D. Depth ~105	~1443	Qlv	N 41° 52.5203' W 111° 57.4165'	W-center of pit in WSW cut; sand and gravel in cobble gravel, 22' lower than base of overlying channel to W	9-26-2016 RO & TE
857	161.5 ± 16.8 OSL	N.D. GPS 4824 Map ~4865	N.D. . Depth ~44	~1470	Qlv	N 41° 52.492' W 111° 57.477'	SW pit in WSW cut; sand & pebble groundmass in cobble gravel; EDM 4821 later at graded site	9-15-2010 TR & MN
2491	169.4 ± 28.6 OSL	~4678 Map ~4805	N.D. Depth ~127	~1426	Qlv	N 41° 52.5548' W 111° 57.3882'	NW pit near S end of headwall; pebbly sand below Qcd calcareous sandy mud intertonguing upward with sandy pebbly cobble gravel clinoforms above	9-26-2016 RO & TE

OSL = optically stimulated luminescence on quartz sand; IRSL = infrared stimulated luminescence on feldspathic sand; ka = thousands of years ago; Google = Google Earth Pro; EDM = total station, electronic distance measurements with laser; GPS = global-positioning-system measurement; HL = hand level used from EDM base station; N.D. = no data; Map: original surface altitudes are interpolated from 1964 U.S. Geological Survey 7.5' Newton [C.I. = 5'] and Trenton [C.I. = 20'] topographic quadrangles; Qlbp = Provo highstand lake stage; Qlbb = Bonneville highstand lake stage; Qfg = Fielding emergent interval with multistory humid over arid geosols, and perhaps higher N-S channel; Qcd = Cutler Dam lake stage; Qlv = Little Valley lake stage; MN = Michelle S. Nelson; RO = Robert Q. Oaks, Jr.; TC = Tomas Capaldi; TE = Thad L. Erickson; TR = Tammy M. Rittenour. Note: Qcd and early Qlbb lakes in Cache Valley may have been separated at Cutler Narrows from lower coeval lakes in the main Bonneville basin.

2016. Thereafter, new contacts were surveyed with an Abney hand level from the EDM base station. These data, combined with our 12 OSL and IRSL ages from the central and western parts of the pit, were used to construct a map and four composite stratigraphic sections across much of the Newton Hill pit (Figures 3, 4). Correlations are tied to: (1) continuous and isolated exposures of the Fielding double geosols (Oviatt and McCoy, 1988) at the top of dated Cutler Dam lake beds in the central part of the pit, and westward atop dated Little Valley beds; (2) a thick green marl low within Bonneville deposits; and (3) an overlying pink marl.

Quantitative Hydrographs

Our new data (Table 1) and prior AAR data (Appendices 2, 3, 4) and thermoluminescence (TL) data, tied to altitudes (Appendix 5), constrain our quantitative hydrographs (Figure 5) of the Cutler Dam and Little Valley lake cycles in both Cache Valley and the main Bonneville basin. These hydrographs update schematic plots of Scott and others (1982, 1983), McCoy (1987), Oviatt and others (1987), and Hart and others (2004), for these two pre-Bonneville lake cycles. Our results align with far more detailed hydrographs of the Bonneville lake cycle in the main Bonneville basin of Currey and Oviatt (1985), Oviatt and others (1992), Nelson (2012), and Oviatt (2015, 2020). Our data also constrain the pre-Bonneville, post-Cutler Dam age of newly identified red-over-white double Fielding geosols in the Newton Hill pit and lithologically similar paleosols in eastern Cache Valley.

RESULTS

Overview of Newton Hill Gravel Pit

On the SE flank of Newton Hill, central Cache Valley, Utah (Figure 3), our ongoing studies have delineated the internal architecture of an east-plunging, nose-shaped compound spit deposited atop an east-sloping, eroded face of Little Valley gravel during the Cutler Dam and Bonneville lake cycles. The most continuous exposures lay between ~1408 m and ~1462 m, mostly below the prominent, higher Provo shoreline (Janecke and Oaks, 2011a, 2011b) at ~1463 m at this locality. Scattered exposures continued to ~1487 m. Exposures in the south-central part of the pit in 2006 were so extensive that the key stratigraphic relations and the overall architecture of the deposits were unambiguous (Figure 6).

The spit's original crest flattened uphill westward into a wave-cut and wave-built platform at the higher Provo shoreline of Lake Bonneville (Figure 2). The crest of the spit was parallel to and slightly north of the southern boundary of the gravel pit (Figure 6D). Pre-Bonneville sediment is mostly exposed in the central and western half of the gravel pit.

Little Valley Lake Beds

Stratigraphic Relationships

In the Newton Hill pit, Little Valley gravel is overlain by the upper red geosol at sample site USU-2490 (Figure 7A). At sample site USU-2491, there is no geosol between Little Valley pebbly sand and overlying Cutler Dam sandy mud (Figure 7B). At USU-1083 (Figures 4B, 4D) and at USU-857 (Figure 4A), Little Valley gravel is overlain by Bonneville deposits, with no geosol between. At USU-2895 Little Valley marl is overlain by a Fielding-like caliche paleosol beneath offshore Bonneville deposits. At USU-3202 Little Valley gravel is overlain by thin sediment of Cutler Dam lake cycle, then the upper Fielding geosol, beneath laminated fine-grained Bonneville deposits (Figures 4A, 4D). Although undated, at USU-1084 probable Little Valley gravel underlies a local channel with ashy sand under surficial gravels with modern soil. We did not find the base of the Little Valley deposits, nor identify pre-Little Valley units. Downward excavation ceased in the central part of the Newton Hill pit because of a noncommercial green marl 4 to 6 m thick according to two pit operators.

The Little Valley deposits are primarily pebble to cobble gravels and sandy gravels with low dips (Figure 7A). Discontinuous exposures west of the Dayton-Oxford fault strands reached at least 8 m thick. Locally there are thin marls and sand beds.

In Hyde Park, Utah, in eastern Cache Valley (Figure 1), at sample site USU-2895, a pale green Little Valley marl with a thin, calcareous, fine- to coarse sand lens is overlain by a white Bk paleosol 0.55 m thick, in turn overlain by a thin lag cobble gravel followed upward by 2.0 m of Bonneville light brown, thinly laminated, silty very fine sand with snails (cf. nearby exposure at Figure 8A). Elsewhere in eastern Cache Valley, weakly laminated to structureless marls and minor fine sands dominate probable Little Valley deposits. These undated older lake beds underlie the double Fielding geosols and Bonneville deposits, and persist at least up to ~1530 m, which is about 40 to 45 m below the local Bonneville shoreline (Figure 8B).

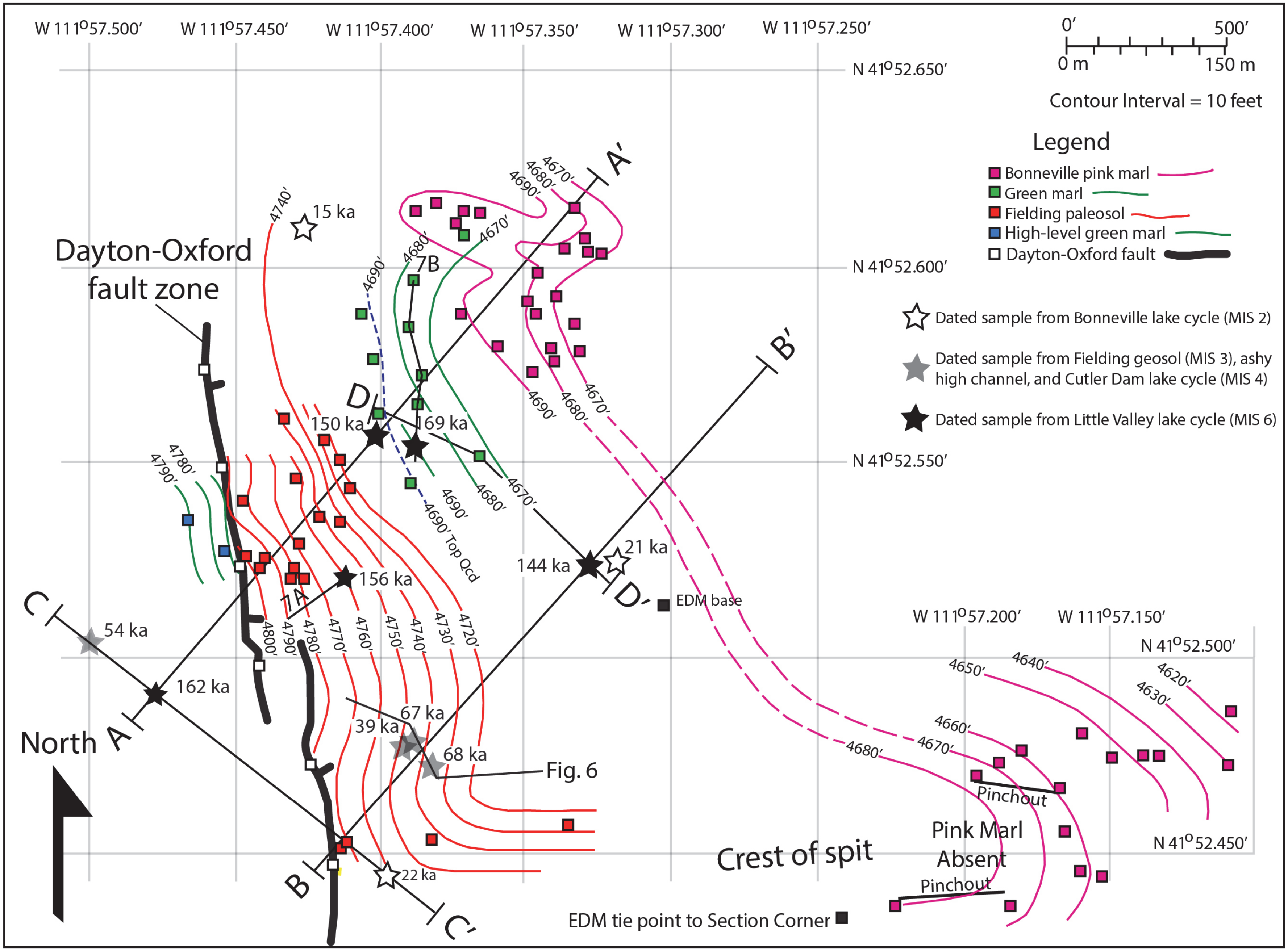

Figure 3. *Map of Staker-Parsons gravel pit SE of Newton Hill shows locations of OSL and ISRL age dates; contours of the tops of the extensive red Fielding geosol in the S and W, the pink/white/green shrinking marl in the N and SE, the laminated green clay between them; locations of geologic cross sections A - A′ to D - D′ in Figure 4, and locations of Figures 6A, B, C and 7A, B.*

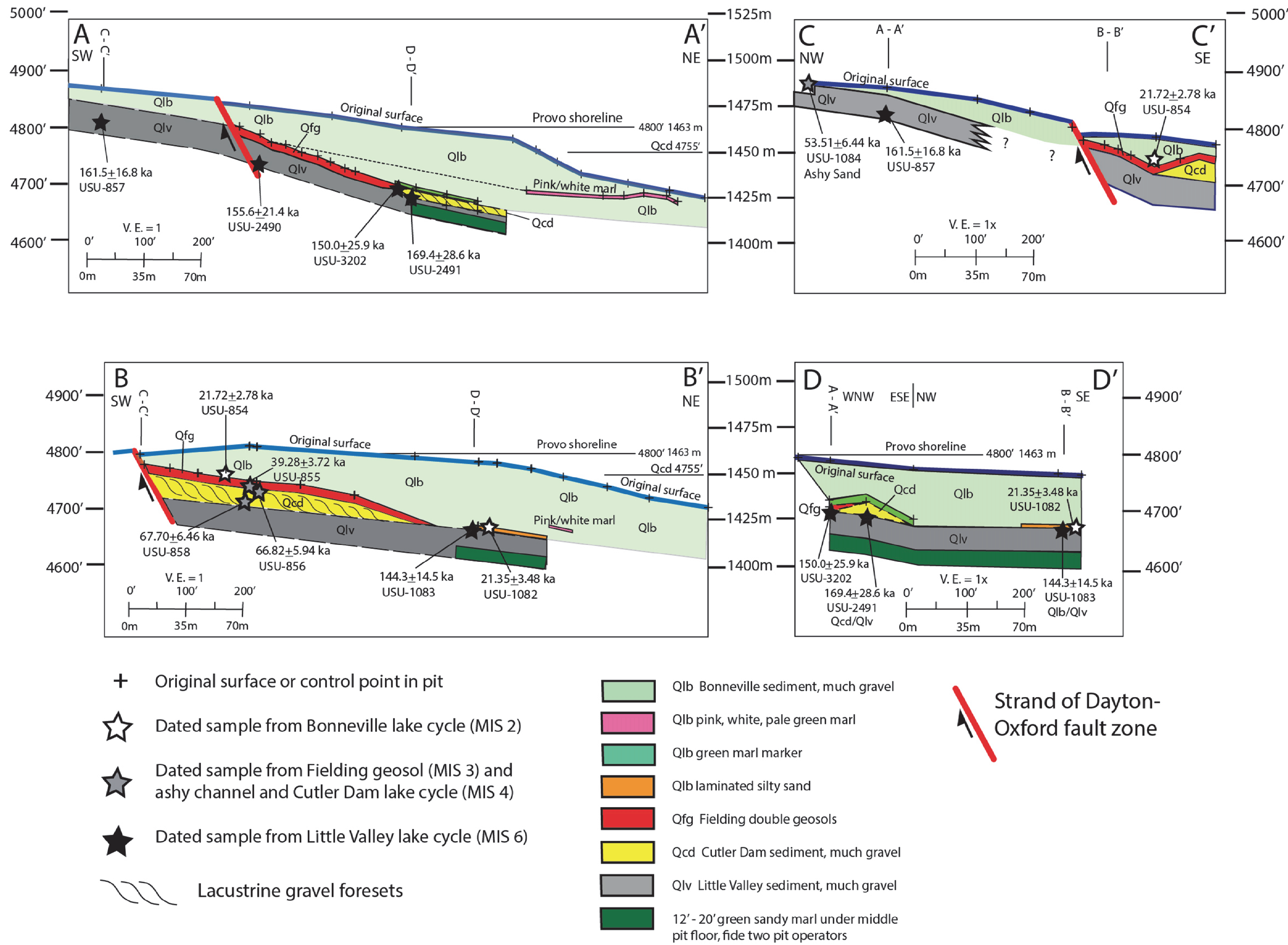

Figure 4. *Geologic cross sections A - A' to D -D' show extents of identified geologic units, original surface, OSL and IRSL age dates, pre-Bonneville lake deposits, and intersections with other geologic cross sections. See Figure 3 for locations.*

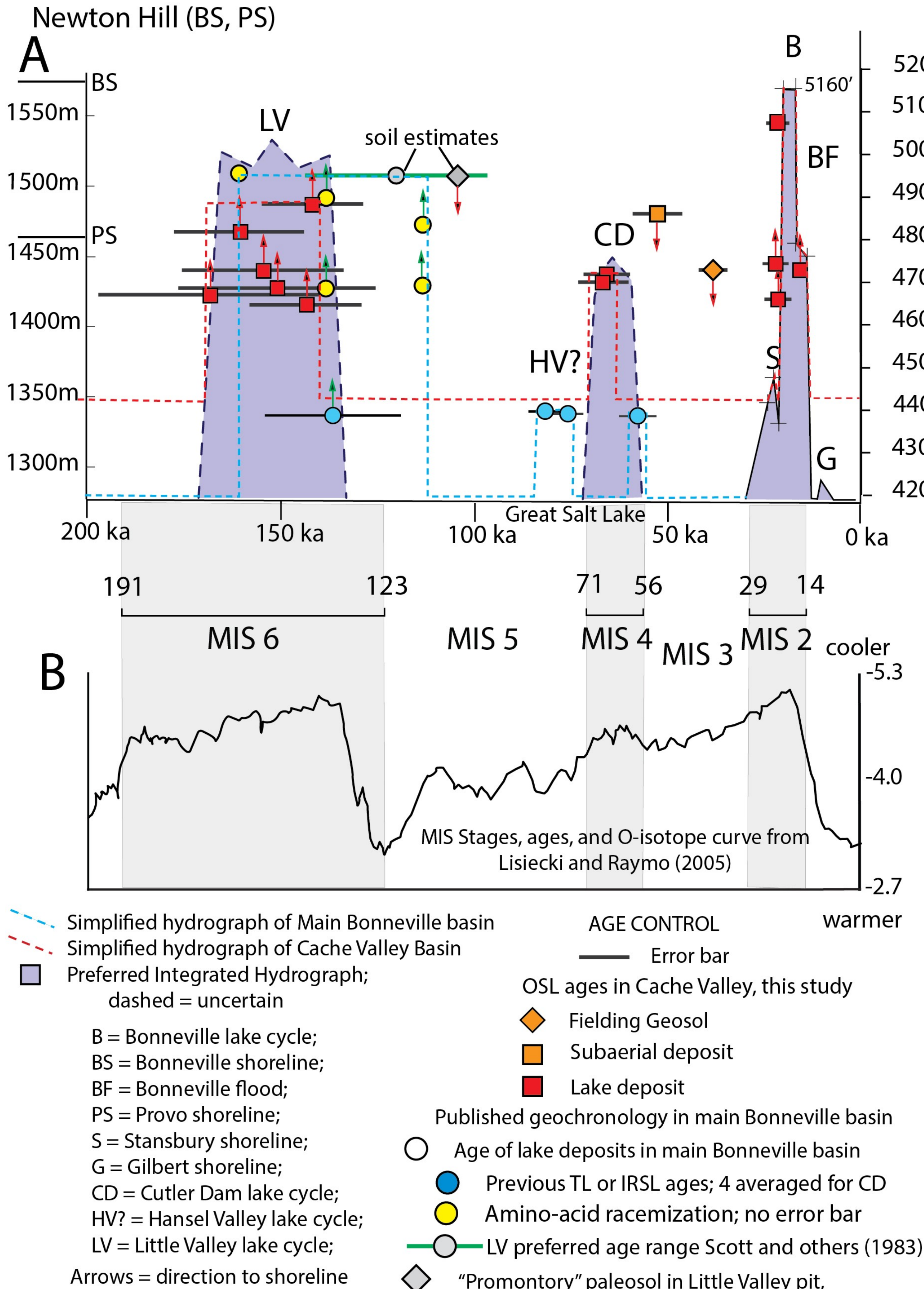

Figure 5. *Hydrographs showing changes in shoreline levels in the main Bonneville basin and Cache Valley since 200 ka compared with simultaneous climatic changes. Dates with error bars, ages of ashes and chrons, and sources are from Table 1 and Appendices 2 and were revised from Oaks and others (2019).*

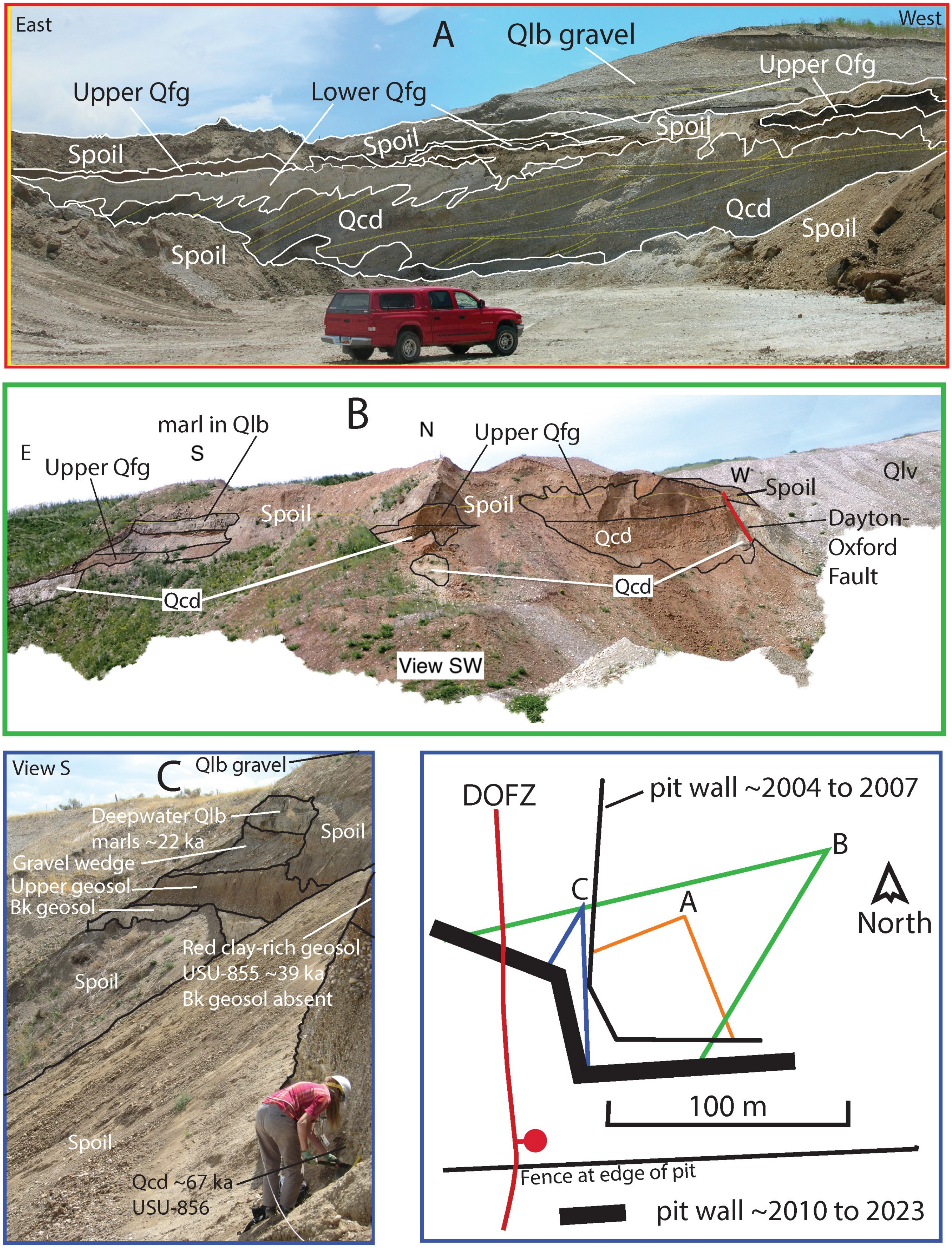

Figure 6. *A) Original exposure of Cutler Dam (Qcd) gravel overlain by the double Fielding geosols (Qfg), beneath deep-water Bonneville and younger Provo deposits (Qlb). B) Exposures W from the above site showed lateral continuity of this sequence in the hanging wall of the Dayton-Oxford fault. The fault dips toward viewer. Figure C) Details of Qcd, Qfg, and Qlb at sample site USU-856. D) Map showing camera positions of Figures 6A, B, C. Locations shown in Figure 3.*

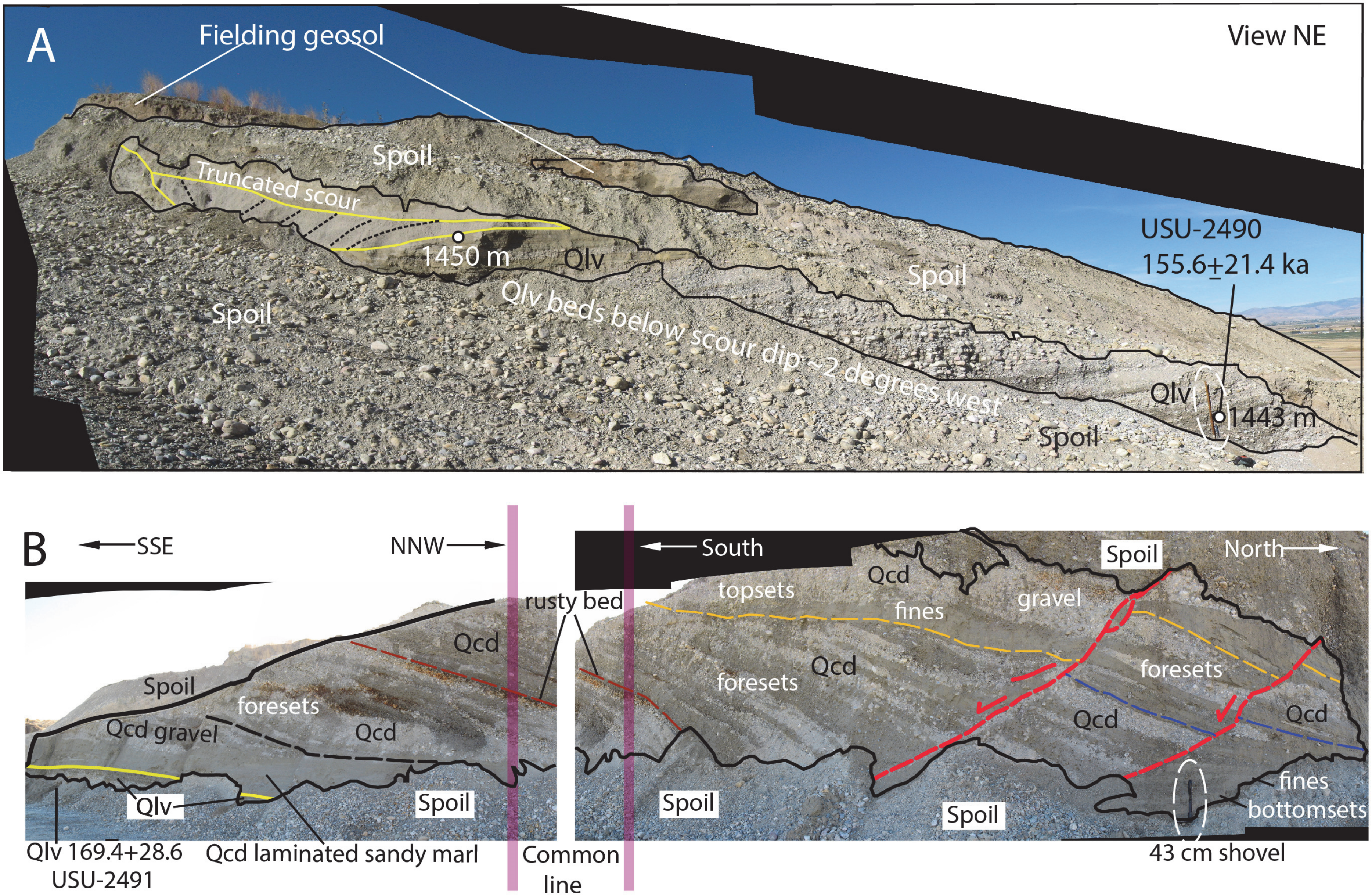

Figure 7. *A) Little Valley (Qlv) deposits. Truncated channel in upper left has curved sand laminae dipping toward the deepest part. Fielding red geosol here extended over Qlv. Staff = 1.50 m. Sample USU-2490 is the same altitude as the highest exposures of Cutler Dam (Qcd) deposits ~170 m SE, but below the highest (projected) Qcd ~1450 m ~120 m south B) Northwest edge of Newton Hill pit shows erosional unconformity (yellow) between Little Valley lake beds (Qlv) and overlying Cutler Dam beds (Qcd). There is no paleosol along this contact. Gravel and fines of the Cutler Dam lake cycle preserve bottomset, foreset, and topset beds (orange base) that formed in the east-plunging spit. Deposits are cut by two subsequent faults or slumps (red). Marker beds within the spit are color-coded. See Figure 3 for locations. Both photos 9-26-2016.*

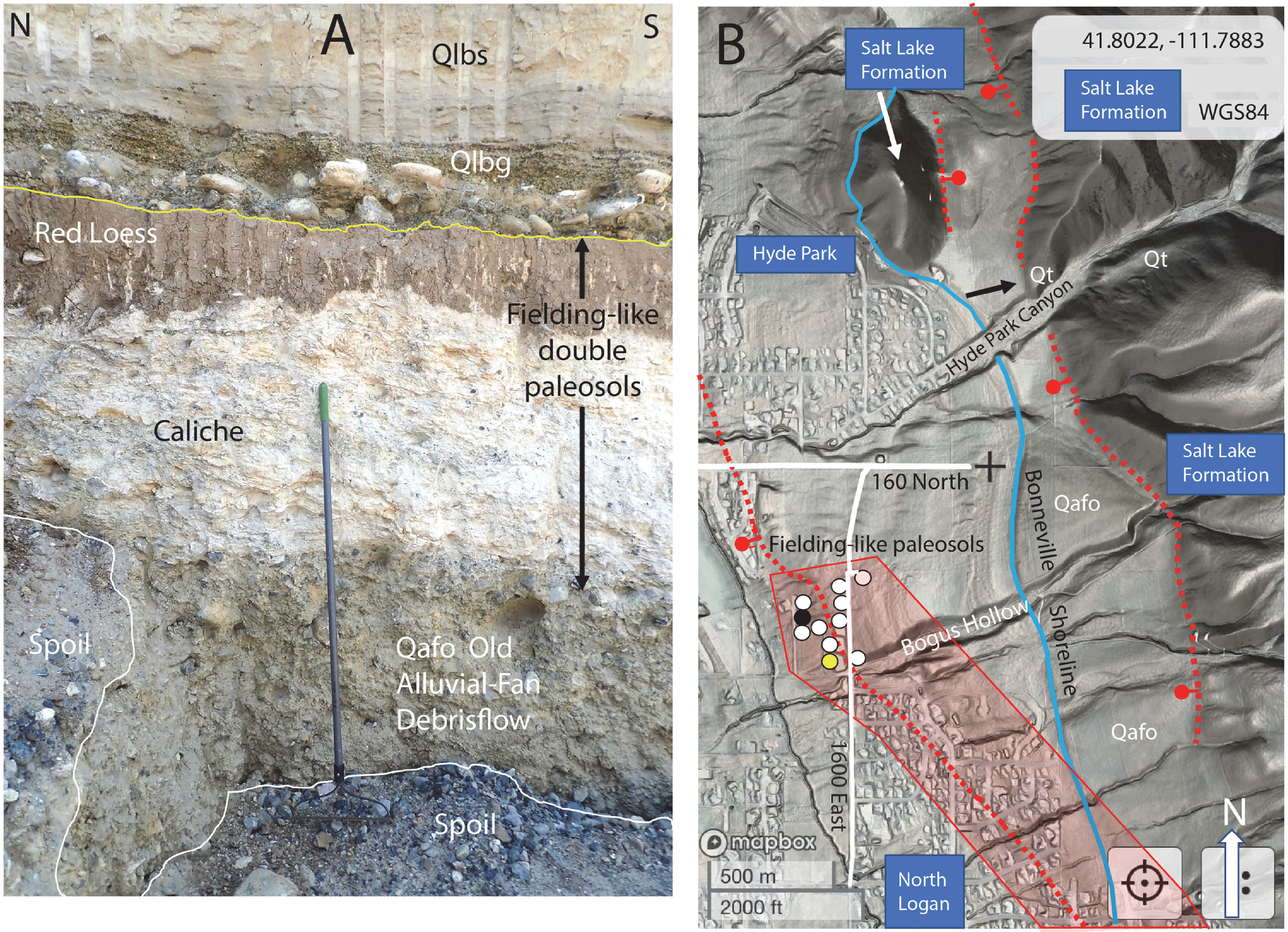

Figure 8. *A) Double paleosols in eastern Cache Valley (Figure 1B) that lithologically match our dated Qfg in the Newton Hill pit. Here they are overlain by Bonneville lag gravel (Qlbg) and sand (Qlbs). Underlying alluvial-fan deposits (Qafo) were not dated, so subaerial exposure and soil-forming could have begun before MIS 3. Location is at yellow dot in 8B. B) Lateral extent of exposures of double paleosols in east Cache Valley. Latitude and longitude indicate the mid-point of this image (+). Black dot marks site of ~143 ka OSL age (USU-2895) sampled within fine-grained Little Valley lake beds (Qlv) beneath a calcrete. Qt fluvial terrace is offset 9 m across a strand of the East Cache fault zone at the black arrow.*

Age Control (N=6)

Five exposures of pre-Bonneville lake gravels in the Newton Hill pit and one exposure in Hyde Park, Utah returned OSL and IRSL ages coeval with the Little Valley Lake cycle (MIS 6). The oldest age of ~169 ka (USU-2491) is from the north-central part of the Newton Hill pit, whereas the youngest age of ~143 ka (USU-2895) is from Hyde Park at ~1493 m. The latter is also the age determination from the highest elevation. The Little Valley lake cycle flooded Cache Valley to elevations well above ~1493 m, possibly as high as ~1530 m, and attained altitudes many tens of meters higher than expected (cf. Scott and others, 1983). The youngest beds dated in the Newton Hill pit (USU-1083; Table 1) are essentially the same age as that from Hyde Park.

Cutler Dam Lake Beds

Stratigraphic Relationships

In the south-central part of the Newton Hill pit, east-sloping foresets of sandy, well-rounded, pebble to cobble gravels underlie the Fielding geosols. The foresets there were >6 m high and extended horizontally about 200 m (Figure 6A). To the north, exposures of these spit gravels are about 6 to 10 m thick and flatten into finer bottomset beds (Figure 7B). There are sharp erosional contacts locally within the foresets (Figure 6A). The highest exposures reach ~1443 m, but early photos (Figure 6B) and projection in Figure 4D suggest that the highest lake beds may have reached ~1450 m (Appendix 5).

Bedding in the S-central part of the pit and the shape of the overlying pink marl (Figure 3) indicate that the spit probably was mainly east-plunging, yet part of this spit also extended northward (Figures 4A, 4B, 4D, 6B). Gravels to the north intertongue with underlying green, silty, fine-sandy laminated marl 2 m thick (Figure 7B). Most gravel lenses there thin downward and pinch out to the north between intercalated marl layers that thin upward and pinch out to the south. Two fault or slump surfaces offset the gravels in the north. These offset the contact between topsets and foresets (Figure 7B).

Age Control (N=2)

Two samples from this deposit in the south-central part of the Newton Hill pit yielded OSL dates of ~67 ka (USU-856, -858). These are coeval with the Cutler Dam lake cycle and MIS 4 (Figures 3, 4, 5; Table 1).

Ashy Channel Fill

Near the former west margin of the Newton Hill pit, a white reworked ashy fine sand filled a scour below thin surficial gravel and modern soil, ~1483 m. Satellite imagery (8-11-2011) in Google Earth Pro shows this narrow channel trended NNW-SSE. Probable Little Valley beds below this channel dip ~4° west and roll over eastward to dip gently east. The upper part of the probable Little Valley beds are truncated eastward at the pre-Cutler Dam erosional face (Figure 7A). This subaerial channel fill yielded an OSL age of ~54 ka (USU-1084), during MIS 3 (Table 1; Figures 3, 4C). This is older than the upper Fielding geosol but younger than the Cutler Dam gravels exposed lower in the Newton Hill pit and the shallow-water Cutler Dam muds in the type area southwest of Cutler Narrows (Figure 5).

Double Fielding Geosols In Newton Hill Pit

Stratigraphic Relationships

In the original south-central part of the pit, two successive geosols developed above and partly within the top of underlying gravel foresets of the Cutler Dam lake cycle (Figure 6A). This unit consists of an upper, humid-climate, red-weathering, loess-dominated interval and a lower, arid-climate, white caliche interval. The contact between the two geosols is primarily erosional, but locally gradational. In one place the upper geosol is separated from overlying deep-water Bonneville deposits by a thin gravel wedge up to 1 m thick (Figure 6C).

The lower of the two geosols typically has only an eroded lower Bk horizon, up to 1.5 m thick, above the Cutler Dam foreset gravels. This geosol pinches out east and west of the south-central part of the pit, and does not reach the east strand of the Dayton-Oxford fault westward in the pit (Figures 6B, 6C). Calcite in the lower geosol penetrated down into the Cutler Dam foreset gravels beneath (Figure 6A). It has amalgamated subhorizontal stringers of carbonate and amorphous nodules. Pieces of the eroded caliche are common in the lower part of the red geosol above (Figure 8A). The eroded upper contact of the caliche has distinct channels up to 15 cm deep filled with, and overlain by, as much as 2.5 m of the red geosol.

The upper geosol is mainly loess and slightly pebbly loess, although locally it contains abundant colluvium. It has considerable organic material, exhibits downward displacement of clay, has a distinctive reddish soil hue (10R5.5/4), displays little cementation, and has a few vertical calcite stringers, but lacks caliche nodules except those reworked into the base

(Figure 6C). Its top has a less prominent erosion surface than its base. This upper geosol thickens to 5 m or more westward, near the hanging wall of the Dayton-Oxford fault (Figures 6B, 7A), and locally on the north flank of the Cutler Dam spit, where the caliche geosol is absent (Figures 4A, 4D). There its upper part is colluvial gravelly mud overlying 2 to 3 layers of gravelly loess with weak subsoils. Locally in the north it pinches out eastward beneath a gray modern soil at the original surface of the pit.

Where absent in the east part of the pit, and locally in the north part of the pit, the upper contact of the double geosols is marked by a lag gravel or the green marl (Figures 4A, 4D) at the base of the Bonneville deposits above Cutler Dam foresets. Surveyed contacts of the top of the reddish geosol suggest that it probably rose at least to ~1463 m in the west part of the pit (Figures 4A, 4B, 4C). It descended to below ~1441 m in the SE part of the pit, and to below ~1444 m locally northward (Figures 3, 4D). Erosion probably removed these geosols from the lower and higher parts of the present Newton Hill pit before Bonneville deposits were laid down. The absence of the Fielding geosols in the footwall of the Dayton-Oxford fault makes it challenging to estimate the throw across the fault, although it must be >2 m.

Age Control (N = 1)

In the S-central part of the pit, the middle part of the red geosol, ~1444 m, contains a lens of sandy sediment that yielded an OSL age of ~39 ka (USU-855) (Figures 3, 4B, 6C). This dates to the penultimate interglacial, MIS 3c (Lisiecki and Raymo, 2005).

Double Geosols in Eastern Cache Valley

In Hyde Park and North Logan, Utah, in eastern Cache Valley, we found numerous examples of pre-Bonneville double paleosols in many trenches for utilities and in basement and landscape excavations (Figure 8B). These paleosols are essentially identical to those in the Newton Hill pit, with a red clay-rich paleosol over an eroded white caliche paleosol. Several of the lower exposures have only the eroded lower white Bk paleosol, locally with a very thin, eroded, red paleosol above. Detailed local mapping with an Abney hand level near sample site USU-2895 demonstrated an undulose paleotopography beneath the paleosol with lateral changes in the underlying sediments uphill and laterally. All exposures lie above the highest Cutler Dam deposits in the Newton Hill pit.

In eastern Cache Valley, either the double paleosol, loess deposits, or a gravel lag underlie the Bonneville offshore sand with snails (west, lower) and Bonneville gravel or post-Bonneville colluvial gravel (east, higher), respectively (Figure 8B). The white caliche paleosol overlies dated Little Valley marl (~143 ka; USU-2895) at ~1493 m in Hyde Park, and both paleosols overlie undated alluvial-fan debris flow deposits at ~1526 m in exposures farther east (Figure 8A). Exposures of these widespread double paleosols were recorded through a vertical range of at least 124 m and a horizontal separation of at least 2.7 km NNW-SSE (Figure 8B). The highest exposure, at ~1607 m, is above the Bonneville shoreline (41.78501, -111.77766). Our current concept of the spatial and stratigraphic relations of the lake cycles and intervening paleosols is shown in Figure 9.

Bonneville Lake Beds

Stratigraphic Relationships

Bonneville deposits originally blanketed the spit in the area of the Newton Hill pit (Figure 2). In the southern exposures, topsets and foresets of sandy pebble to cobble gravels of the Bonneville lake cycle (Figure 6A) grade downward into finer bottomsets that overlie more than 3 m of transgressive deep-water marls and laminated silty sand (Figure 6C). Northward, where the pre-Bonneville relief was lower, deposition included lower green marls and a single higher pink marl that form distinctive marker beds (Figures 3, 4) between thicker Bonneville gravels (Figure 10). The pink marl is a calcareous, very fine sandy, clay-rich silt. It is plastic, weakly laminated, and thin (tens of cm thick). It is either pink throughout (oxidized reddish orange (5R7/2) or greenish-gray to whitish color at the base. It might be Gilbert's "white marl", which dates from the highstand of Lake Bonneville. Its red stain may be due to iron supplied by the proximal Bear River.

Locally, a lower green Bonneville marl directly overlies Cutler Dam deposits where the Fielding geosols are absent (Figures 4A, 4D), but there are other traceable pale greenish marls higher in the Bonneville sequence. Several marls produced low-angle slip surfaces that repeat layers within the Bonneville deposits in small slumps and slides (Figure 10). These might have been triggered by earthquakes, the Bonneville flood, or both.

Age Control (N=4)

Near the south-center margin of the pit, gently east-dipping, gray, laminated silty sand yielded an OSL age of ~22 ka (USU-854) (Figures 3, 4B, 4C).

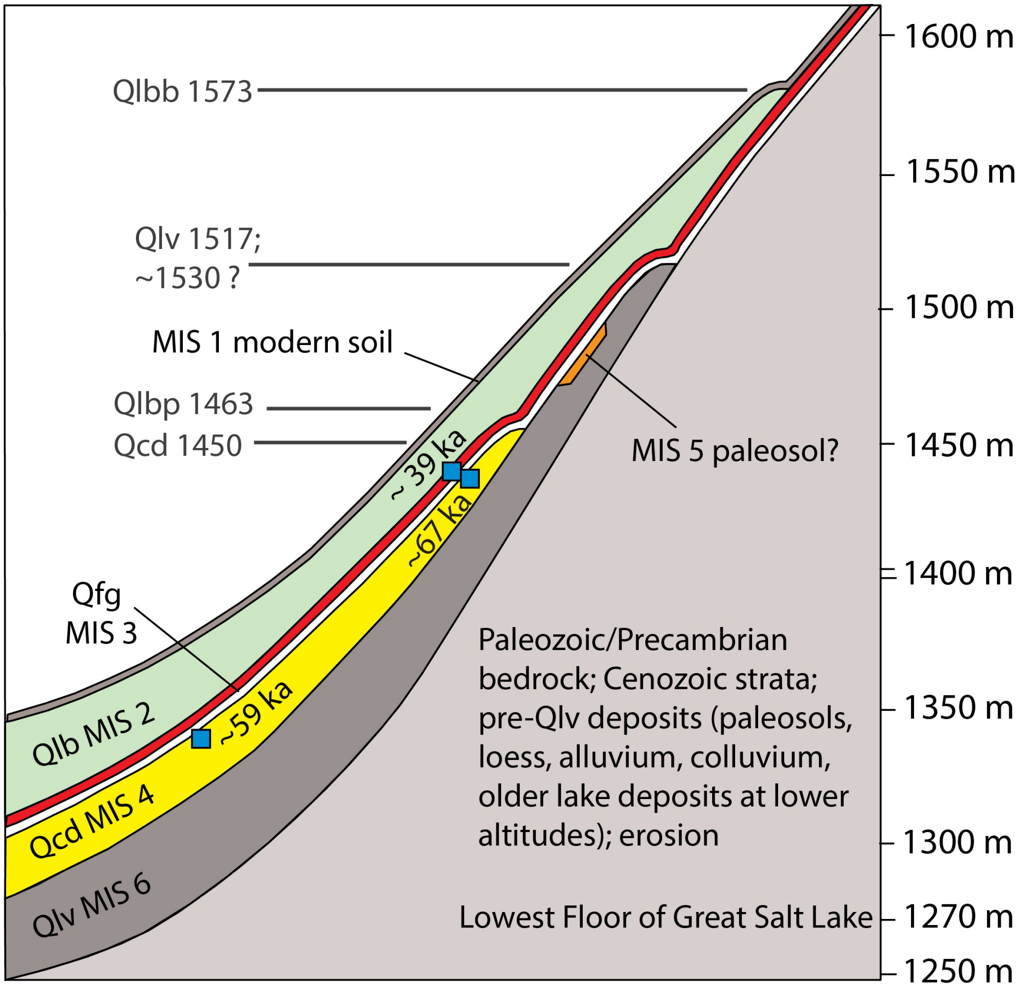

Figure 9. *Schematic cross section of the relative geometries of deposits of three pluvial lakes in Cache Valley, intervening double soils, the modern geosols, and the modern surface soil on the double paleosols above the Bonneville shoreline in eastern Cache Valley and the Newton Hill pit. Qlb = Bonneville lake cycle; Qlbb = Bonneville shoreline; Qlbp = Provo shoreline; Qfg = double Fielding geosols; Qcd = Cutler Dam lake cycle; Qlv = Little Valley lake cycle; MIS = marine oxygen-isotope stage. Although we found no distinct MIS 5 paleosol developed on Qlv, it might be incorporated in the base of Qfg above Qcd deposits. Above the Bonneville shoreline, modern soil is developing on and augmenting exposed Qfg. Horizontal scale is tens of kilometers. Concept from Oviatt and others (1987). Any paleosols within lake cycles are omitted. Altitudes are not corrected for rebound.*

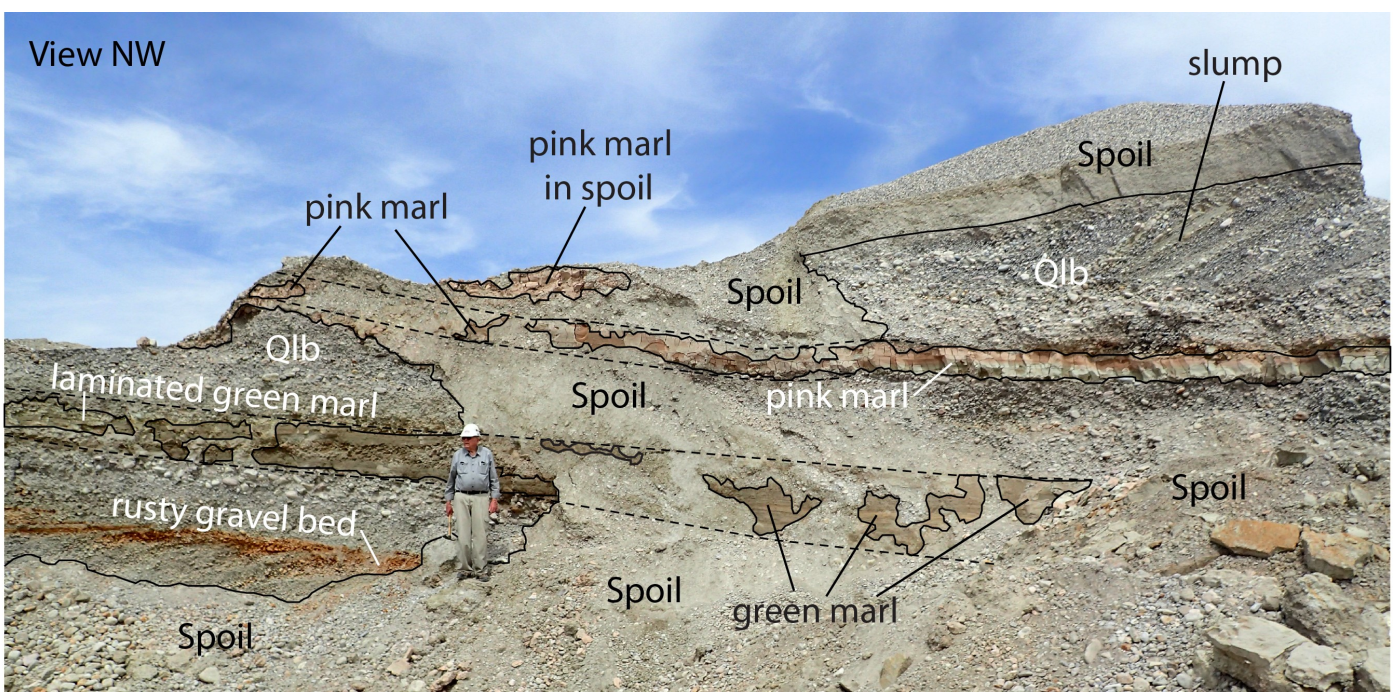

Figure 10*. Exposure of distinctive marls within Bonneville (Qlb) nearshore gravels in Newton pit. The pink marl is widespread in the Newton Hill pit whereas the underlying laminated green marl is more restricted. Thad Erickson = 1.8 m. NW part of pit. The stratigraphic position and gravel of the slump above the pink marl suggests a possible trigger by the Bonneville flood. The pink marl records the deepest water depths.*

These deep-water deposits sharply overlie an unconformity and the upper Fielding geosol (Figure 6B). A laminated silty sand lens in cobble gravel from the lower part of Bonneville deposits, in the central part of the pit, yielded a slightly younger OSL age of ~21 ka (USU-1082). There the Bonneville deposits directly overlie eroded Little Valley gravels (USU-1083) with no paleosol between (Figures 4B, 4D). A sand bed intertongued with northeast-dipping gravel beds in the north-central part of the pit yielded a post-flood Provo age of ~15 ka (USU-859) (Figure 3). At Muley Hill in Millville, Utah, gravel atop an eroded delta, at ~1550 m, between the Bonneville and Provo levels, yielded an age of ~21 ka (Table 1).

Subsurface Evidence of Pluvial Lakes

Drillers' logs from >1000 water wells across the center of Cache Valley southeast and east of Newton Hill document two gravelly layers and two clay-rich layers in the subsurface. An upper confining silty clay (marl?) unit ~18 m thick, an intervening, persistent gravel unit ~9 m thick, and a lower confining silty clay unit ~9 m thick, overlie thick underlying gravel and sand (Williams, 1962; Bjorklund and McGreevy, 1971; Clyde and others, 1984; Kariya and others, 1994; Robinson, 1999; Thomas and others, 2011). Figure 11 shows these relations along part of U.S. Highways 89/91 (Figure 1). Within the upper confining layer there are typically two horizons of non-persistent gravels associated laterally with oxidized brown silty clays. Gray, blue, or black silty clays lie both above and below these gravel and oxidized intervals. The lower confining layer also encloses lenses of gravels and related oxidized horizons. These clays overlie sandy gravels of Pleistocene age and underlying older gravels in the Salt Lake Formation that cumulatively reach ~150 m to 300 m thick between Smithfield, Wellsville, and Hyrum (Robinson, 1999) (Figure 1A). These coarse sediments are the Principal Aquifer in Cache Valley (Figure 11).

The unoxidized clays probably are deep-water lake deposits. They likely are coeval with the three lacustrine deposits in the Newton Hill pit, and perhaps earlier pluvial lakes in the main Bonneville basin (Williams, 1962), including older lake cycles identified in the Saltair and Burmester cores (Eardley and Gvosdetsky, 1960, Eardley and others, 1973; Williams, 1994; Oviatt and others, 1999). The gravels and oxidized muds at distinct levels within the unoxidized muds either indicate interglacial epochs or major oscillations within long pluvials (Williams, 1962; this study). In the southwest part of Figure 11, a persistent gravel within the upper confining layer may be a chance intersection laterally along a former stream channel.

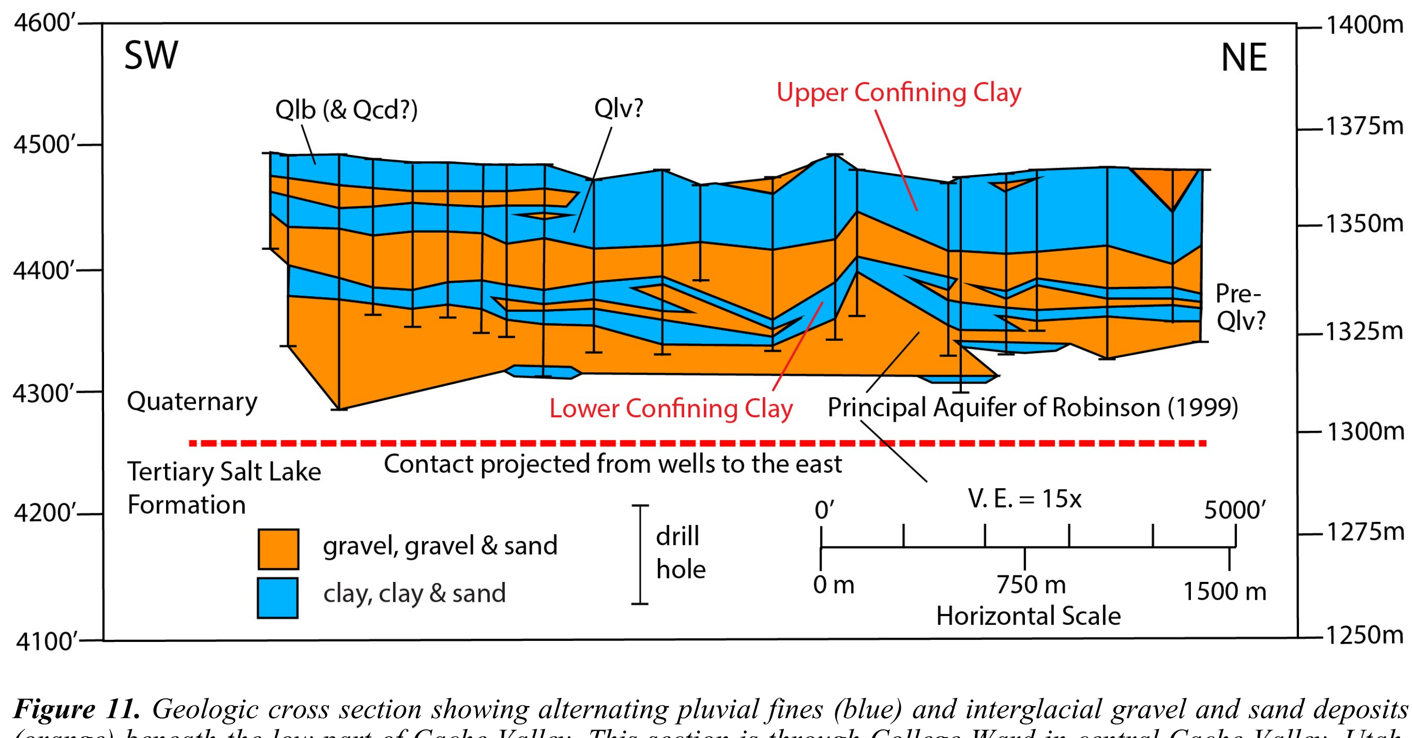

Figure 11. Geologic cross section showing alternating pluvial fines (blue) and interglacial gravel and sand deposits (orange) beneath the low part of Cache Valley. This section is through College Ward in central Cache Valley, Utah, along U.S. Highways 89/91. Qlb = Bonneville; Qcd? = Cutler Dam; Qlv? = Little Valley. See Figure 1A for location. Question marks indicate that correlations with other lake cycles are possible. Williams (1962) first documented these repeating coarse and fine intervals of lacustrine and fluvial deposits in drill holes in five geologic cross sections across the Utah part of Cache Valley.

Elsewhere in Cache Valley, the underlying Salt Lake Formation has many different lithologies. These include conglomerates, tuffaceous green (zeolite-bearing) to dark and light gray shales, sandstones, siltstones, thick to thin, pale brown very fine crystalline (micritic) limestones, oolitic limestones, and diabase (Adamson and others, 1955; Goessel and others, 1999; Oaks and others, 1999; Janecke and Evans, 1999; Janecke and others, 2003). These distinctive lithologies are repeated by extensional folds and normal faults, so that the Salt Lake Formation commonly exhibits tilts. Dips as high as 78° distinguish the Salt Lake Formation from the overlying Quaternary deposits (Oaks, 2000).

DISCUSSION

Correlations Related to the Hydrographs

Overview of the Hydrographs

Data for the hydrographs in Figure 5 are in Table 1 and Appendices 1 to 5. The hydrographs for Cache Valley and the main Bonneville basin show good correlation of lake highstands and lowstands in both basins and also with the O-isotope marine record of climatic fluctuations for MIS 6 through MIS 1. The Little Valley lake rose higher than the local Provo shoreline, whereas the Cutler Dam lake cycle did not rise quite as high (Figure 9).

The MIS 5 interglacial persisted for ~55 kyr, twice as long as the ~27 kyr- long MIS3 interglacial. The isotopic data also suggest that MIS 5 was warmer than MIS 3 (Figure 5). Yet there are no distinct, widespread soils associated with MIS 5 in Cache Valley, and the only possible exceptions elsewhere are the Promontory/Dimple Dell geosols in the Little Valley pit and other parts of the main Bonneville basin (Scott and others, 1983). It is noteworthy that well-dated Fielding humid soil and the underlying arid soil, both of which are widespread in Cache Valley, formed during the relatively short and mild interglacial MIS 3 before the Bonneville lake cycle, yet they are exceptionally thick and robust paleosols (Figures 3, 5, 6, 8).

The lake was at least 150 m deep during the 68 to 67 ka part of the Cutler Dam lake cycle, in the early part of MIS 4, yet it coincided with a relatively minor oscillation in the climate record (Lisiecki and Raymo, 2005). This seems anomalous compared with the climatic and hydrologic conditions that favored deep lakes during MIS 6 and MIS2. The oscillations of benthic marine isotopes are only about 60% as intense during MIS 4 as during MIS 6 and MIS2 (Figure 5).

Perhaps deep lakes can form with less Milankovitch forcing than glaciers. Alternatively, added water may have begun to flow across a waterfall in Oneida Narrows into Cache Valley then, followed ~20 kyr later by the complete, final diversion of the Bear River into the Bonneville basin (Pederson and others, 2016). A complex history of incision of Oneida Narrows is suggested by one or more widespread subsurface gravels below a mud layer under surficial gravel from Oneida Narrows through several kilometers downstream in drillers' logs of water wells (Oaks, 2010).

Little Valley Lake Cycle

The age and duration of the Little Valley lake cycle is constrained by our six new absolute ages, five published AAR estimates, one published TL age, and one extrapolation from the estimated rate of formation of the overlying Promontory paleosol (Figure 5; Table 1; Appendices 2, 3, 4). Combination of all the data for the main Bonneville basin (blue dashes in Figure 5) suggests that the Little Valley lake cycle might have persisted 20-30 ky into interglacial MIS 5. However, an end closer to 123 ka, at the end of MIS stage 6, is more likely based on the climate record and our new absolute ages (preferred model in Figure 5).

In the main Bonneville basin, altitude control for the Little Valley lake cycle is limited, with some corrected for rebound, others not (McCoy, 1981, 1987; Scott and others, 1982, 1983). The highest probable but undated Little Valley gravels in the main Bonneville basin are at ~1512 m in the Geneva quarry at Point of the Mountain, south of Salt Lake City (Scott and others, 1983) and at ~1517 m in the Little Valley pit, where they were initially misidentified as "Alpine" by Morrison (1965, 1966) and reinterpreted by Scott and others (1983). These older lake beds are about half way between the local Bonneville and Provo shorelines (Scott and others, 1983).

In Cache Valley the highest dated Little Valley deposits, at ~1493 m in Hyde Park are sandy, weakly laminated marl, and undated deposits traced uphill from dated beds in the upper Newton Hill pit, at ~1483 m. These also lie between the Bonneville and Provo shorelines. Thus, the highest level attained by the Little Valley pluvial lake is not certain, but elevation ranges are high and roughly similar in both basins (Appendix 5). Active tectonics in both basins may have raised or lowered individual sites, which is especially critical for older lakes. Further discovery of higher shoreline exposures and absolute ages are needed to determine if the actual highest water levels of the Little Valley lake cycle were the same or different across Cutler Narrows.

Cutler Dam Lake Cycle

Our ages of Cutler Dam deposits in Cache Valley confirm that this pluvial lake rose at least 110 m above that of marshy sediments in the type area (Oviatt and McCoy, 1988, 1992) in the main Bonneville basin SW of Cutler Narrows (Figures 1B, 6B; Appendix 5). Two IRSL ages from Cutler Dam deposits and two from the base of the Fielding geosol in the type area averaged ~59 ka (Kaufman and others, 2001). This is younger than the average of ~67 ka for two OSL ages near the higher level in Cache Valley. Although the error limits of the ages from both sites overlap slightly (Figure 5; Table 1; Appendix 2), the central ages differ. These data may indicate a drop to the lower level near the end of MIS 4, consistent with the climatic data (Figure 5).

Additional OSL age control from distal Cutler Dam beds in the Newton Hill pit would further constrain the hydrograph in Figure 5. Re-dating lake beds between those of the Little Valley and Bonneville lake cycles in Hansel Valley (Robison and McCalpin, 1987) with OSL might show that they are coeval with the Cutler Dam lake cycle, which seems likely.

Fielding Double Geosols

Our dated samples of the upper Fielding geosol and the ashy sand channel fill indicate that subaerial deposition replaced the Cutler Dam lake after the end of MIS 4, at ~56 ka. Our double geosols are similar to the sequence described by Kaufman and others (2001, p. 324) in the type area SW of Cutler Narrows. Their Figure 2 showed three successive geosols that comprise their Fielding geosol, described in the figure as: "Massive red-brown silt and clay; at least three petrocalcic horizons, each topped by a snail-rich horizon; oxidized rootlets on blocky weathered surfaces".

The similarity of our double geosols to descriptions of the Promontory and Dimple Dell double paleosols in the Little Valley pit (Morrison,1965) is also striking. There, a lower caliche geosol and an upper red (10YR) loess-derived geosol lie between Little Valley and Bonneville deposits. All exposures there are above the highest known Cutler Dam lake beds in Cache Valley.

Despite the similar lithologic features and nearly identical stratigraphic relationships, the Promontory and Dimple Dell geosols are interpreted to be much older, ~104 ka (Scott and others, 1983; their Table 5). If so, the Promontory and Dimple Dell palesols are significantly older than the Fielding geosols. Absolute ages are needed to resolve this puzzle.

An OSL age is needed in Hyde Park within the double paleosols there, to determine if these paleosols are definitely coeval with, or differ in age from, the dated upper Fielding geosol in the Newton Hill pit.

Bonneville Lake Cycle

The final diversion of the Bear River into Cache Valley ~ 45 to 55 ka (Pederson and others, 2016) was too late to raise the Cutler Dam lake, and all earlier lakes, above a divide ~2 km north of Red Rock Pass, at the north end of Cache Valley (Gilbert, 1890) (Figure 1A). Its final addition raised Lake Bonneville higher than earlier lakes, to overtop that divide (Bright, 1963; Hochberg, 1996; Bouchard and others, 1998; Link and others, 1999; Janecke and Oaks, 2014; Pederson and others, 2016; Utley, 2017). An earlier overflow across Oneida Narrows (Oaks, 2010) may have raised the Cutler Dam lake above that expected from the O-isotope data (Figure 5).

Our two OSL ages of ~21 ka in the Newton Hill pit, at ~1422 m and ~1447 m, lie within the wide envelope of ^{14}C dates with confidence intervals for the rising limb of the Bonneville transgression in the main Bonneville basin (cf. Oviatt, 2015, 2020). However, both are minimum depths for the lake level at those times. Furthermore, well-rounded gravels at Muley Hill, with an age of ~21 ka, at ~1550 m elevation, is close to the local Bonneville shoreline at ~1573 m (Figure 9), and above the Oviatt envelope of dates. Janecke and others (2013) obtained a ^{14}C age ~22 ka in nearshore sands at ~1500 m in a gravel pit at the mouth of Green Canyon in eastern Cache Valley, between Logan River and City Creek (Figure 1A), somewhat above the Oviatt envelope.

Thus, although the age-altitude data from Cache Valley plotted in Figure 5 might suggest a slightly earlier rise of Lake Bonneville during its transgression, the data do not differ enough from those compiled in Oviatt (2015, 2020) to be compelling. More precise and diverse age control is needed to improve the earlier curve for Lake Bonneville, which was compiled from ^{14}C age determinations.

We believe that a prolonged Bonneville highstand during oscillatory (?) overflow to the north, is needed to explain high, steep, wave-cut bedrock cliffs at the Bonneville shoreline throughout the Bonneville basin (Janecke and others, 2019). Significant time is also required to backfill Gem Valley, Oneida Narrows, lower Bear River-Mink Creek Canyon, and finally deposit the large Bonneville delta north of Preston, Idaho, with a surface area of >125 km^2 in Cache Valley (Figures 1A, 1B). The Bonneville delta of the Bear River back-filled a reach that was ~55 km long, between Gem Valley and northeast Cache Valley (Janecke and Oaks, 2011b).

Implications for Incision of Cutler Narrows

It is unclear if Cutler Narrows was incised well below the ~1450 m Cutler Dam gravels of Cache Valley before the Bonneville flood because the evidence is incomplete and inconclusive. Sr isotopes indicate likely entry of water of the Bear River west of Cutler Narrows during both the Little Valley and Cutler Dam lake cycles (Hart and others, 2004). The flow could have been through a fully incised Cutler Narrows, with lakes at the same or similar levels on both sides, or as flow across a lip near or slightly below the ~1450 m Cutler Dam gravel of Cache Valley that separated lakes with different levels. Although Oviatt and McCoy (1988, 1992), Oviatt and others (1987), and Kaufman and others (2001) found no deep-water Cutler Dam deposits in ~15 m of shallow-water Cutler Dam deposits west of Cutler Narrows, such could be present in the subsurface there.

Several arguments suggest that deep incision almost to the modern level of the Bear River is a reasonable interpretation of the existing data. These arguments include: (1) the $\geq$4 Ma age of the east side of the horst block, so that considerable time was available to incise the canyon at Cutler Narrows; (2) the short and low canyon in Cutler Narrows, compared to dozens of deeper and longer canyons cut by streams with a fraction of the discharge nearby (e.g. Logan Canyon), which include some carved by now minor and intermittent streams (e.g. Weston Canyon); and (3) subsurface fluvial (?) sand and gravel deposits, hundreds of meters thick, that alternate with clay and silt that settled from lakes (Williams, 1962). This facies pattern continues from the Quaternary units down into the underlying Pliocene Salt Lake Formation (~12 to ~2[?] Ma; Goessel and others, 1999; Oaks and others, 1999; Janecke and others, 2003) (Figure 11). The thick and laterally continuous fluvial (?) gravels beneath the center of Cache Valley suggest protracted external drainage because continuous playa and lake deposits would have formed if there had been a long-lived barrier in Cutler Narrows. Williams (1962) also argued that external drainage during most of the Pleistocene is required to produce the consistently thin Quaternary deposits beneath Cache Valley.

To determine if pre-Little Valley lakes extended through Cutler Narrows and how high they reached relative to those in the main Bonneville basin, absolute ages are needed from more lake beds between the Provo and Bonneville shorelines in both basins. A continuous core where the Quaternary deposits are thickest in Cache Valley, perhaps near the location of Figure 11, could provide further age control.

Altogether, we conclude that the narrow, low horst between Cache Valley and the main Bonneville basin was probably breached early because it is neither high enough nor wide enough to separate high pluvial lakes for an extended period of time (Figure 1). Much, possibly nearly all, of the excavation of Cutler Narrows in bedrock probably took place before the Little Valley lake cycle (Oaks and others, 2014, 2019, 2020; cf. Maw, 1968, Hunt, 1982).

Complete resolution could come from finding: (1) ~59 ka Cutler Dam shallow-water lake beds in Cache Valley near the same elevation as the Cutler Dam beds in the type section; or (2) high-elevation Cutler Dam beds in the main Bonneville basin that date from ~67 ka; or (3) that the dated Cutler Dam gravels between 1450 - 1410 m in Cache Valley are coeval with the low- elevation shallow-water deposits in the main Bonneville basin.

CONCLUSIONS

Our 14 new OSL and IRSL ages establish the first evidence of Cutler Dam lake deposits and double Fielding geosols, and provide the first absolute ages of Little Valley deposits in Cache Valley. Our quantitative hydrographs show firm correlation of deposits in Cache Valley with the Little Valley (MIS 6), Cutler Dam (MIS 4), Fielding (MIS 3), and Bonneville (MIS 2) units in the main Bonneville basin.

None of our contacts between dated sediment of the Little Valley and Cutler Dam lake cycles preserve paleosols. In contrast, our double Fielding geosols lie between well-dated Cutler Dam and Bonneville deposits up to the highest near-shore gravel deposits of the Cutler Dam lake cycle in the Newton Hill pit (Figures 6, 7A). Higher in the Newton Hill pit and in Hyde Park (Figure 8A) double paleosols lie between the Little Valley and Bonneville deposits. Above the Bonneville shoreline in North Logan (Figures 8B, 9) they lie above pre-Bonneville loess and alluvial-fan deposits. These paleosols consistently exhibit an eroded arid-climate white calcic Bk horizon overlain by a loessic humid-climate red soil, and thus are provisionally correlated here with the dated Fielding geosols in the Newton Hill pit despite the absence of additional geochronology.

Drillers' logs of water wells identify two thick, confining clay-rich layers separated by a continuous gravel layer. These overlie thick gravels of the gravels of the Principal Aquifer of Cache Valley (Figure 11). Each confining clay sequence contains local gravels with adjacent oxidized clays that may indicate emergence due to oscillations within protracted lake cycles or interglacial episodes between pluvials. Lake deposits older than Little Valley may be present here.

The majority of incision of Cutler Narrows probably predates the Little Valley lake cycle. Although the evidence for when Cutler Narrows was cut below the ~1450 m Cutler Dam deposits in Cache Valley is incomplete, we believe that the evidence supports early incision to near its present depth.

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Appendix 1. *Optically Stimulated Luminescence (OSL) and Infrared Stimulated Luminescence (IRSL) age-date information, Newton Hill Pit, SE Hyde Park, and NE Millville, Cache County, Utah, March 2023.*

USU-Sample Number	Depth (m)	Number of aliquots[1]	Dose rate (Gy/ka)	D_E[2] ± 2σ (Gy)	Age[3] ± 2σ (ka)	In-situ H_2O (%)[3]	Grain size (µm)	K (%)[4]	Rb (ppm)[4]	Th (ppm)[4]	U (ppm)[4]	Cosmic (Gy/ka)	OSL/ IRSL[5]
859	16.2	22 (57)	1.76 ± 0.07	27.11 ± 2.17	15.42 ± 1.39	5.9 (15%)	90-150	1.14 ±0.03	52.0 ±2.1	6.2 ±0.6	1.7 ±0.1	0.05 ±0.01	OSL
3243	1	22 (30)	0.80 ± 0.04 [6]	16.74 ± 1.92	20.98 ± 3.04	1.81	150-250	0.59 ±0.01 0.26 ±0.01 0.51 ±0.01	15.0 ±0.15 5.9 ±0.06 11.7 ±0.12	1.76 ±0.2 0.67 ±0.07 1.32 ±0.1	1.0 ±0.1 0.7 ±0.04 1.0 ±0.1	0.25 ±0.02	OSL
1082	35.1	11 (42)	2.17 ± 0.09	46,31 ± 12.75 [4]	21.35 ± 3.48	7.4	150-250	1.48 ±0.04	66.5 ±2.7	8.8 ±0.8	1.9 ±0.1	0.02 ±0.00	OSL
854	11.3	24 (37)	2.98 ± 0.12	64.72 ± 9.88 [4]	21.72 ± 2.78	14.4	90-150	1.91 ±0.05	97.2 ±3.9	12.3 ±1.1	2.4 ±0.2	0.08 ±0.01	OSL
855	21.6	24 (49)	3.90 ± 0.16	153.29 ± 15.01	39.28 ± 3.72	10.2	63-150	2.41 ±0.06	119.5 ±4.8	14.6 ±1.3	3.4 ±0.2	0.04 ±0.00	OSL
1084	3.0	13 (32)	2.74 ± 0.11	146.65 ± 19.32	53.51 ± 6.44	12.7	75-150	1.72 ±0.04	74.3 ±3.0	10.5 ±1.0	1.8 ±0.1	0.19 ±0.02	OSL
856	24.7	20 (42)	1.77 ± 0.07	118.71 ± 8.36	66.82 ± 5.94	1.9	125-250	1.03 ±0.03	40.9 ±1.6	6.8 ±0.6	1.9 ±0.1	0.03 ±0.00	OSL
858	24.7	16 (57)	1.56 ± 0.06	92.17 ± 9.47	67.70 ± 6.46	3.2	150-250	1.27 ±0.03	34.7 ±1.4	4.4 ±0.4	1.1 ±0.1	0.03 ±0.00	OSL
2895	2.8	16 (29)	1.22 ± 0.05	173.72 ± 14.76	142.8 ± 13.1	-	150-250	0.69 ±0.02	24.9 ±1.0	3.5 ±0.3	1.2 ±0.1	0.19 ±0.02	OSL
1083	38.1	15 (34)	1.14 ± 0.05	164.12 ± 19.32	144.3 ± 14.5	3.3	150-250	0.85 ±0.02	29.7 ±1.2	3.9 ±0.4	0.9 ±0.1	0.02 ±0.00	OSL

USU-Sample Number	Depth (m)	Number of aliquots[1]	Dose rate (Gy/ka)	D_E[2] ± 2σ (Gy)	Age[3] ± 2σ (ka)	In-situ H_2O (%)[3]	Grain size (µm)	K (%)[4]	Rb (ppm)[4]	Th (ppm)[4]	U (ppm)[4]	Cosmic (Gy/ka)	OSL/ IRSL[5]
3202	59.4	19 (34)	1.39 ± 0.06 [7]	208.47 ± 31.80	150.0 ± 25.9	7.6	63-250	1.09 ±0.03 1.05 ±0.03 0.43 ±0.01	49.0 ±2.0 31.4 ±1.3 13.4 ±0.5	5.8 ±0.6 5.27 ±0.5 1.81 ±0.2	1.3 ±0.1 1.1 ±0.1 0.7 ±0.1	0.01 ±0.00	OSL
2490	32.0	15 (17)	2.29 ± 0.10 [8,9]	234.56 ± 25.82	155.6 ± 21.4	3.8	125- 250	0.73 ±0.02 1.06 ±0.03	23.6 ±0.9 25.2 ±1.0	4.0 ±0.4 3.6 ±0.3	1.0 ±0.1 1.0 ±0.1	0.02 ±0.00	IRSL
857	13.4	20 (63)	0.94 ± 0.04	152.56 ± 19.30	161.5 ± 16.8	3.7	90-250	0.66 ±0.02	22.0 ±0.9	2.6 ±0.2	0.6 ±0.1	0.07 ±0.01	OSL
2491	38.7	23 (36)	1.13 ± 0.05	191.02 ± 28.12	169.4 ± 28.6	3.8	125- 250	0.74 ±0.02	19.6 ±0.8	4.0 ±0.4	1.0 ±0.1	0.01 ±0.00	OSL

[1] Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

[2] Equivalent dose (D_E) calculated using the Central Age Model (CAM) of Galbraith and Roberts (2012), unless otherwise noted.

[3] Assumed 10±3% for moisture content over burial history for in-situ values <10%, excluding USU-859.

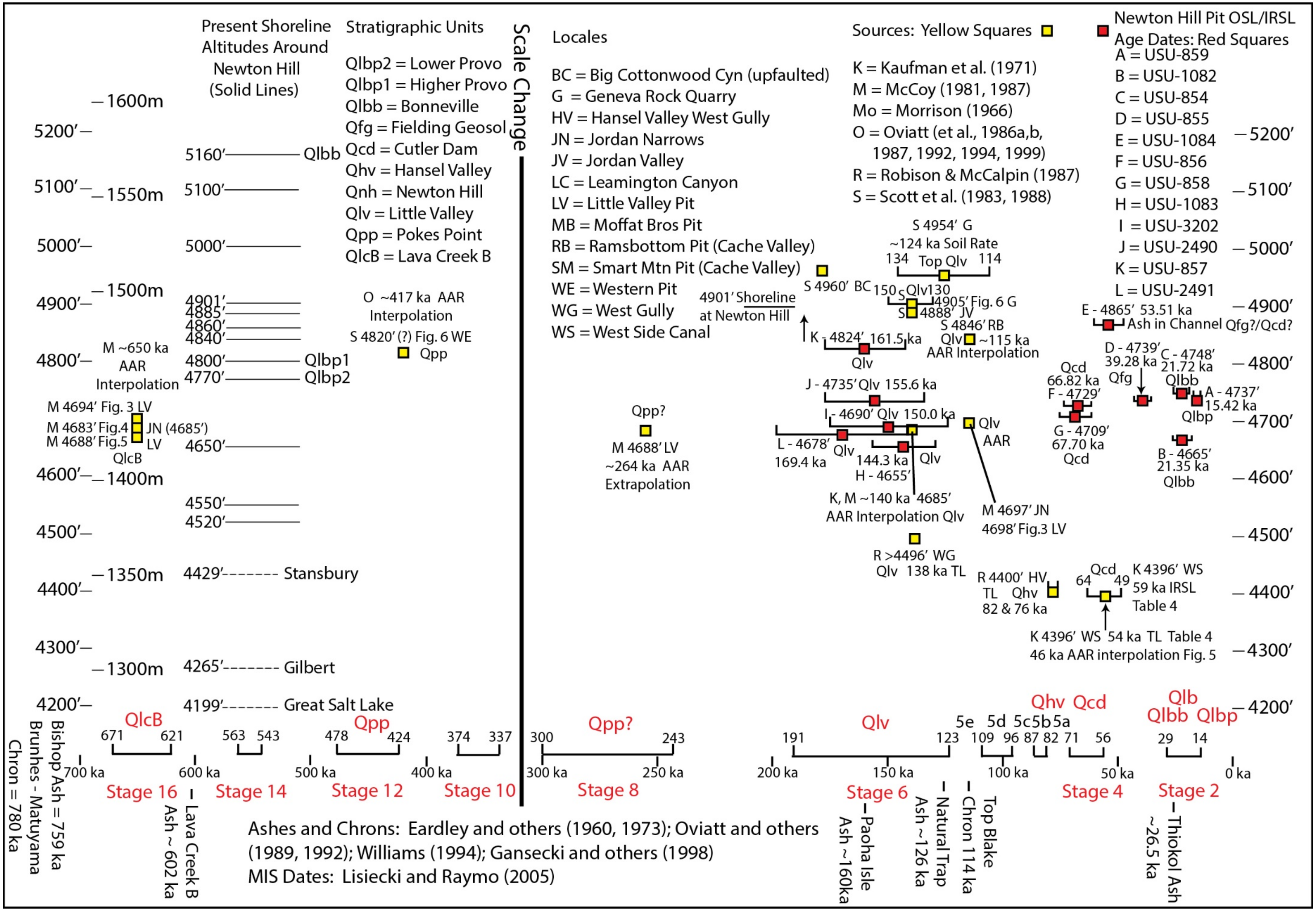
[4] Radioelemental concentrations determined using ICP-MS and ICP-AES techniques; dose rate is derived from concentrations by conversion factors from Guérin et al. (2011).

[5] OSL age analysis using the single-aliquot regenerative-dose procedure of Murray and Wintle (2000) on 1-2mm small-aliquots of quartz sand. IRSL age analysis using the two-temperature step (50°C, 225°C) pIR IRSL protocol of Buylaert et al. (2009) on 1-2 mm small-aliquots of potassium-rich feldspar. IRSL age on each aliquot corrected for fading following the method by Auclair et al.

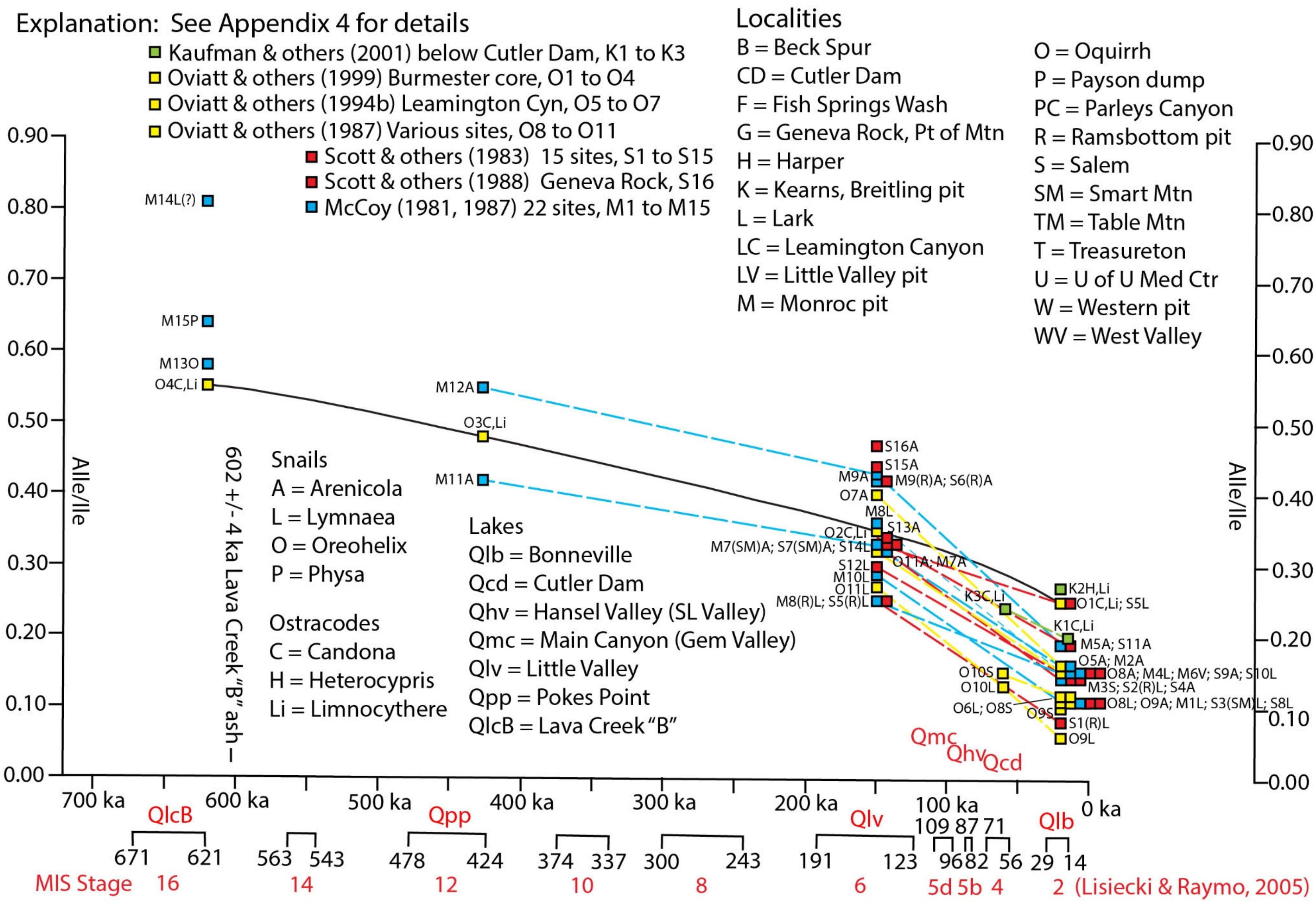
[6] Grain-size based internal beta dose rate determined assuming 12.5% K and 400ppm Rb using Mejdahl (1979). Alpha contribution to IRSL dose rate determined using an efficiency factor, or 'a-value', of 0.09±0.01 after Rees-Jones (1995).

[7] Dose rate includes weighted average of radioelemental chemistry based on sand fraction (top value, 35%) and gravel fraction (bottom value, 65%).

Appendix 2. *Data for hydrographs. See Appendix 3 for AAR correlations supporting ~417 ka age for Qpp (Oviatt and others, 1999).*



Appendix 3. *Amino-acid-racemization data interpolated between known ages of ashes, chrons and 14C and TL data in the Bonneville basin prior to our study. See Appendix 4 for data.*



Appendix 4. *Sources for original AAR data used for Appendices 2 and 3.*

Kaufman and others (2001), West Side Canal; Thatcher Valley ID (Qmc); and Little Valley pit

Unit	Sample	Fossils (# of samples)	Racemization (D/L) Table 5 (Alle/Ile)	^{14}C age ka Calibrated Table 2	TL age ka 8 hr UV Table 4	IRSL age ka 3+ hr sun Table 4
Qlb	K-1 (#6)	C (8) Li (8)	0.202±0.009 0.154±0.014	14.5±0.4 [a]	12.2±1.3	12.0±1.2
Qlb	K-2 (#5)	H (8) Li (13)	0.184+0.011 0.221+0.016	~24 [b]	19±2	23±2
Qlb (?)	(#4)				63.0±6.0 25.4±3.6	32.4±3.1 (16 hr sun)
Qcd	(#3)			~43 [c]		
Qcd	K-3 (#2)	C (14) Li (9)	0.254±0.014 0.235±0.014		55.6±5.2	59.3±5.2
Qcd	K-4 (#1)					59.0±5.5
Qmc	K-5	C (12)	0.347±0.136	1.5 m above	St Helens ash	~110 ka
Qlb	K-6 (LV)	C (12)	0.237±0.015	20.2±0.3 [d]		
Qlv	K-7 (LV)	C (23)	0.414±0.021			

[a] Fluminicola sp. [b] Limnocythere spp. [c] Heliosoma sp. [d] Arenicola sp.

[e] Figure 5; interpolation based on Bouchard and others (1998) in Gem Valley near Thatcher ID

Oviatt and others (1999), Burmester core

Unit	Sample	Fossils (# of samples)	Racemization (D/L) (Alle/Ile)	Ages in ka and basis
Qlb	O-1	C, Li (5)	0.25±0.01	~20; numerous ^{14}C ages
Qlv	O-2	C, Li (52)	0.35±0.03	~150±20; Scott and others (1983); ^{230}Th & extrapolation from Ca accumulation rate
Qpp	O-3	C, Li (15)	0.48±0.02	~417±55; Interpolation between Qlv& QlcB
QlcB	O-4	C, Li (15)	0.55±0.02	~620; below ~602 Lava Creek B ash, above ~760 Brunhes Chron base

Oviatt and others (1994b), Leamington Canyon

Unit	Sample	Fossils (# of samples)	Racemization (D/L) (Alle/Ile)	Ages in ka and basis
Qlb	O-5	A (11)	0.16±0.03	14 ages between 14 & 21 (their Table 1)
Qlb	O-6	L (7)	0.12±0.02	
Qlv	O-7	A (4)	0.40±0.06	^{230}Th >90 ka & ~140 ka (their Table 1)

Oviatt and others (1987), West Side and Hammond Canals below Cutler Dam

Unit	Sample	Fossils Racemization (# of samples) (D/L) (Alle/Ile)			
Qlb [f]	O-8	L 0.11±0.03	S 0.12±0.01	A 0.15±0.03	
Qlb	O-9 (#3, 5)	L (1) 0.06	S (1) 0.011	A (5) 0.10±0.005	
Qcd	O-10 (#5, 6)	L (2) 0.12±0.01	S (3) 0.15±0.01	H (3) 0.11±0.01	V (3) 0.14±0.01
Qlv [f]	O-11	L 0.27±0.03		A 0.32±0.03	

[f] Average for Bonneville basin from McCoy (1981) and this paper

Scott and others (1983) Cache Valley (Table 2)

Unit	Sample	Location	Fossils Racemization (# of samples) (D/L) (Alle/Ile)	
Qlb	S-1 [g]	R	L (?)	0.08±0.01
Qlb	S-2	R	L (?)	0.14±0.00
Qlb	S-3	SM	L (1)	0.11
Qlb	S-4	SM	A (1)	0.14
Qlv	S-5 [g]	R	L (?)	0.24±0.01
Qlv	S-6 [g]	R	A (?)	0.42±0.06
Qlv	S-7	SM	A (?)	0.33±0.01

R = Ramsbottom pit; SM = Smart Mountain

Scott and others (1983) Bonneville Basin and Cache Valley, combined averages (Table 1)
Locations: B, BC, G, JN, K, LC, LV, MC, MO, MU, OR, P, R, SM, W (See Appendix 3)

Unit	Sample	Fossils Racemization (# of samples) (D/L) (Alle/Ile)
Qlb	S-8	L (50) 0.11±0.03
Qlb	S-9	A (35) 0.15±0.04
Qlb	S-10 [gh]	L (33) 0.15±0.04
Qlb	S-11 [gh]	A (28) 0.19±0.04
Qlv	S-12	L (2) 0.30±0.02
Qlv	S-13	A (13) 0.34±0.03
Qlv	S-14 [gh]	L (10) 0.33±0.08
Qlv	S-15 [gh]	A (28) 0.44±0.06

[g] 1980 preparation differed from the other samples and resulted in higher values

[h] Table 5 and page 280: Assumed constant rate of addition of calcium to Promontory paleosol based on rate in post-Qlb soils = 70 ka to 120 ka plus 20 ka for burial by Qlb = 90 ka to 140 ka for top of Qlv. ^{230}Th Qlv age: > 105 ka from Kaufman and Broecker (1965, p. 4035). Oviatt and others (1999) assumed ~150±20 ka for average age of Qlv (see above).

Scott and others (1988)

Unit	Sample	Location	Fossils Racemization (# of samples) (D/L) (Alle/Ile)	
Qlv	S-16	G	A (?)	0.47±0.02

McCoy (1981; 1987)

Unit	Sample	Location	# of sample s	Fossils Racemization (D/L) (Alle/Ile)
Qlb	M-1	JV, LC, LV, M, P, SM, TM, U	L (22)	0.11±0.01
Qlb	M-2	JV, LC, LV, M, SM	A (190	0.16±0.01
Qlb	M-3	LC	S (2)	0.14±0.02
Qlb	M-4 [g]	B, F, JN, L, O, P, PC, R, S, T	L (12)	0.15±0.02
Qlb	M-5 [g]	B, H, JN, K, LC, LV, O, P, S, T	A (12)	0.19±0.02
Qlb	M-6	S	V (3)	0.15±0.00
Qlv	M-7	B, LV, SM	A (13)	0.32±0.03
Qlv	M-7	SM	A (3)	0.33±0.01
Qlv	M-8 [g]	G, JN, K, LV, R	L (10)	0.36±0.04
Qlv	M-8 [g]	R	L (2)	0.25±0.01
Qlv	M-9 [g]	G, JN, K, LV, R, W	A (28)	0.43±0.02
Qlv	M-9 [g]	R	A (2)	0.42±0.02
Qlv	M-10	LV	L (2)	0.29±0.07
Qpp	M-11	LV	A (22)	0.42±0.06
Qpp	M-12 [g]	LV	A (12)	0.55±0.05
Qpp	M-13	LV	O (1)	0.58±0.05
QlcB	M-14 [g]	LV	L? (2)	0.81±0.04
QlcB	M-15 [g]	JN	P (5)	0.64±0.07

Correlations of matched samples for same fossils and same author(s) in Appendix 3.

Color	Qlb	Qcd	Qmc	Qlv	Qpp	QlcB	unused	Unmatched
Green	K1Li	K3Li					K2Li	K2H
Green	K1C	K3C	K5C	K7C			K6C	
Yellow	O9L	O10 L	O11L				O8L	
Yellow	O5A	O7A						
Yellow	O8A		O11A				O9A	
Yellow	O9S	O10 S						
Yellow	O1C, Li			O2C,Li	O3C,Li	O4C,Li		
Red	S1(R)L			S5(R)L	S2(R) L			S3(SM)L
Red	S4(SM)A			S7(SM)A				
Red	SSL			S14L				
Red	S9A			S13A			S11 A	S6(R)A
Red	S10L			S12L				
Red	S11A			S15A			S16 A	
Blue	M1L			M19L				M13O M15P
Blue	M2A			M7A	M11A			M34S M6V
Blue	M4L			M8L		M14L?		M8(R)L
Blue	M5A			M9A	M12A			M7(SM)A

Appendix 5. Shoreline Altitudes of Lake Cycles in Main Bonneville Basin Compared to Coeval Shorelines in Cache Valley. Altitudes of Samples for These Lakes are Uncorrected for Isostatic Rebound.

Main Bonneville Basin				Cache Valley Bay			
Lake Cycle	**Location; Source**	**Age in ka**	**Shoreline Altitude**	**Location; Source**	**Age in ka**	**Shoreline Altitude**	**Altitude Difference in Cache Valley**
Little Valley	Point of Mountain Scott and others, 1988	~124	~4954' ~1510 m	Hyde Park cut wall	~142.8	>4889' >1490 m	< -65' < -20 m
Little Valley	Big Cottonwood Canyon, Scott and others, 1983	~175	~4960' ~1512 m	Newton Hill Pit	~144.3 ~169.4	>4865' >1483 m	< -95' < -29 m
Little Valley?	Alpine under Promontory Geosol in Little Valley Pit Morrison, 1965b, 1966	Uncertain, probably Little Valley	~4986' ~1519 m'	Millville Eroded Delta Between Bonneville Highstand and Provo Delta; includes Muley Hill	Unknown; might be Little Valley	~4975' ~1516 m	~ -11' ~ -3 m
Hansel Valley	West Gully; Robison & McCalpin, 1987	~82 ~76	~4400' ~1341 m	Newton Hill Pit	None	None at pit level	None
Cutler Dam	Westside Canal; Kaufman and others, 1971	~59.4	~4396' ~1340 m	Newton Hill Pit	~66.82 ~67.70	~4733' [4757'] ~1443 m [1450 m]	+ 337' [361'] + 103 m [110 m]
Early Bonneville	Oviatt, 2015 Data Oviatt, 2020 Curve	~21	~4954' ~1510 m	Muley Hill, Millville	~20.98	~5085' ~1549 m	~+131' ~+40 m