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The Composite Nature of the Provo Level of Lake Bonneville, Great Basin, Western North America

Dorothy Sack

Department of Geography, Ohio University, 122 Clippinger Labs, Athens, Ohio 45701

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Deposits of a transgressive-phase Lake Bonneville stillstand or oscillation are found just below the elevation of the regressive-phase Provo shoreline at numerous exposures throughout the Bonneville basin. Existence of these subProvo shoreline deposits provides a new explanation for the massive size of Provo depositional and erosional landforms, which can no longer be explained by a long stillstand at the Provo shoreline. Provo coastal landforms are large because they are superimposed on subProvo landforms. Results also help to clarify divergent interpretations regarding the relative age of the Provo shoreline and the number of times it was occupied by the water plane. Occupation of approximately the same level during both the transgressive and the regressive phase of Lake Bonneville may be coincidental, or it may indicate that a bedrock sill controlled outflow at subProvo as well as Provo time. Rise to the Bonneville level could have occurred after massive slope failure plugged the outlet pass.

Key Words: **Lake Bonneville chronology; Provo shoreline; subProvo shoreline deposits.**

INTRODUCTION

G.K. Gilbert (1890) named Lake Bonneville and its major shorelines and postulated the first relative chronology of its water-level fluctuations (Figs. 1 and 2). According to his interpretation, this large late Pleistocene paleolake was a closed-basin lake for most of its duration. It eventually achieved open-basin status, however, when it reached the lowest point along its divide and began overflowing into a tributary of the Snake River in southeastern Idaho. That threshold, now known as the Zenda threshold (Currey, 1980b), determined the elevation of the lake's highest shoreline, the Bonneville. In Gilbert's (1890) view, Bonneville shoreline time ended when alluvium at the outlet failed, causing the Bonneville Flood (Malde, 1968). Flood-water erosion lowered the initial outlet about 110 m, to the level of a bedrock sill at Red Rock Pass. Gilbert maintained that a second major shoreline, the Provo, formed over an extended open-basin period during which the lake level was controlled by this lower threshold. Lake Bonneville returned permanently to closed-basin conditions when climatic factors caused it to fall below the bedrock sill.

Since publication of Gilbert's (1890) Lake Bonneville monograph, many different interpretations of the chronology of the megalake's oscillations have been presented by numerous researchers. Some of these Lake Bonneville chronology reconstructions vary only slightly from Gilbert's rendition, while others diverge substantially from it. Interpretations are especially mixed regarding certain aspects of the lake's chronology, such as the Provo shoreline. An examination of the Lake Bonneville chronology literature reveals two major problems regarding the Provo shoreline portion of the hydrograph. One involves the common and long-accepted practice of using the size of Provo-level coastal landforms to infer the duration of the lake at the Provo shoreline. The second problem concerns the relative age of the Provo shoreline, which has, over the years, been the subject of considerable difference of opinion. This paper helps to resolve both problems by presenting data from a comprehensive investigation of the Provo shoreline.

Because the Provo shoreline is the second most prominent shoreline of Lake Bonneville, an accurate understanding of its nature and history is necessary for a correct reconstruction of the Lake Bonneville hydrograph. Accurate paleohydrologic histories of late Quaternary paleolakes like Lake Bonneville are important for such goals as reconstructing regional paleoclimates, refining climate models, and assessing flooding and neotectonic hazard potential.

At least some mention of the Provo shoreline is made in almost every document that has been published on Lake Bonneville, and lengthier discussions of it appear in many Bonneville contributions. It is therefore surprising that only one previous publication, a site-specific study, has been found that focuses solely on the Provo shoreline (Smith and Jol, 1992). The basinwide scope of the research reported on here also differs from that of several past contributions which support conclusions regarding the Provo shoreline with evidence from a small number of field sites or cores, or from sites concentrated in the eastern Bonneville basin (e.g.,

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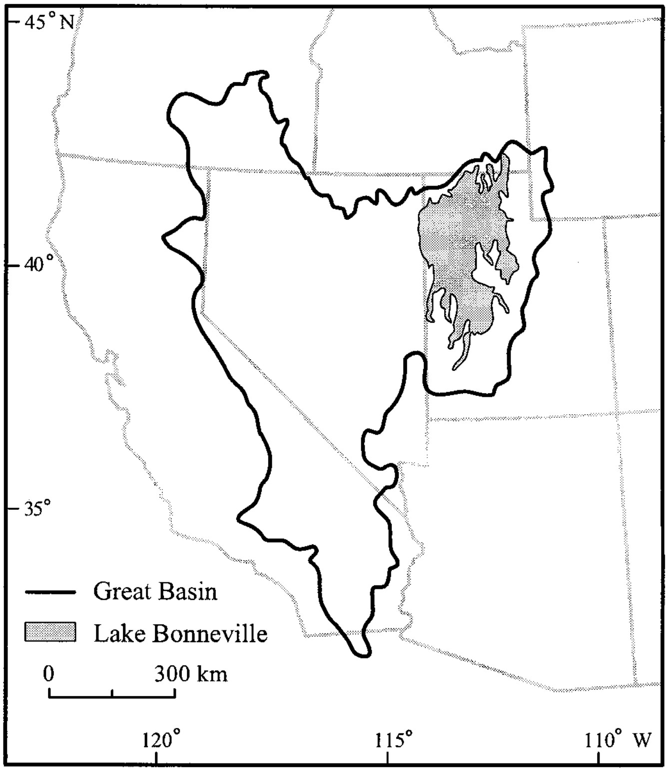

FIG. 1. Map showing the location of Lake Bonneville (after Sack, 1989).

Jones and Marsell, 1955; Bissell, 1963; Morrison, 1965a; Spencer *et al.*, 1984).

TWO PROBLEMS REGARDING THE PROVO SHORELINE

Size of Provo Shoreline Landforms

Gilbert (1890) maintained that in the modern landscape the Bonneville shoreline is the most conspicuous of the paleolake's levels because of its position; as the highest shoreline, it stands in sharp contrast to the subaerially shaped topography above. Gilbert (1890) also noted that the coastal landforms of the Provo shoreline are much larger than those of the Bonneville shoreline despite the fact that the lake area was one-third smaller at the Provo than at the Bonneville level (Fig. 3). Gilbert (1890) concluded that in order to have created the larger Provo landforms, Lake Bonneville must have stood much longer at the Provo shoreline than at the Bonneville shoreline. By comparing the volume of sediment deposited in the Provo and Bonneville components of the American Fork River Delta, he calculated a duration differential for the two stillstands (Gilbert, 1890, pp. 158–159). After deducting from the Provo-level delta the estimated volume of sediment reworked from the Bonneville component, he concluded that Lake Bonneville had occupied the Provo shoreline roughly five times longer than it had occupied the Bonneville level.

Subsequent workers have overwhelmingly accepted Gilbert's assessment of the longer duration of the lake at the Provo compared to the Bonneville level as evidenced by the size of the Provo landforms (e.g., Ives, 1951; Antevs, 1952; Crittenden, 1963; Currey, 1980a). Pack (1939) bolstered the argument by calculating a 3:2 duration differential using erosional segments of the two shorelines, thus circumventing the need to estimate the volume of reworked sediments.

Despite the long-standing acceptance of the relative durations of the Bonneville and Provo stillstands, much of the radiocarbon-based research depicts Provo shoreline time as about equal to or even shorter than Bonneville shoreline time (e.g., Bright, 1963; Scott *et al.*, 1983; Burr and Currey, 1988; Morrison, 1991; Oviatt *et al.*, 1992). Burr and Currey (1988), for example, suggested that the lake lingered at the Provo shoreline for 300 years following 850 years of intermittent threshold control at the Bonneville level. Oviatt *et al.* (1992) inferred a Provo shoreline duration of 500 years after an 800-year occupation of the Bonneville shoreline. This, then, is the first problem regarding the current interpretation of the Provo shoreline. If the inordinately massive size of depositional and erosional Provo landforms cannot be explained by a very long stand of the water plane at that shoreline, how can the size of those features be explained?

Relative Age of the Provo Shoreline

The second difficulty addressed here regarding the Provo shoreline concerns its relative age. Gilbert (1890) was definite in his conclusion that the Provo shoreline formed during the regressive phase of Lake Bonneville, immediately after the Bonneville Flood. Alternatives to Gilbert's (1890) understanding of the Lake Bonneville chronology did not start to appear in the literature until the mid-1940s, but since then many different interpretations have been published. Thirty-eight distinct post-Gilbert reconstructions of the chronology of Lake Bonneville's water-level oscillations have been found, most of them in diagram form. Study

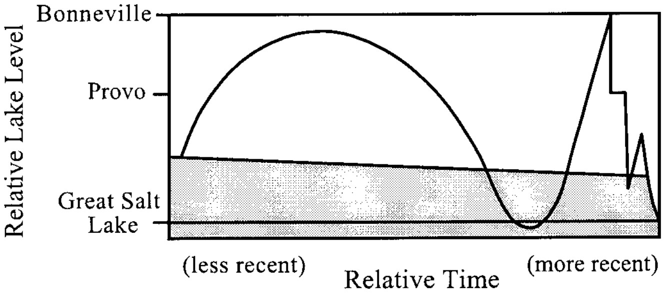

FIG. 2. Gilbert's account of Lake Bonneville water level versus relative time (after Gilbert, 1890, Fig. 34). According to Gilbert (1890, p. 262), "the shaded area indicates ignorance."

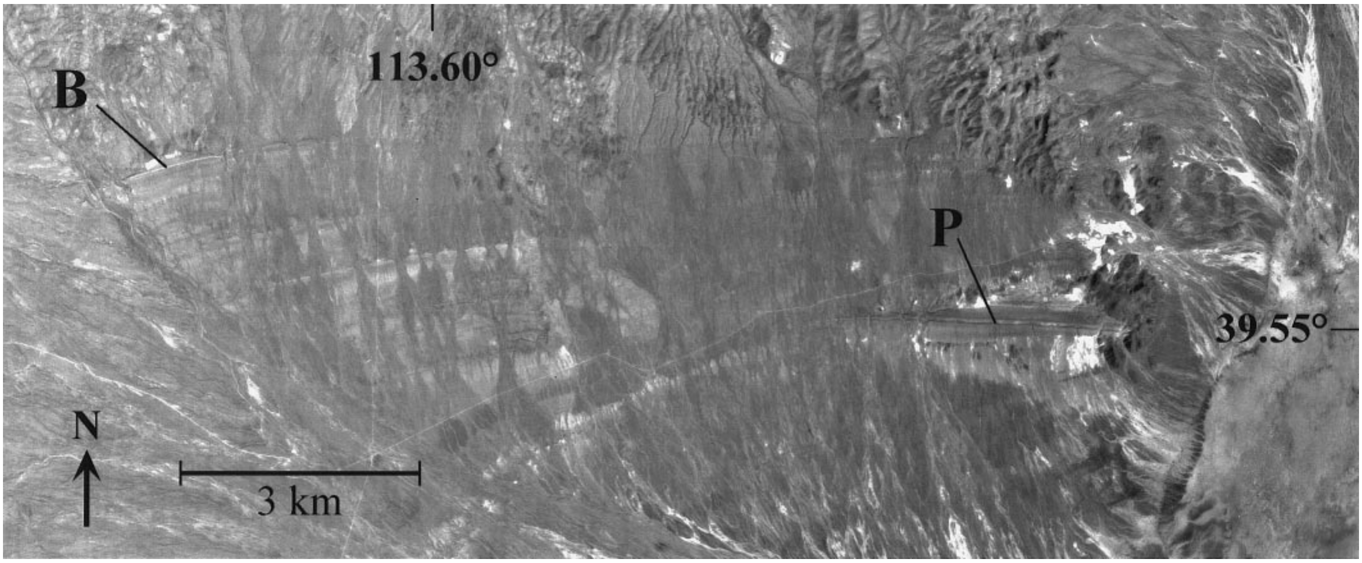

FIG. 3. Portion of a vertical aerial photograph (NHAP 1983, 418-63) illustrating the relative size of depositional segments of the Bonneville shoreline (B) and Provo shoreline (P).

of these published chronologies reveals a wide variety of interpretation regarding the relative age and number of occupations of the Provo level (Table 1). Varying renditions of the Provo zone appear even among the more recently published hydrographs.

Thirteen of the 38 post-Gilbert chronologies are very similar to Gilbert's (1890) with respect to the Provo shoreline. They portray only one occupation of the Provo shoreline and place it during the regressive phase of Lake Bonneville immediately after the Bonneville Flood (Fig. 4a). Twenty-one of the reconstructions deviate substantially from Gilbert's (1890) interpretation of the Provo. Eleven of these 21 do so by indicating occupations of the Provo shoreline during more than one lake cycle (Fig. 4b); the other ten show one or more occupations of the Provo shoreline during a single lake cycle, but none during the regressive phase of Lake Bonneville. The remaining four post-Gilbert chronologies agree with Gilbert's (1890) interpretation by placing the Provo shoreline just after the Bonneville Flood, but they also portray some kind of unnamed stillstand (Currey and Oviatt, 1985; Burr and Currey, 1988) or oscillation (Benson *et al.,* 1990; Oviatt, 1997) during the transgressive phase of the Bonneville lake cycle at varying distances below the elevation of the regressive-phase Provo shoreline. Burr and Currey's (1988) paper, however, is the only one of the four to include field descriptions from a specific, identified site, the Stockton Bar, in support of their interpretation (Fig. 4c).

Clearly there exists in the literature considerable disagreement regarding the relative age and number of occupations of the Provo shoreline. Evidence presented in this paper helps to resolve these chronologic disagreements and explain the unusually large size of Provo shoreline landforms.

METHODS

Thirty-four stratigraphically well-exposed depositional segments of the Provo shoreline widely distributed across the Bonneville basin were identified using air photos, maps, and field observations (Fig. 5). Geomorphic and stratigraphic field descriptions were recorded at all 34 localities, with stratigraphic columns or cross sections measured at many of them. Elevations at the measured exposures were determined using an electronic total station. Radiocarbon ages were obtained from some of the sites. A previous publication by Scott (1988) provided the details for site 6. In the following discussion the word coastal is used to designate littoral coarse-grained sediments deposited and landforms created primarily by lacustrine waves and currents.

DATA

The representative stratigraphic columns presented in Figure 6 document what is found with little variation at 25 of the 34 studied localities. At each of these Group I sites (Table 2), the distinctive Lake Bonneville white marl crops out. The white marl represents deep-water deposition during the transgressive and Bonneville shoreline phases of Lake Bonneville, and it therefore makes a very useful time-stratigraphic marker. Overlying the white marl, the exposures exhibit a coarsening upward, conformable sequence that extends from sandy marl and/or marly sand through sand and gravel of the Provo shoreline. Gravel constituting Provo shoreline beaches, spits, barriers, and tombolos is typically rounded, well sorted, and deposited in crossbeds. Each Group I site, however, also displays commonly cross-bedded, subrounded to rounded, well-sorted

TABLE 1

Post-Gilbert Lake Bonneville Chronology Reconstructions, Grouped by their Portrayal of the Provo Level

Like Gilbert (1890), as a single regressive-phase occupation: Ives (1951), Antevs (1952), Bright (1963), Currey (1980a), Scott (1980), Scott *et al.* (1980), Scott *et al.* (1983), Currey *et al.* (1984), Oviatt (1984), McCoy (1987), Thompson *et al.* (1990), Oviatt *et al.* (1992), Light (1996).

	Provo-level occupations				
Very different from Gilbert (1890)	Total no.	More than one cycle before LB	Pre-Bonneville lake cycle	Bonneville lake cycle[a]	Post-Bonneville cycle(s)
Antevs (1945)	2			1r	1
Gvosdetsky and Hawkes (1953)	1				1
Antevs (1955)	2				2
Jones and Marsell (1955)	2				2
Eardley *et al.* (1957)	2			1r	1
Feth and Rubin (1957)	≥1			≥1t	
Broecker and Orr (1958)	1				1
Goode and Eardley (1960)	1	1			
Morrison (1961a, 1961b, 1965a)	2			1r	1
Bissell (1963)	2				2
Crittenden (1963)	2			1r	1
Broecker and Kaufman (1965)	2			1r	1
Morrison and Frye (1965)	4		2	1r	1
Morrison (1965b)	2–3	1?	1		1
Morrison (1965c, 1966)	3–4	1?	2		1
Crittenden (1967)	3			1i, 1r	1
Bissell (1968)	2				2
Condie and Barsky (1972)	3		2		1
Fisher (1974)	3				3
Spencer *et al.* (1984)	1			1t	
Morrison (1991)	2–3		1?	1r	1

With a transgressive-phase stillstand or oscillation near the regressive-phase Provo shoreline: Currey and Oviatt (1985), Burr and Currey (1988), Benson *et al.* (1990), Oviatt (1997).

[a] Here, t indicates transgressive phase, r indicates regressive phase, and i indicates between two Bonneville cycle occupations of the Bonneville shoreline.

gravel or sandy gravel *below* the white marl. This lower coarse-grained unit, interpreted as coastal, is separated from the marl by a thin (≈0.1 m) sand unit, also interpreted as coastal (Fig. 7). The base of the lower gravel is not exposed at most of the sections; at the measured sections the exposed (i.e., minimum) thickness of the gravel averages about 3 m. Contacts between the lower gravel and overlying sand and between the sand and overlying marl appear conformable. At some of the stratigraphic sections the lower gravel clearly comprises buried beaches (Fig. 8). At other Group I localities the lower gravel has geomorphic expression in the modern landscape as large embankments lying just below the Provo shoreline. From air photos and field observations most of the embankments appear to be cuspate or arcuate barriers, or spits, that are partially covered by and have had landward depressions filled in with later fine-grained lacustrine sediments (Fig. 9). Typically the surface of these lower coastal landforms is capped by the marl and Provo shoreline sequence on the landward side, by carbonate-rich fine-grained sediment and tufa on the lakeward side.

Two of the 34 studied localities, those assigned to Group II, display sections that are virtually identical to those in Figure 6 except that the lower gravel is not necessarily coastal. The exposure at locality 32 lies where a Provo-level cuspate barrier connects to the mainland. The lower gravel there has large, subangular clasts intermixed with fine-grained sediments, but rounding and sorting improves near the top of the unit. This is interpreted as an alluvial fan deposit that has been reworked slightly at the top by wave action. The other Group II site, locality 27, lies in a streamcut 275 m lakeward of a Provo barrier beach. The lower gravel at that site is sandy and horizontally bedded and might be alluvium, coastal deposits, or alluvium slightly reworked by waves. The thin sand unit overlying the lower gravel, however, contains gastropod shells and is definitely coastal.

As in Group I, coastal sand and gravel crop out stratigraphically below Provo shoreline deposits at the three Group III and four Group IV localities (Table 2). At these places, however, the intervening marly sediment is thin, silty to sandy, or absent. At Group III sites, the lower gravel forms depositional land-

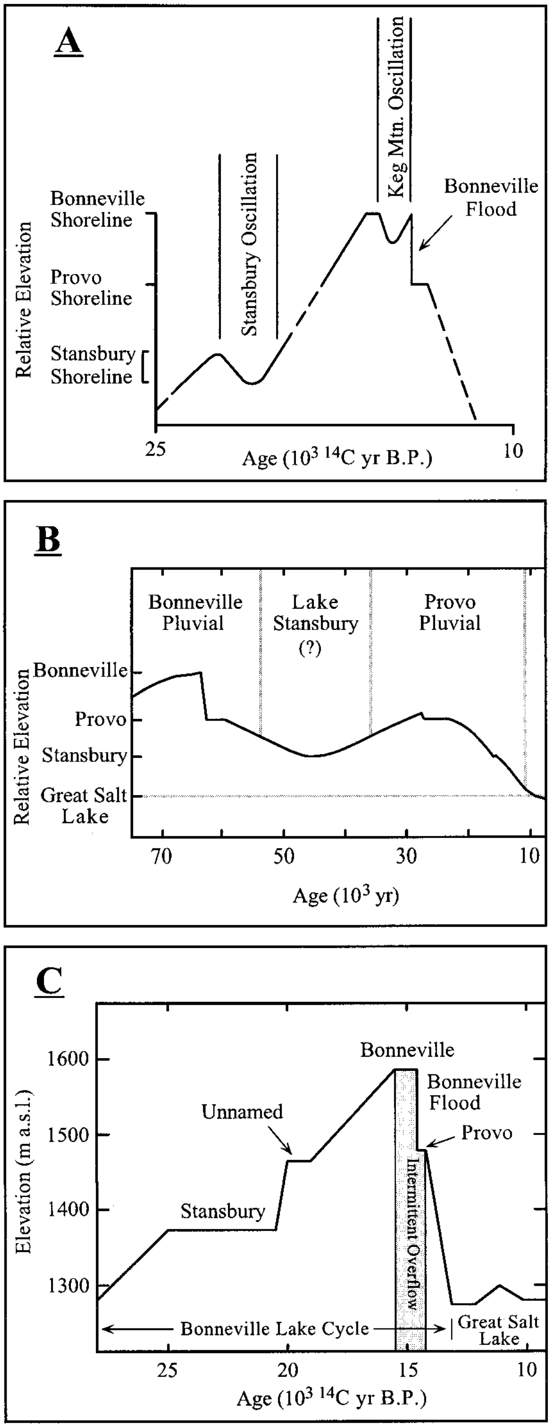

FIG. 4. Representative hydrographs (redrafted) of Lake Bonneville illustrating three major ways in which the Provo level has been portrayed in the twentieth century: (A) essentially as Gilbert (1890) did, as a single occupation immediately after the Bonneville Flood (Oviatt, 1984), (B) departing greatly from Gilbert's interpretation, in this case as having been occupied on two separate occasions (Antevs, 1945), and (C) like Gilbert's interpretation in placing the Provo shoreline immediately after the Bonneville Flood, but with the addition of a stillstand or oscillation near that elevation during the transgressive phase of Lake Bonneville (Burr and Currey, 1988). The authors derived their age information from radiocarbon ages not corrected for isotope fractionation (A), by geomorphic and correlation methods (B), and from a combination of δ^{13}C-corrected and uncorrected radiocarbon ages (C).

forms just below the Provo shoreline, but these are overlain by silty to sandy marl and tufa, not the entire marl sequence. Nevertheless, similarity in all other respects to the lakeward margin of the lower coastal landforms observed at Group I sites suggests that these are examples of the same type. Absence of the standard marl sequence leaves the relationship between the upper and lower coastal units equivocal at Group IV localities.

Conventional radiocarbon ages were obtained on gastropod shells collected from the top of the lower gravel or from the overlying thin coastal sand unit at seven of the study sites. Scott (1988) previously reported two radiocarbon ages of wood found in a lagoon associated with the lower gravel at site 6. All nine radiocarbon ages and related information appear in Table 3. Because many of the published radiocarbon ages relating to Lake Bonneville are not corrected for isotope fractionation, uncorrected (measured) ages are listed as well as the δ^{13}C-corrected ages. None of the ages listed in Table 3 are corrected for the hard-water effect, which for Lake Bonneville is generally assumed to fall within the range of analytical error (Oviatt *et al.*, 1992).

RESULTS

Seventy-five percent of the studied exposures, those in Group I, extend upsection from a lower coastal gravel and sand to pelagic Bonneville white marl to a coarsening upward sequence culminating in Provo shoreline sand and gravel (Fig. 6). The conformable nature of the sequence and the radiocarbon ages prove that the coastal sand and gravel below the marl were deposited during the transgressive phase of Lake Bonneville rather than during an earlier lake cycle. As the water level rose higher, pristine white marl accumulated at these sites and at the Group II sites, and its accumulation continued until approximately the end of the Bonneville Flood. When the water level restabilized after the flood, most areas along the Provo shoreline initially consisted of deep-water sediments deposited during the transgressive and Bonneville shoreline phases of the lake. Provo waves and currents would have eroded through the white marl with relative ease to the transgressive sand below, eventually reaching transgressive coastal gravel and/or older subaerial sediments. Streams and mudflows on the newly exposed landscape above the Provo shoreline probably also reworked the cover of lacustrine deposits, delivering reworked marl and clastic sediments to the lake. The Provo water body deposited reworked sandy marl then marly sand in the lower nearshore to upper offshore zones. At some localities, tufa formed in the photic zone on top of the marl and reworked marl (Sack, 1990). Heading upsection and toward shore, the re-

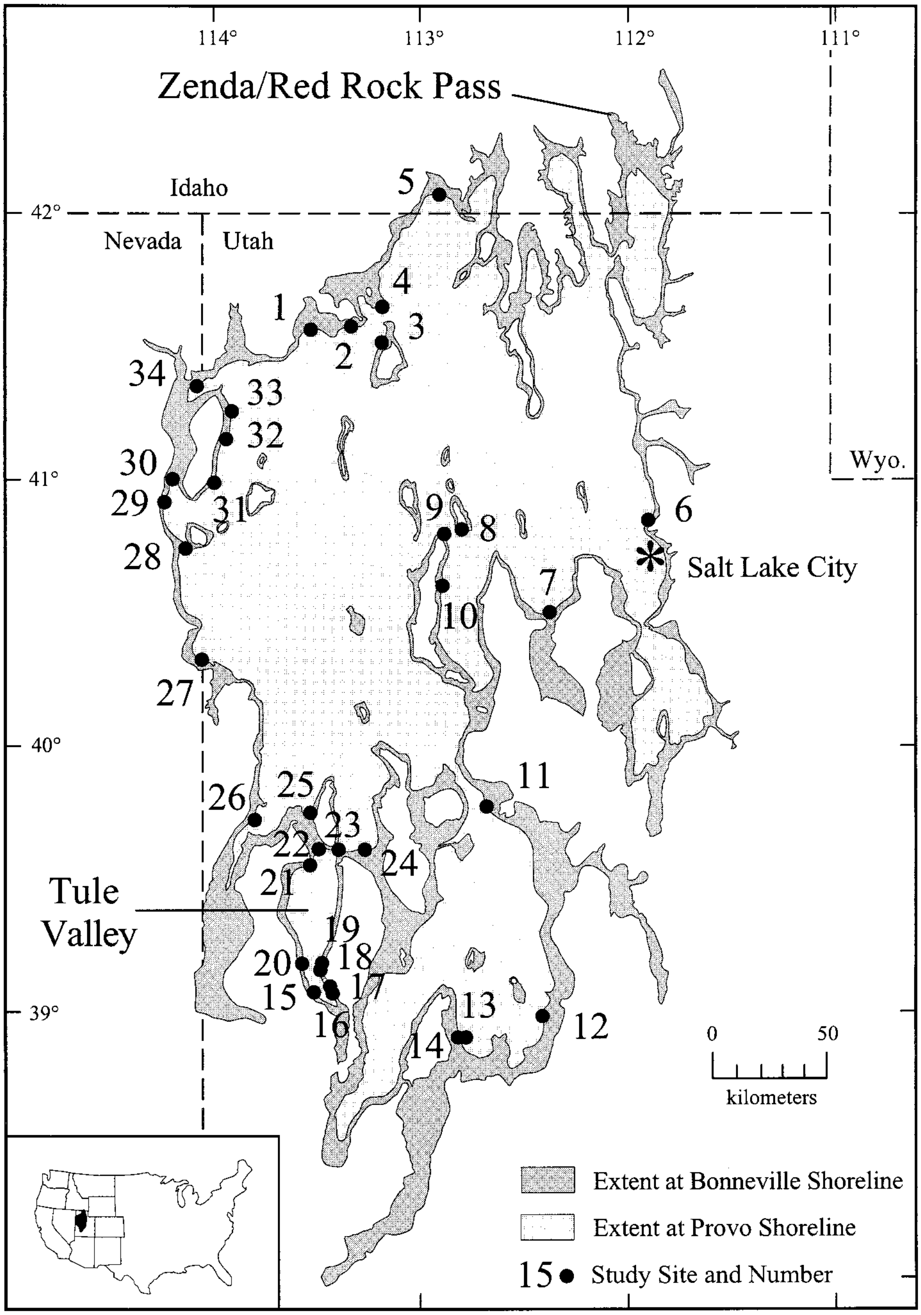

FIG. 5. Map showing the extent of Lake Bonneville at the Bonneville and Provo shorelines, Provo study sites (see Table 2), and additional localities mentioned in the text.

worked marl was eventually overlain by Provo coastal sand and gravel.

Deposition of Provo shoreline sand and gravel at the top of the sequence definitely above the white marl at the 27 Group I and II sites provides solid stratigraphic support for the conclusion that there is a substantial regressive component to the Provo shoreline, as Gilbert (1890) and many subsequent workers have maintained. In addition, the strong geomorphic and morphostratigraphic expression of the transgressive coastal gravel at 17 of the 28 Group I and III sites as beaches, barriers, or spits covered or partially covered with younger lake sediments (Figs. 8 and 9), its thickness, and its wide distribution in the lake basin (Fig. 5) suggest that a significant stillstand or oscillation occurred during the transgressive phase of Lake Bonneville close below the elevation that the regressive Provo shoreline would later occupy.

Evidence from the Group II and IV sites does not negate the notion that the lower gravel represents an important transgres-

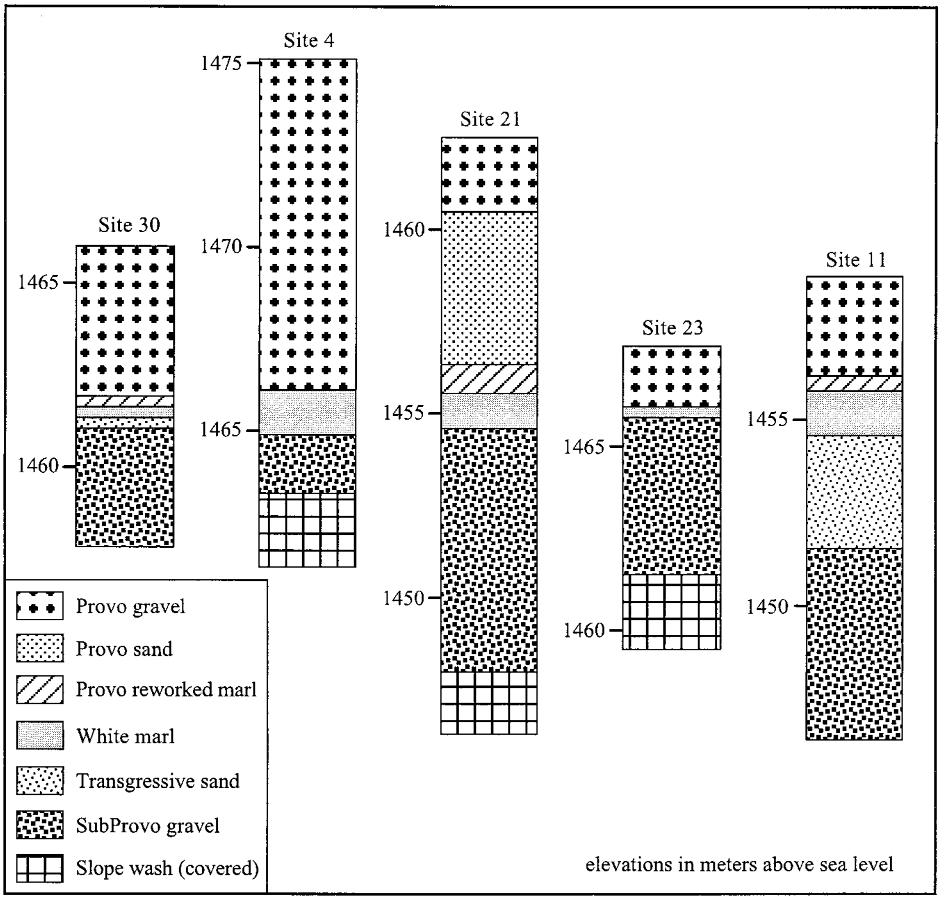

FIG. 6. Measured stratigraphic columns from representative Group I localities (see Table 2). At none of these sites was the bottom of the lower gravel unit encountered, hence the portrayed thicknesses of that unit are minimum values. The top of a measured exposure is not always the highest point on the local Provo shoreline. Both gravel categories include sandy gravel and gravelly sand. Transgressive sand is found between the transgressive gravel and white marl at all localities, but is too thin to be portrayed for sites 4, 21, and 23.

sive Lake Bonneville stillstand or oscillation. Absence of substantial transgressive coastal sediments at the two Group II exposures may be due to their marginal location, out in front of a Provo landform in one case and at the side of it in the other. Both could have been situated beyond the local locus of deposition of the transgressive stillstand or oscillation. The four Group IV sites may eventually be found to support the existence of this transgressive-phase shoreline. Absence of the classic marl sequence at those localities may be the result of syn- or post-depositional local effects, such as large influxes of clastic sediments during deposition or sublacustrine erosion. As yet, however, without the classic white marl it has not been determined with confidence if the lower coastal gravel at those sites marks the Bonneville transgression, an oscillation of the regressive-phase Provo shoreline, or deposits of a previous lake cycle.

Gilbert (1890) applied the name Provo to the geomorphically well-preserved relict shoreline that is found approximately 110 m below the Bonneville shoreline. He also concluded that the Provo shoreline was created during the regressive phase of Lake Bonneville soon after formation of the Bonneville shoreline, with only Bonneville Flood time intervening (Gilbert, 1890). Therefore, it is inappropriate to extend the name Provo to include older shoreline sediments lying near the Provo shoreline. As a result, the term subProvo has been suggested for the Lake Bonneville transgressive-phase coastal deposits found close below the elevation of the regressive-phase Provo shoreline (Sack, 1990), and that term is adopted here.

At the various Group I and III study sites, the highest exposure of the subProvo deposits has been found 4 to 22 m below the local elevation of the Provo shoreline (Table 2). Several different factors likely contribute to this variation in elevation. First, some of the exposures are not extensive, and the exposed top of the subProvo gravel may not represent the highest point of the gravel unit. Second, rather than representing a single water level, the subProvo interval might consist of a shoreline complex marked itself by some oscillations or

TABLE 2
Study Sites and Selected Attributes

No.	Name	Group	Depth to lower gravel from Provo shoreline (m)[a]
1	Muddy Creek	IV	6
2	Matlin	I	(14)
3	W Hogup Mtn	I	15
4	Peplin Pond	I	13
5	Black Pine	IV	6
6	CPC Pit N	I	12
7	Stockton Bar	III	16
8	N Skull Valley	I	17
9	N Cedar Mtns	I	(20)
10	W Skull Valley	I	20
11	South Pine Wash	I	12
12	Chalk Creek	IV	7
13	Bloom East	I	22
14	Bloom West	I	15
15	King Cove	I	(12)
16	Hell'n Maria	I	(11)
17	N Hell'n Maria	I	6, 10
18	Notch Peak	I	(9)
19	Painter Spring	I	(11)
20	Megacomplex	I	(12)
21	Millab	I	8
22	Roadside Reservoir	I	9
23	Sand Pass	I	4
24	Fish Spr Flat	I	11
25	Honeycomb Hills	III	9
26	Trout Creek	I	9
27	Ferber Wash	II	23
28	W Pacific RR Cut	I	14
29	S Cliffside	III	(12)
30	N Cliffside	I	5, 11
31	SE Pilot Peak	I	(15)
32	E Pilot Range	II	(13)
33	Lion Mtn	I	13
34	Thousand Spr Cr	IV	20

Note. Group I, white marl lies between coarse-grained coastal sediments below and a coarsening upward shore-zone sequence of sandy marl, marly sand, sand, and gravel above. Group II, white marl and overlying deposits as in I; bulk of lower gravel may not be coastal. Group III, coastal gravel overlain by silty to sandy marl and tufa located close below the Provo shoreline. Group IV, lower and upper coarse-grained coastal deposits separated by calcareous sandy silt.

[a] Values in parentheses are estimated from topographic maps.

stillstands. Two well-exposed subProvo sites, localities 17 and 30, reveal two transgressive-phase beaches, one at 5–6 m and the other 10–11 m below the local elevation of the Provo shoreline (Fig. 8). Third, the vertical distance between a transgressive-phase and regressive-phase shoreline will change around the lake basin because of differential hydroisostatic depression and rebound histories.

CONCLUSIONS AND DISCUSSION

This investigation differs from most previous Lake Bonneville research by focusing on the Provo shoreline and by using evidence and presenting representative measured sections from numerous specific localities widely distributed around the basin in support of conclusions regarding the Provo level. Results demonstrate that at many locations coarse-grained coastal sediments from the transgressive phase of Lake Bonneville lie close below deposits of the regressive-phase Provo shoreline. Twenty-eight of the 34 localities studied here, those assigned to Groups I and III, display firm evidence of these transgressive, subProvo deposits and their stratigraphic relationship to the Provo shoreline. Because of the widespread occurrence of the subProvo deposits and their commonly strong morphostratigraphic expression as beaches, barriers, or spits, the subProvo is interpreted here as constituting a significant transgressive-phase stillstand or oscillation of Lake Bonneville. Correcting elevations of the top of subProvo gravel exposures to their pre-hydroisostatic rebound values (Currey

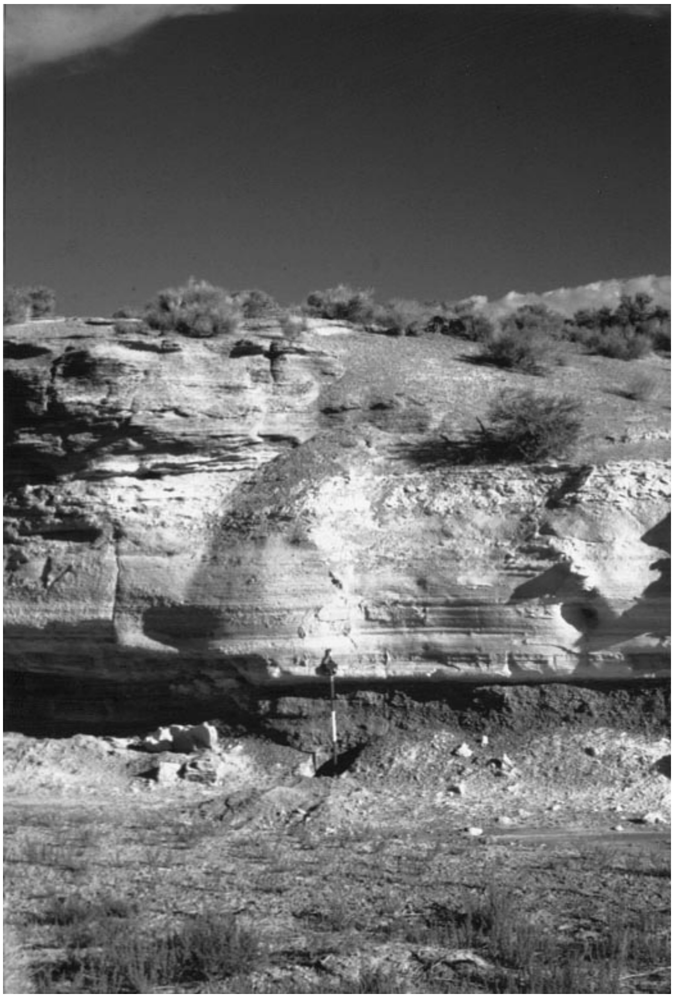

FIG. 7. Ground view of a Group I stratigraphic section, site 24. The prism pole, which has 30-cm high divisions, marks the lower coastal gravel. The lower gravel is overlain by a thin sand unit, followed by the cliff-forming white marl, sandy marl, and marly sand, with pebbly sand and sandy gravel of the Provo shoreline zone at the top of the sequence.

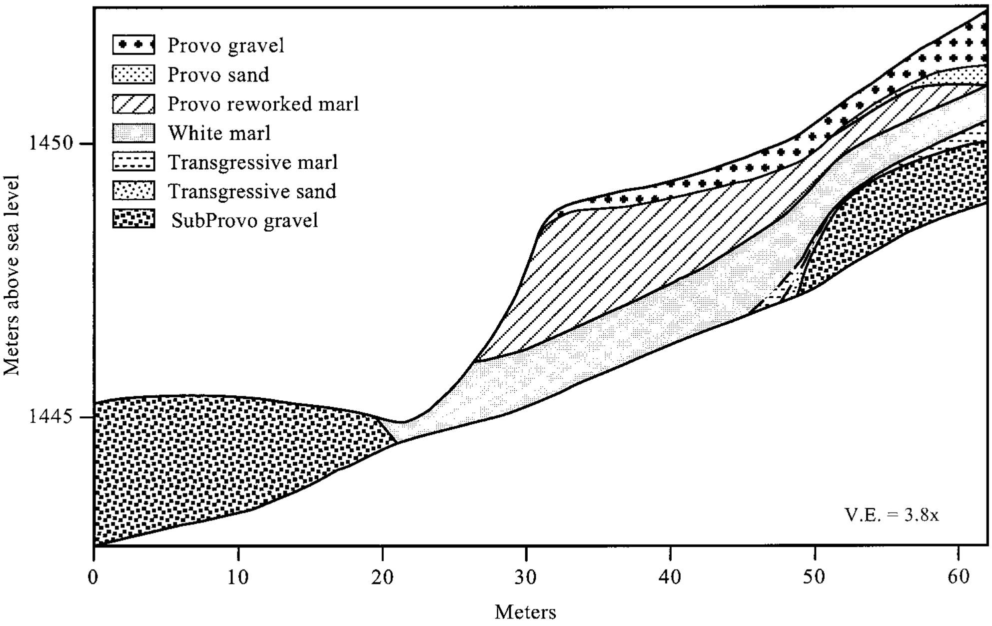

FIG. 8. Measured cross section from site 17 showing two separate transgressive-phase (subProvo) beaches lying stratigraphically beneath the white marl and deposits of the Provo shoreline (after Sack, 1990). The top of the Provo shoreline is not included; it lies farther to the southeast (right) at an elevation of approximately 1456 m a.s.l. Crossbeds in the higher subProvo beach dip 4° to the northwest.

and Oviatt, 1985) suggests deposition when the water level was between adjusted elevations of about 1430 and 1440 m. Radiocarbon ages indicate that the subProvo sediments were deposited between about 20,800 and 17,700 ^{14}C yr B.P. (Table 3).

The top of the transgressive-phase subProvo gravel or sandy gravel unit has been found from 4 to 22 m below the local (i.e., rebounded) elevation of the Provo shoreline. Some variation of the subProvo water level is suggested by the clear morphostratigraphic exposure of two distinct subProvo beaches at two localities. Some deviation from site to site in vertical distance between the Provo and subProvo shoreline deposits, however, also reflects limited exposures and differential hydroisostatic rebound histories. Because the older subProvo shoreline experienced more isostatic depression than the younger Provo shoreline, the modern elevation differences between the Provo and subProvo deposits should be greater in more heavily loaded areas of the lake basin. Indeed, there is a moderate, statistically significant positive correlation ($r = 0.51$; $p < 0.002$) between local Provo shoreline elevation and vertical distance to subProvo deposits.

The results of this research help to resolve two problems regarding the Provo level of Lake Bonneville, one involving its relative age and the other concerning the massive size of its coastal landforms. About half of the published Lake Bonneville chronology reconstructions depict multiple occupations or near-occupations of the Provo shoreline, but they disagree on when those occupations occurred. This basinwide investigation helps to resolve this problem by demonstrating that Lake Bonneville stood near the elevation of the Provo shoreline twice in the latest deep-lake cycle, at subProvo and Provo shoreline time. Only four of the many previously published Lake Bonneville chronology reconstructions suggest that some kind of transgressive-phase stillstand or oscillation occurred relatively close below the elevation of the regressive-phase Provo shoreline (Currey and Oviatt, 1985; Burr and Currey, 1988; Benson *et al.*, 1990; Oviatt, 1997). The interpretation of the Provo zone advanced by Burr and Currey (1988) in their study of the Stockton Bar agrees most closely with the results of this study. Additional work is needed to refine the chronology of the subProvo and other postulated transgressive-phase stillstands and oscillations of Lake Bonneville.

Traditional wisdom has followed Gilbert (1890) in crediting the comparatively large size of Provo depositional and erosional landforms to longer duration of the lake at the Provo than at the Bonneville shoreline. With radiocarbon refinements to the chronology of Lake Bonneville showing Provo shoreline time of equal or shorter duration than Bonneville shoreline time, a new explanation for the massive size of Provo-level features is needed. Documentation of the subProvo shoreline deposits also provides a solution to this problem. At many sites, Provo shoreline coastal sediments are piled on top of a significant accumulation of subProvo sand and gravel, Bonneville white marl, and reworked marl. Superposition or near-superposition of the two water levels would also have resulted in the wider abrasion platforms of the Provo compared to the Bonneville level (Gilbert, 1890).

Finally, it is worth considering why a significant shoreline was created at the approximate elevation of the Provo during both the transgressive and regressive phase of Lake Bonne-

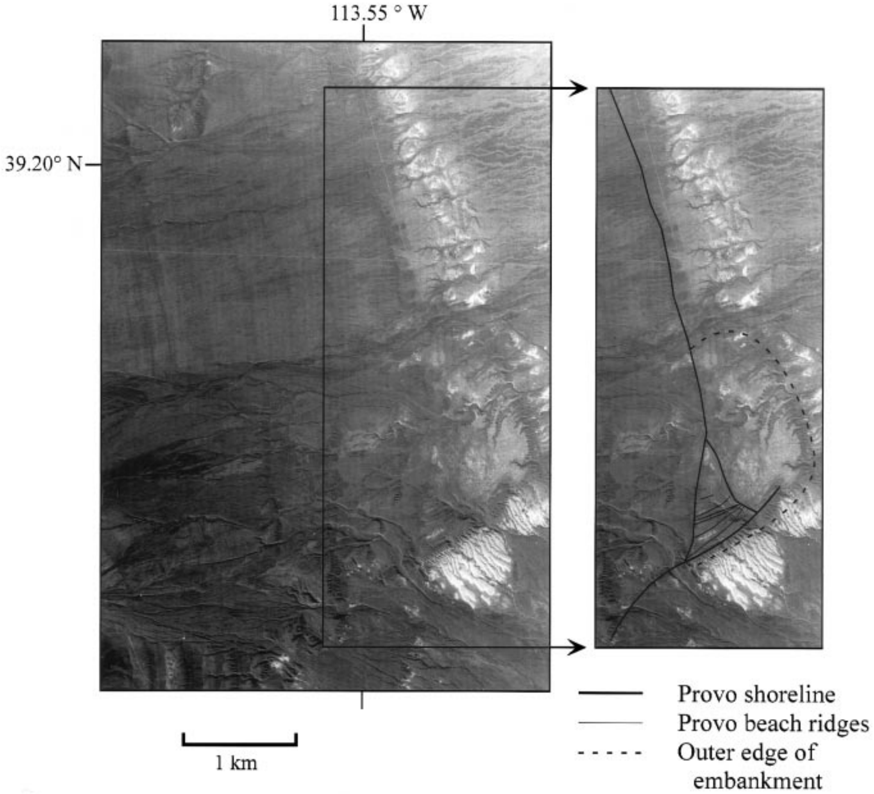

FIG. 9. Portion of a vertical aerial photograph (CSR-F, 28-7) of site 20, where a large depositional embankment lies just below the Provo shoreline. The embankment consists of the lower coastal gravel and sand units, the white marl, and overlying reworked marl, sand, and tufa, and it is capped by a gravelly Provo shoreline cuspate foreland at its southern and landward (western) margins.

ville. Explanation of the Provo shoreline is well established; it was constructed under open-basin conditions with the lake level maintained by the bedrock sill at Red Rock Pass (Gilbert, 1890). What conditions created the subProvo? First, it may merely be coincidental that a climatically induced stillstand or oscillation occurred under closed-basin conditions during sub-Provo time near the future elevation of the Provo shoreline (Sack, 1990). Second, Lake Bonneville may have been held at the subProvo level while the water spilled over an internal threshold into one of its major subbasins (Eardley *et al.*, 1957;

TABLE 3

Radiocarbon Ages of Material Collected from the Top of the Lower Gravel or Base of the Overlying Unit

Lab no.	Material	Measured age (^{14}C yr B.P.)	δ^{13}C corrected age (^{14}C yr B.P.)	Calibrated age (cal yr B.P.)[a]	Sample elevation (m)[b]	Locality	Reference
SI-4124	wood	20,500 ± 200	20,520 ± 200[c]	n/a	1434	6	Scott (1988)
Beta-47,752	shells	20,430 ± 420	20,830 ± 420	n/a	1433	24	this paper
Beta-52,614	shells	20,160 ± 270	20,540 ± 280	n/a	1431	8	this paper
W-4421	wood	19,700 ± 200	19,720 ± 200[c]	23,830 (23,370) 22,940	1434	6	Scott (1988)
Beta-17,622	shells	19,110 ± 180	19,520 ± 190	23,590 (23,140) 22,720	1437	28	D. Currey (pers. comm., 1998)
Beta-47,753	shells	18,860 ± 140	19,260 ± 140	23,250 (22,840) 22,460	1430	27	this paper
Beta-57,131	shells	18,700 ± 160	19,100 ± 160	23,070 (22,660) 22,270	1442	30	this paper
Beta-57,132	shells	18,590 ± 180	18,990 ± 190	22,960 (22,530) 22,130	1434	3	this paper
Beta-26,795	shells	17,300 ± 320	17,710 ± 320	21,560 (21,060) 20,570	1437	20	Sack (1990)

[a] Obtained using the CALIB 4.0 program (Stuiver and Reimer, 1993). Value in parentheses is calibrated age; values outside parentheses are the maximum and minimum age ranges obtained from intercepts (±1σ).

[b] Isostatic rebound removed (see Currey and Oviatt, 1985).

[c] The δ^{13}C age correction estimated using CALIB 4.0 (Stuiver and Reimer, 1993).

Sack, 1994). Currey and Oviatt (1985), in fact, attribute the stillstand at approximately the subProvo point on their hydrograph to the level of Lake Bonneville being held constant as it spilled into and filled the Tule Valley subbasin. That explanation, however, can be rejected because subProvo deposits are found within Tule Valley (Fig. 5) (Sack, 1990), and no other internal threshold lies close to the appropriate elevation. A third hypothesis is that the subProvo, like the Provo, was controlled by an external threshold.

Gilbert (1880, 1890) conducted a thorough study of possible outlets of Lake Bonneville. Only one point along the basin divide, the Zenda/Red Rock Pass area at the northeast margin of the lake (Fig. 5), shows any evidence of overflow (Gilbert, 1890, p. 172). At the Bonneville shoreline the lake discharged over the Zenda threshold, located about 3 km north of and 110 m higher than the Red Rock Pass threshold, which controlled the Provo shoreline (Currey, 1980b; Currey and Oviatt, 1985). Sewell and Shroder (1981) documented massive landsliding contemporaneous with the Bonneville Flood in the Red Rock Pass area, and noted the probability of pre- and post-Flood mass movements. Currey and Oviatt (1985, p. 1095) attributed characteristics of the Provo shoreline to “a Flood-triggered, persistently-active landslide of massive proportions that slowly raised the Red Rock Pass threshold, but which in turn was partially incised several times.” Juxtaposition of the Provo and subProvo deposits suggests that the bedrock sill that stabilized the lake at the Provo level at the end of the Bonneville Flood may have controlled the level of an overflowing or intermittently overflowing Lake Bonneville during subProvo time. In an outlet area prone to persistent landslides of massive proportions, such large mass movements could have occurred at the end of subProvo time, blocking the outlet and allowing the lake level to rise over the course of the next 2,400 or more years until it reached the top of the blockage at Zenda. During that interval, the small streams draining toward the pass from the adjacent ranges would have reworked and covered the surface of the landslide deposits until it attained the alluvial fan surface profile noted by Gilbert (1890). Discharge over this mass of landslide deposits and alluvium at Bonneville shoreline time eventually caused the plug to fail, unleashing the Bonneville Flood. The catastrophic proportion of that discharge would have eradicated any downstream evidence of outflow during subProvo time. Clearly, additional work is needed to test this hypothesis.

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