Sequence stratigraphy of lacustrine deposits: A Quaternary example from the Bonneville basin, Utah

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ABSTRACT

The late Quaternary lacustrine sedimentary record in the Bonneville lake basin in the eastern Great Basin provides an excellent example of sequence stratigraphy. Two sequences, referred to as the Little Valley and Bonneville Alloformations, are exposed in the bluffs of the Sevier River where it has entrenched its Pleistocene delta between Leamington and Delta, Utah. Both alloformations contain offshore marl units and fine-grained deltaic or underflow-fan deposits. They can be identified and mapped by tracing the unconformity separating them and employing a number of geochronometric tools, including amino acid epimerization in fossil gastropods, radiocarbon and thorium-230 ages, and basaltic tephrochronology. Thin transgressive sand of the Little Valley Alloformation is overlain by deeper-water marl and down-lapping regressive-phase deltaic silt. The Bonneville Alloformation lies unconformably above the Little Valley deposits. Fine-grained deltaic sediments deposited during the transgressive phase of Lake Bonneville fill the entrenched Sevier River valley that was eroded subsequent to the Little Valley lake cycle. Marl deposited during the deep-water phase is overlain by down-lapping deposits of the regressive phase below the Provo shoreline but is the uppermost unit in the altitudinal range where the lake was lowered catastrophically during the Bonneville Flood.

The sequence stratigraphic interpretation leads to the conclusion that the Sevier River delta as a whole is probably made up of a number of sediment sequences, each composed of several facies. Recognition of this complexity could be important in potential applications of the stratigraphic model.

INTRODUCTION

Sequence stratigraphy may provide a more appropriate theoretical basis than traditional lithostratigraphy for classifying and interpreting the stratigraphic record in lacustrine basins, especially in closed basins. Each sequence of deposits is bounded by unconformities and contains lithofacies that represent transgression and regression in the lake basin. Lacustrine sequences are analogous to sequences defined in marine rocks and sediments (for example, Van Wagoner and others, 1988), although they may be of smaller spatial scale. The use of sequence stratigraphy encourages the recognition and correlation of genetic packages of sediments rather than lithologically similar sedimentary units (formations).

The history of the development of concepts of sequence stratigraphy is long (International Subcommission on Stratigraphic Classification, 1987), and the concepts have been mostly applied to marine sequences (Vail and others, 1977, 1991), although they also work well in studies of nonmarine deposits (Scholz and Rosendahl, 1990; Hanneman and Wideman, 1991). Cyclic sedimentation may be caused by many different processes operating on a range of time scales (see Einsele and others, 1991). At the time scale considered in this paper (10 to 100 kyr), the primary control on cyclicity in the stratigraphic record is lake-level change, which is determined by changes in water balance or climate.

In the Bonneville basin, lacustrine sequences have been referred to as alloformations (Currey and others, 1984; McCoy, 1987; Oviatt and others, 1987) and used in field studies and interpretations. "An allostratigraphic unit is a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities" (North American Commission on Stratigraphic Nomenclature, 1983). Sequence concepts are useful in the Bonneville basin because virtually identical lithofacies can be deposited during each major lake cycle in the basin. By recognizing that each lake cycle is likely to be represented by numerous lithofacies, allostratigraphic classification is more conducive to accurate reconstruction of the history of lake cycles. In contrast, through the use of traditional lithostratigraphic correlations, deposits of similar lithology deposited during two or more lake cycles of vastly different age might be assigned to a single unit; or different lithofacies deposited during a single lake cycle might be assigned to separate lithostratigraphic units. Therefore, allostratigraphic classification is superior to lithostratigraphy where accurate reconstructions of geologic history are required for such applications as studies of paleoclimate or the recurrence intervals of faulting events (for example, Machette and others, 1992). In the Sevier River delta (Fig. 1), we have defined sequence tracts by recognizing unconformities, identifying facies that represent transgression and regression, and dating the deposits.

Morrison (1991) suggested alloformation nomenclature for lacustrine units in the Bonneville basin that differs conceptually from the terms we use here. We use the terms *Bonneville* and *Little Valley Alloformation*, although we recognize that in a strict sense they require more precise definition than they have received. They have proved to be useful in recent work, however, and in this paper we wish to emphasize the stratigraphic relationships of the deposits rather than define new type sections. This paper demonstrates the utility of sequence stratigraphic concepts in the study of the history of lake cycles in the Bonneville basin based on data from a relatively small area in west-central Utah (Fig. 1).

Data Repository item 9402 contains additional material related to this article.

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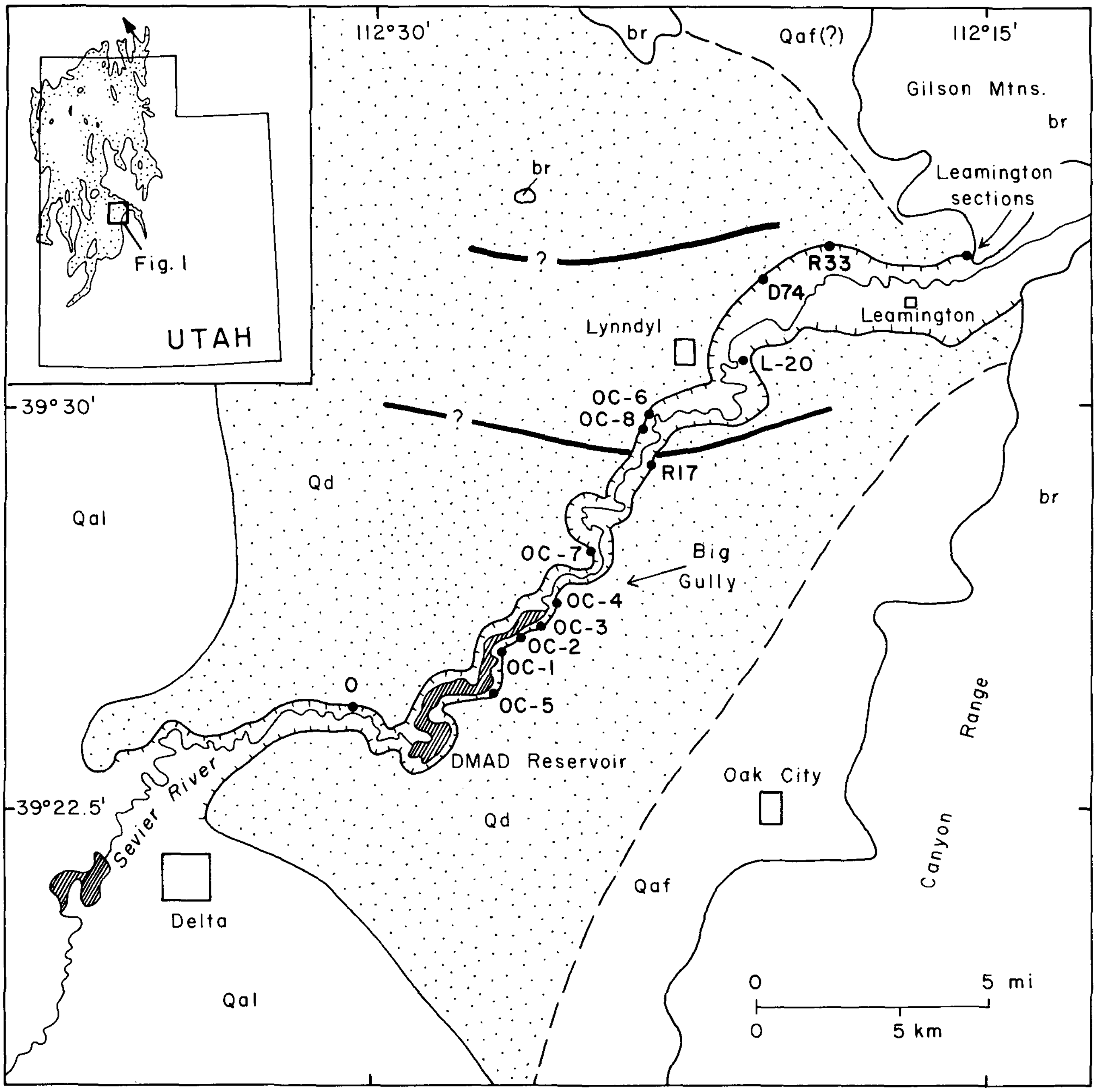


Figure 1. Map of the Sevier River delta area showing the locations of measured sections and sample localities (that is, OC-6, R33) along the river bluffs (hachured lines). The schematic cross section in Figure 4 is drawn by projecting information from these localities onto an arbitrary vertical plane drawn down the middle of the river valley. The inset map shows the position of Figure 1 relative to the maximum shoreline of Lake Bonneville in western Utah. The small arrow at the north end of the inset indicates the overflow point at Zenda and Red Rock Pass, Idaho. Heavy lines with queries indicate the inferred positions of the paleo–Sevier River bluffs prior to the Bonneville lake cycle (both pre–Little Valley and pre-Bonneville). Qd = Quaternary deltaic, lacustrine, fluvial, and eolian deposits; Qal = alluvium of Holocene age; Qaf = alluvial-fan deposits; br = bedrock of Precambrian through Tertiary age.

PREVIOUS STUDIES

Lake Bonneville, a large late Pleistocene lake in the eastern Great Basin, has been studied for over a century (Machette and Scott, 1988; Sack, 1989), and the Sevier River delta area has been the focus of a number of these studies. Gilbert (1890) examined the exposures of Lake Bonneville deposits near Leamington, Utah (Fig. 1; Hunt, 1982). He recognized two fine-grained lacustrine units that he correlated with the "yellow clay" and "white marl" (Fig. 2), units he first described at their type section at the Old River Bed exposures ~60 km northwest of Leamington. The two fine-grained units at Leamington are separated by gravel that Gilbert interpreted as alluvium (AG in Fig. 2), and he suggested that the lake transgressed and regressed in two major lake cycles, the yellow clay epoch and the white marl epoch.

Varnes and Van Horn began working in the Sevier River delta

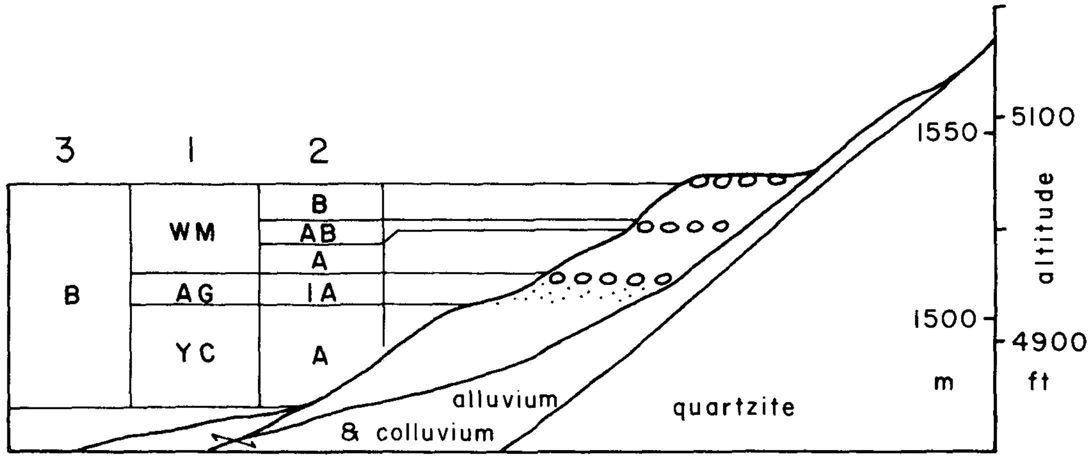


Figure 2. Schematic cross section of the changing interpretations of the Bonneville stratigraphy at Leamington (modified from Varnes and Van Horn, 1961). (1) Gilbert's (1890) interpretation: YC, yellow clay; AG, alluvial gravel; WM, white marl. (2) Varnes and Van Horn's (1961, 1984, 1991) interpretation: A, Alpine Formation (or "A Unit"); IA, intra-Alpine sand and gravel; AB, inter-Alpine/Bonneville gravel; B, Bonneville Formation (or "B Unit"). (3) Interpretation of McCoy (1981, 1987), Oviatt (1984), and this paper: B, Bonneville Alloformation.

area in the late 1940s (Varnes and Van Horn, 1951, 1961, 1984, 1991; Van Horn and Varnes, 1988). Their work has involved mapping of lacustrine deposits and lithostratigraphic correlation with the units defined by Hunt and others (1953) and Morrison (1965a, 1966). Varnes and Van Horn (1961) identified a second gravel unit (AB in Fig. 2) at Leamington higher than the gravel observed by Gilbert. They correlated all the fine-grained deposits below this upper gravel with the Alpine Formation of Hunt and others (1953). Varnes and Van Horn (1984, 1991; Van Horn and Varnes, 1988) also correlated fine-grained sediments above a fluvial gravel unit along the Sevier River with the Draper Formation of Morrison (1965a, 1966, 1991) and therefore implied a lake transgression to approximately the level of the Provo shoreline (Fig. 3) at about 13 ka (Varnes and Van Horn, 1988) or during the early Holocene (10–8 ka; Morrison, 1991). Broecker and Kaufman (1965) and Kaufman and Broecker (1965) published the results of radiocarbon and uranium-series age analyses of gastropod,

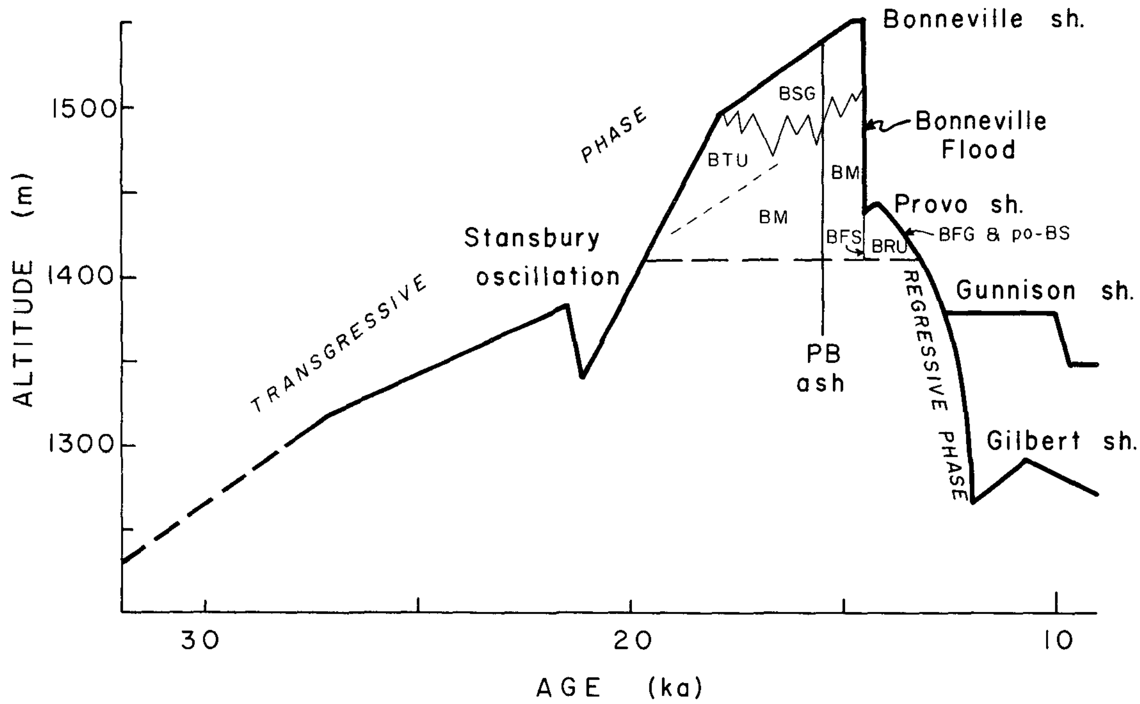


Figure 3. Hydrograph of the Bonneville lake cycle modified from Oviatt and others (1992). The horizontal dashed line indicates the approximate lower altitudinal limit of exposures in the Sevier River delta area. Altitudes are adjusted for the effects of isostatic rebound for the lake basin as a whole and therefore are not representative of altitudes in the Sevier delta area. Facies of the Bonneville Alloformation recognized in Figure 4 are schematically shown (see Fig. 4 for explanation of symbols). PB ash = Pahvant Butte ash. The Gunnison shoreline formed at 1,390-m altitude in the Sevier Desert, and the Stansbury oscillation and Gilbert shoreline are features of the Great Salt Lake basin.

ostracode, and tufa samples collected in the delta area, and most of those results have been shown on cross sections by Varnes and Van Horn (1984, 1991).

McCoy (1981, 1987) and Oviatt (1984) both concluded that the two fine-grained units observed by Gilbert were most likely deposited during a single major lake cycle (Fig. 2). Mapping of surficial deposits in the Sevier Desert region (Oviatt, 1988, 1989, 1991a, 1991b, 1992; Oviatt and others, in press) and studies of basaltic tephrochronology (Oviatt and Nash, 1989; Oviatt, 1989, 1991a) have provided a regional context within which we have interpreted the Sevier delta stratigraphy.

METHODS

In an area such as the Sevier River delta, where the sediment source for the river is unlikely to have changed significantly for a long time period, the deposition of virtually identical deltaic and offshore lithofacies should be expected with each major lake cycle. Therefore, the challenge in stratigraphic correlation, both local and basin-wide, is to identify unconformities separating the units of different ages. In some cases, unconformities are easy to identify and are marked by strongly developed buried soils. But in other cases, buried soils or other obvious indications of unconformable relationships are not present, and other stratigraphic tools must be employed to determine the ages of lithologically similar units. Conversely, some local unconformities may represent erosion events that are of minor importance within a transgressive-regressive sequence, and geochronologic tools may be used to help determine the length of time represented by those unconformities.

Listed below in order of perceived reliability are the methods used in dating and correlating stratigraphic units in this study: (1) physical tracing of unconformities (including buried soils) across undisturbed and clearly exposed outcrops; (2) results from two or more numerical-, calibrated-, relative-, or correlated-age methods (nomenclature after Colman and others, 1987) that converge on a single age, such as geochemical correlations of a volcanic ash for which independent age determinations are available; (3) radiocarbon ages of gastropods or ostracodes, or amino acid ratios from gastropod shells; (4) uranium-series (thorium-230) ages of gastropods or ostracodes (interpreted at an order-of-magnitude scale); (5) similarity of grain size, texture, color, composition, or stratigraphic order.

The results and interpretations reported here are summarized in Figures 4, 5, A, and B, and Tables 1, A, B, C, D, and E.[1] Figure 4 was drawn by using the cross section of Varnes and Van Horn (1984, 1991) as a base and modifying it to accommodate new and previously published amino acid (McCoy, 1981, 1987), radiometric (Kaufman and Broecker, 1965; Broecker and Kaufman, 1965; Currey and Oviatt, 1985; Varnes and Van Horn, 1991; Oviatt and others, 1992), and tephrochronologic (Oviatt and Nash, 1989; Oviatt, 1989) data, and information from field studies.

Amino Acid Epimerization

The deposits of at least the last two major lake cycles in the Bonneville basin (Little Valley, Bonneville) can be easily differentiated on the basis of the ratio of alloisoleucine to isoleucine (aIle/Ile) in the free fraction and the total acid hydrolysate of fossil shells of the fresh-water gastropods *Amnicola* and *Lymnaea* recovered from those deposits (Scott and others, 1983; McCoy, 1981, 1987). Therefore, aIle/Ile ratios in fossil shells can be a useful stratigraphic tool for assessing the relative ages of surficial deposits of the Sevier River delta area. See McCoy (1987) for a description of the laboratory techniques used in this study.

TABLE 1. SUMMARY OF GEOCHRONOMETRIC DATA*

Stratigraphic unit	Amino acid†	Radiocarbon§	Thorium-230**
Bonneville Alloformation	0.16 ± 0.03 (*Amnicola*) 0.12 ± 0.02 (*Lymnaea*)	14 ages between 21 and 12 ka	Five ages between 40 and 13 ka
Little Valley Alloformation	0.40 ± 0.06 (*Amnicola*)	Five ages >30 ka	>90 ka and 140 ka

*Tables A, B, C, and D, which consist of amino acid, radiocarbon, thorium-230, and microprobe data, may be obtained free of charge by requesting Supplementary Data 9402 from the GSA Documents Secretary.

†Ratio of alloisoleucine to isoleucine in the total hydrolysate. Average values are reported here based on 11 *Amnicola* samples and 7 *Lymnaea* samples of Bonneville age, and 4 *Amnicola* samples of Little Valley age.

§Radiocarbon ages of gastropods, ostracodes, and tufa.

**Thorium ages of gastropods and ostracodes.

The ratios of aIle/Ile in shells from deposits of the last two major lake cycles (Bonneville and Little Valley) examined around the Bonneville basin are distinctly different (Fig. 6). There is no overlap between the ranges of the two sets of ratios despite differences in temperatures around the basin. For *Amnicola* shells from deposits of the last (Bonneville) lake cycle, mean aIle/Ile ratios in the free fraction (FREE) range from 0.22 to 0.29 and from 0.08 to 0.22 in the total acid hydrolysate (HYD) (McCoy, 1987). Mean aIle/Ile ratios from *Lymnaea* shells from the same deposits range from 0.13 to 0.26 in the free fraction and from 0.07 to 0.16 in the hydrolysate. Mean aIle/Ile ratios in shells from deposits of the penultimate (Little Valley) lake cycle are much higher. For *Amnicola* they range from 0.48 to 0.57 in the free fraction and from 0.29 to 0.35 in the hydrolysate. For *Lymnaea* shells they range from 0.46 to 0.52 in the free fraction and from 0.25 to 0.29 in the hydrolysate. The range of values within each group is a function of (in probable order of decreasing importance) (1) the actual range in age of the shells, which is, in turn, a function of the duration of the lake cycle; (2) the range in effective diagenetic temperatures experienced by the shells; and (3) analytical error.

Tephrochronology

Tephra-bearing stratigraphic units are often correlated on the basis of the chemical composition of tephra. The composition of volcanic glass, as opposed to bulk tephra, is particularly useful because it is usually homogeneous and not subject to heterogeneities introduced by selective winnowing of phenocrysts or admixture of foreign material. Basaltic tephras have been used less often than silicic tephras because basaltic eruptions are generally less energetic and the tephra is less widely dispersed. Nonetheless, the same principles apply.

Within the Black Rock Desert province, individual volcanic centers are characterized by tephra whose glass compositions are distinct (Fig. 7). Tephra from Ice Springs volcano (<1 ka) contains less iron than either Pahvant Butte or the Tabernacle. Glass from Tabernacle Hill (14.3 ka) can be distinguished from Pahvant Butte glass by being more enriched in CaO and P_2O_5. A fourth variety (BRD glass, Fig. 7),

[1]GSA Data Repository item 9402 (Figs. A and B, which consist of measured stratigraphic sections, and Tables A, B, C, D, and E, which consist of data tables and a locality roster) is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

whose source has not been identified but shares affinities with Pahvant lavas, is characterized by distinctly higher CaO contents. In contrast to glasses from the Tabernacle, which are homogeneous within the limits of analytical precision of the electron microprobe, glasses from Pahvant Butte display moderate chemical variation. Nonetheless, analysis of Pearce element ratios in these glasses (Oviatt and Nash, 1989) demonstrates that they are comagmatic residual liquids related by fractionation of phenocryst phases and thus can be correlated despite measurable, but systematic, differences in composition.

The Pahvant Butte ash has been found at many localities in the Sevier and Black Rock Deserts, including the Sevier River delta area. In all sections its stratigraphic position is near the top of the Bonneville "white marl" (BM, Fig. 4) and a few centimeters below an abrupt facies boundary interpreted as representing a change in sedimentation within the lake basin caused by the Bonneville Flood (Fig. B; see discussion below and Oviatt, 1984, 1987, 1989, 1991a, 1991d, 1992; Oviatt and others, 1992, in press; Oviatt and Nash, 1989). The age of the ash is between 15.9 and 15.3 ka by radiocarbon ages (Oviatt and Nash, 1989; Oviatt and others, 1992) and is rounded off to the nearest 500 yr (15.5 ka). The Bonneville Flood occurred after about 15 ka and before 14.3 ka, and its age is rounded off to 14.5 ka (Oviatt and others, 1992). Taken together the Pahvant Butte ash and the Bonneville Flood marker bed provide a precise means of correlating deposits of the Bonneville Alloformation.

We have correlated the basaltic ash exposed in the Sevier River delta area with the Pahvant Butte ash based on microprobe analyses (Table D). Broecker and Kaufman (1965) and Kaufman and Broecker (1965) reported radiocarbon and thorium-230 ages that suggested there was only one basaltic ash in the lake deposits exposed in the Sevier River delta, but a cross section by Varnes and Van Horn (1984) showed two ashes, one in the Alpine Formation (labeled A_1) and one in the Bonneville Formation (labeled A_3). Later, Varnes and Van Horn (1991) released a cross section showing only a single ash (in their "B Unit").

RESULTS

We have identified two sequences (or alloformations) in the Sevier River delta area, the Bonneville and Little Valley Alloformations, each of which includes an open-water marl facies and a fine-grained deltaic or underflow-fan facies. By mapping unconformities and employing the available numerical- and relative-age data, the two sequences are readily distinguished (Table 2). Radiocarbon and thorium-230 ages of materials from these deposits fall into two distinct groups (Fig. 8). The thorium-230 ages of Bonneville materials are more scattered than the radiocarbon ages because gastropod and ostracode shells do not always remain chemically closed systems after burial (Kaufman and Broecker, 1965; Kaufman and others, 1971). Kaufman and others (1971, p. 1181) concluded that "the types of migration which occur among U-series isotopes in mollusks are undoubtedly complicated and possibly multistaged. Every reported age based on these isotopes is suspect until these processes are first thoroughly understood." Therefore, the thorium-230 ages in this study are interpreted only at an order-of-magnitude scale.

The aIle/Ile ratios of *Amnicola* shells from the Sevier River delta (Table A) area also fall into two groups: (1) those with HYD ratios of about 0.20 or less and FREE ratios of less than 0.30 and (2) those with HYD ratios of 0.32 or greater and FREE ratios of more than 0.50 (Fig. 6). The first group falls in the middle of the range of aIle/Ile values from Bonneville Alloformation deposits from elsewhere in the Bonneville basin (Fig. 6). Two of the latter group fall very close to the range of aIle/Ile values from the Little Valley Alloformation. The other two samples from the latter group (A19 and A21) have higher aIle/Ile ratios than found elsewhere in Little Valley–age deposits; in fact, they are similar to ratios found in Pokes Point Alloformation deposits (McCoy, 1987). This may be due to greater antiquity of these samples or to their shallow depth of burial and the consequent high effective diagenetic temperature from surface heating that they may have experienced. Alternatively, they could be reworked from older deposits. In any case, all four of the samples of the second group are clearly much older than those of the first group and come from a previous lake cycle.

TABLE 2. SYSTEMS TRACTS IN THE BONNEVILLE AND LITTLE VALLEY ALLOFORMATIONS

Lithofacies	Lower boundary	Upper boundary	Analogous marine systems tract*
Bonneville Alloformation			
Marl (BM)	Unconformity or gradational with BTU	Top of section or abrupt facies boundary	Transgressive; condensed section
Underflow-fan (under marl) (BTU)	Unconformity	Gradational with BM	Transgressive; onlapping, retrogradational
Underflow-fan (above marl) (BRU)	Abrupt facies boundary or unconformity	Abrupt facies boundary with BFG	Highstand; downlaps onto downlap surface (base of BFS) at top of BM
Point-bar and overbank deposits (BFG)	Abrupt facies boundary with BRU or other facies	Top of section	Lowstand
Little Valley Alloformation			
Marl (LVM)	Unconformity	Gradational with LVRU	Transgressive; condensed section
Underflow-fan (LVRU)	Gradational with LVM	Unconformity or abrupt facies boundary with LVA	Highstand
Alluvium (LVA)	Abrupt facies boundary with LVRU	Unconformity	Lowstand

Note: The Bonneville Alloformation is a sequence, "a relatively conformable succession of genetically related strata bounded by unconformities . . ." (Van Wagoner and others, 1988), although it is much smaller in spatial scale than a marine sequence. Note also that the lake's transgressive phase was relatively long compared to its rapid regression (Fig. 3); thus the cycle is asymmetric but is opposite in form to a typical marine transgressive-regressive cycle. In addition, the only control on the shape of the curve is lake-level change; subsidence or uplift are insignificant.
*Following definitions in Van Wagoner and others (1988).

The unit we refer to as the Little Valley Alloformation is exposed over a much smaller area than the Bonneville deposits (Fig. 4). Unconformities bounding the unit are well exposed in outcrops, except for the steeply sloping unconformity at the northern end of the Little Valley exposures, which is inferred based on age relationships and subtle lithologic differences. This unconformity, which is near OC-8, is dashed in Figure 4. The unconformity at the base of the Little Valley Alloformation is marked by a thin sand bed overlying a truncated calcic paleosol that has stage II to III carbonate morphology. A paleosol that developed in sandy alluvium (LVA, Fig. 4) at the top of the Little Valley Alloformation marks the upper bounding unconformity. It has stage III carbonate morphology and is overlain by Bonneville fluvial gravel (BFG, Fig. 4).

The fine-grained deltaic or underflow-fan facies of the Little Valley Alloformation (LVRU) is practically identical in lithology to the deltaic facies of Bonneville age (BTU and BRU), except that the Little

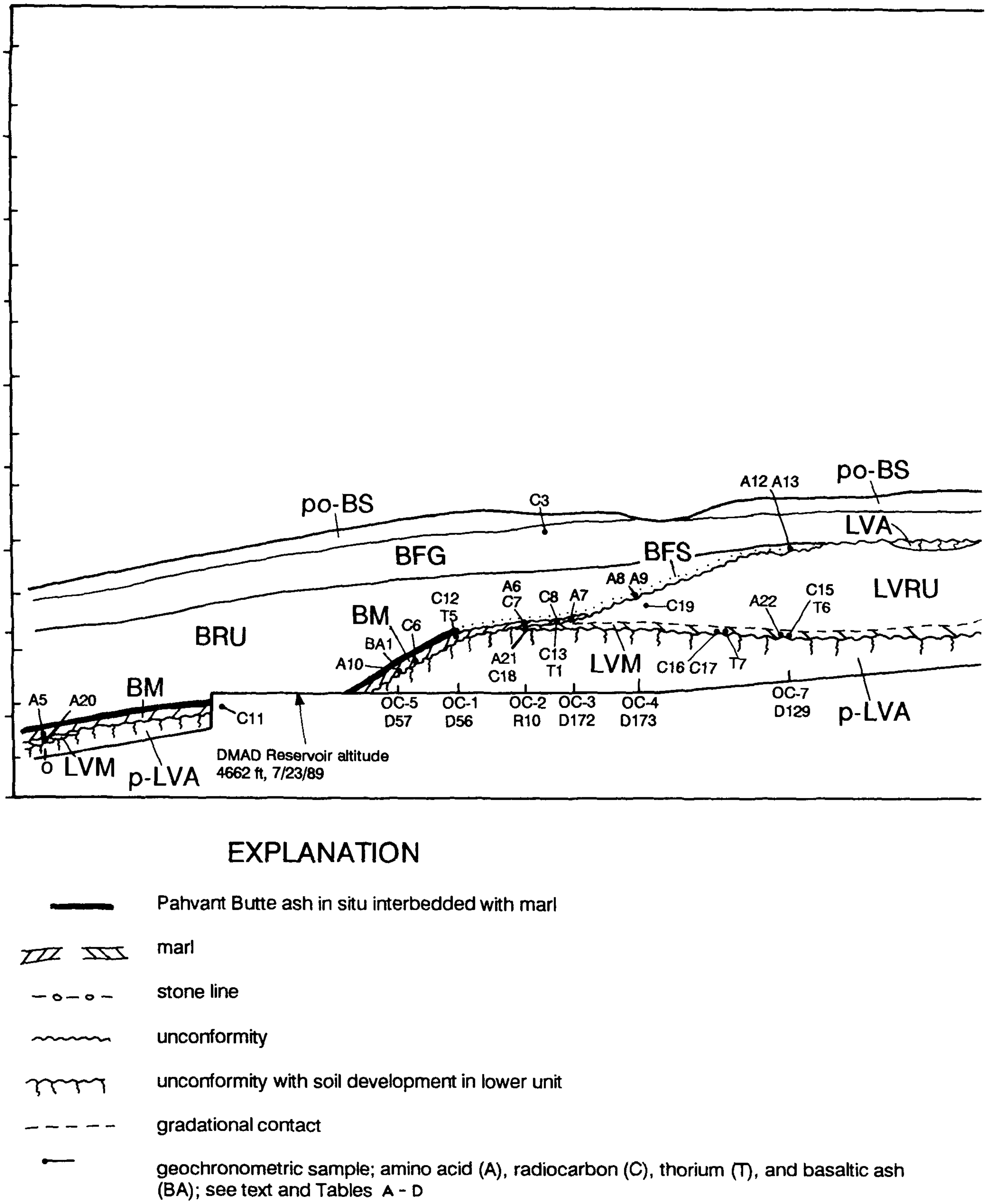
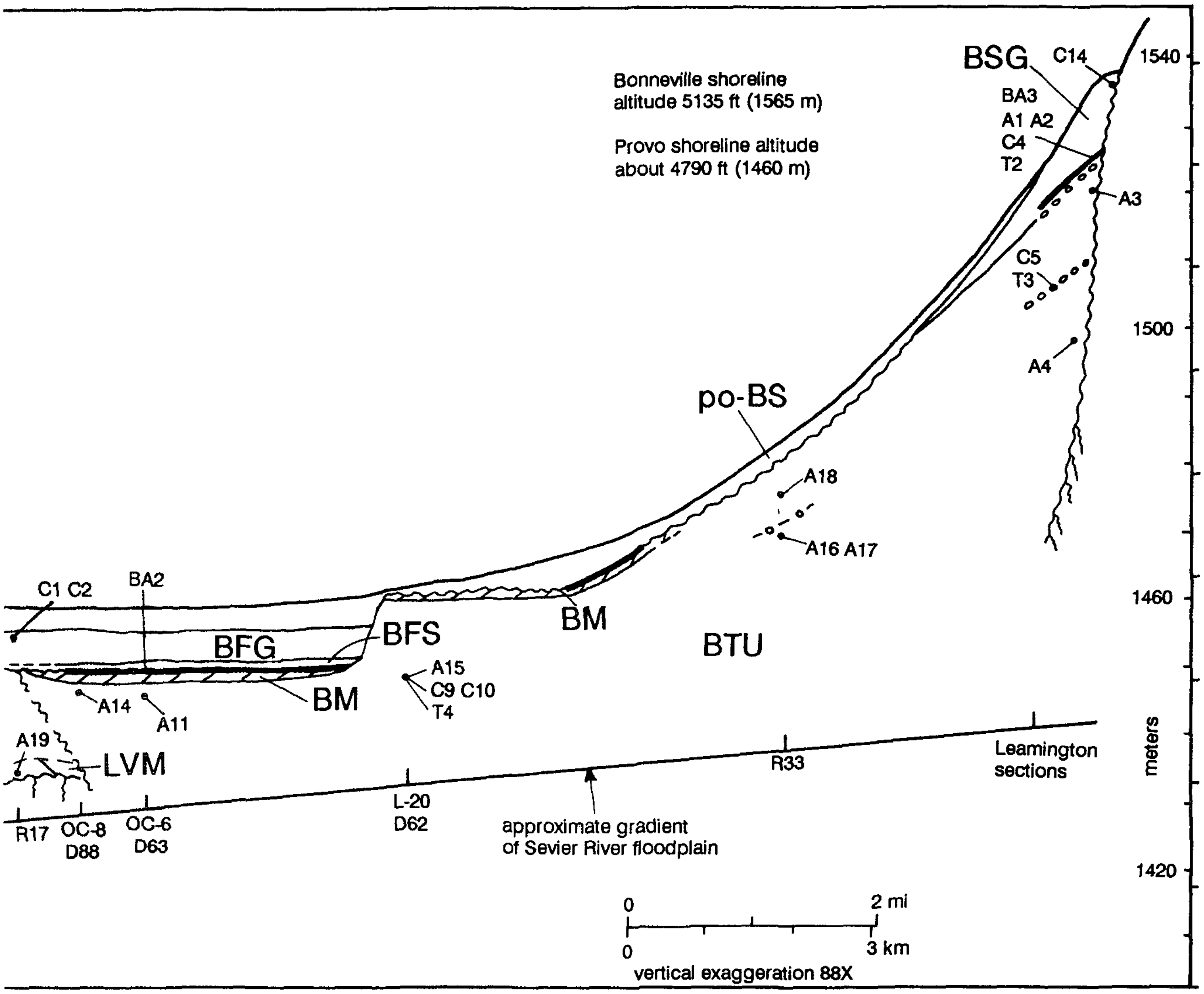


Figure 4. Schematic cross section modified from the cross sections of Varnes and Van Horn (1984, 1991) showing the approximate stratigraphic relationships that can be observed in exposures along the Sevier River below Leamington. See Figures 1 and A for sample localities. Between section L-20 and the Leamington sections, BFG and po-BS are not shown on the cross section, although they are present in the river valley in this area. The abrupt change in elevation of the base of BM near L-20 is mostly an artifact of the method used to draw the profile (projection of measured sections from opposite sides of the river onto an arbitrary line) and does not represent a major unconformity between BTU and BM.



po-BS	post-Bonneville eolian silt and sand, and reworked gravel

BONNEVILLE ALLOFORMATION:

BFG	Bonneville fluvial gravel and overbank silt
BRU	Bonneville regressive-phase underflow-fan deposits
BFS	sand deposited after the Bonneville Flood
BSG	shorezone sand and gravel of Bonneville age
BM	Bonneville marl
BTU	Bonneville transgressive-phase underflow fan

LITTLE VALLEY ALLOFORMATION

LVA	Little Valley alluvium
LVRU	Little Valley regressive-phase underflow fan
LVM	Little Valley marl
p-LVA	pre-Little Valley alluvium

Figure 4. (*Continued*). Relative positions of measured sections and sample-collection localities are indicated by symbols such as OC-1 and R33 along the line marking the Sevier River flood-plain gradient. OC- and L- designations indicate sections measured by Oviatt for this paper (Figs. A and 5); D- and R- designations indicate sections of Varnes and Van Horn (1984, 1991).

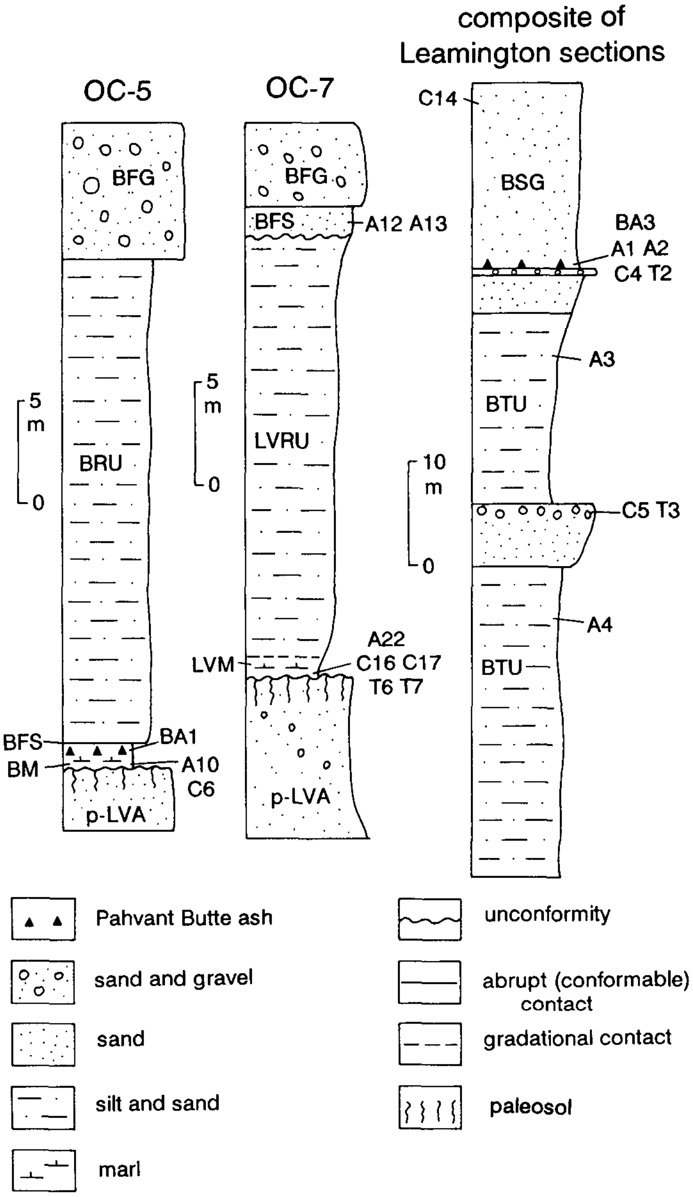


Figure 5. Representative measured stratigraphic sections (see Figs. 1 and A for locations). Refer to Figure 4 for explanation of symbols and to Tables 1, A, B, C, and D for geochronometric data.

Valley sediments commonly are slightly more carbonate cemented, especially near unconformities. The Little Valley underflow-fan deposits were probably deposited during the regressive phase of that lake cycle as indicated by their stratigraphic position above the marl, which is interpreted as a relatively deep-water facies because of its similarity in lithology and ostracode fauna to the deep-water Bonneville marl.

Deposits of the Bonneville Alloformation consist of transgressive- and regressive-phase underflow-fan deposits (BTU and BRU), deep-water marl (BM), shorezone sand and gravel (BSG), sand deposited during and after the Bonneville Flood (BFS), and fluvial deposits (BFG) (see Fig. 4).

Between the Leamington sections and section OC-8 (Fig. 4), the thickest and most widespread deposits consist of horizontally bedded silt and fine sand, which are interpreted as fine-grained deltaic or underflow-fan deposits of the Sevier River (BTU). Their stratigraphic position below the deep-water Bonneville marl (BM) shows that these deltaic sediments were deposited during the transgressive phase of Lake Bonneville between about 19 and 17 ka (Fig. 3). Disconformities documented by Varnes and Van Horn (1991) within the transgressive underflow-fan sediments (BTU; their "A Unit"), such as the stone line at R33 (Fig. 4), were probably created by oscillations on the order of 10 to 30 m during the transgressive phase. Oscillations such as this were hypothesized by Gilbert (1890) and others and are not surprising because the lake occupied a closed basin and responded quickly to minor climatic changes. There is no evidence to suggest that the stone line represents an unconformity between deposits of major lake cycles (sequences); amino acid ratios indicate that the deposits above and below the stone line are of Bonneville age (samples A16, A17, and A18, Table A, Fig. 4).

The Bonneville marl (BM in Fig. 4) is the "white marl" of Gilbert (1890; Oviatt, 1987) and is identified as Bonneville in age by its stratigraphic position above a major unconformity, the presence of the Pahvant Butte basaltic ash (Fig. 4, Table D), radiocarbon ages between about 20 and 15 ka (Figs. 4 and 8, Table B), and relatively low amino acid ratios of gastropods (Figs. 4 and 6, Table A). The Bonneville marl is thinly bedded to massive and contains from 15% to 50% calcium carbonate, gastropods and diatoms in its lower and upper

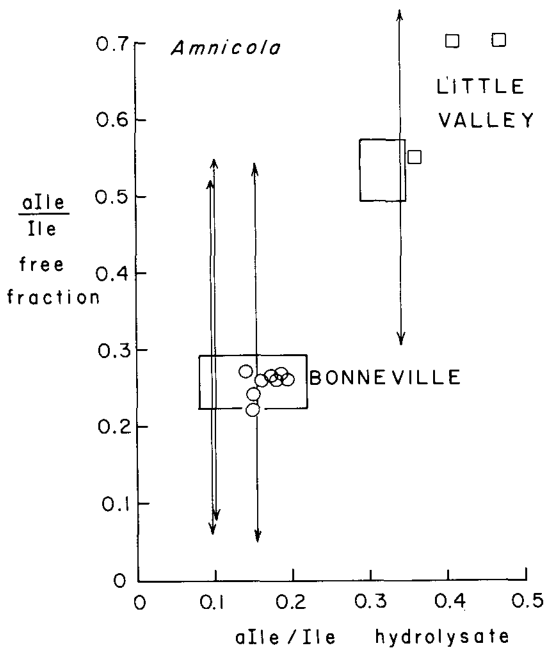


Figure 6. Plot of *Amnicola* aIle/Ile ratios from samples collected in the Sevier River delta area (circles and squares) compared to results from elsewhere in the Bonneville basin (large rectangles). Vertical double-pointed arrows are for analyses that lack data for the free-fraction ratio. Note that two of the data points labeled *Little Valley* are much greater than the Bonneville basin average for shells of that age, suggesting that some of the deposits referred to as Little Valley in this paper could belong to an older stratigraphic unit (such as Pokes Point Alloformation of McCoy, 1987).

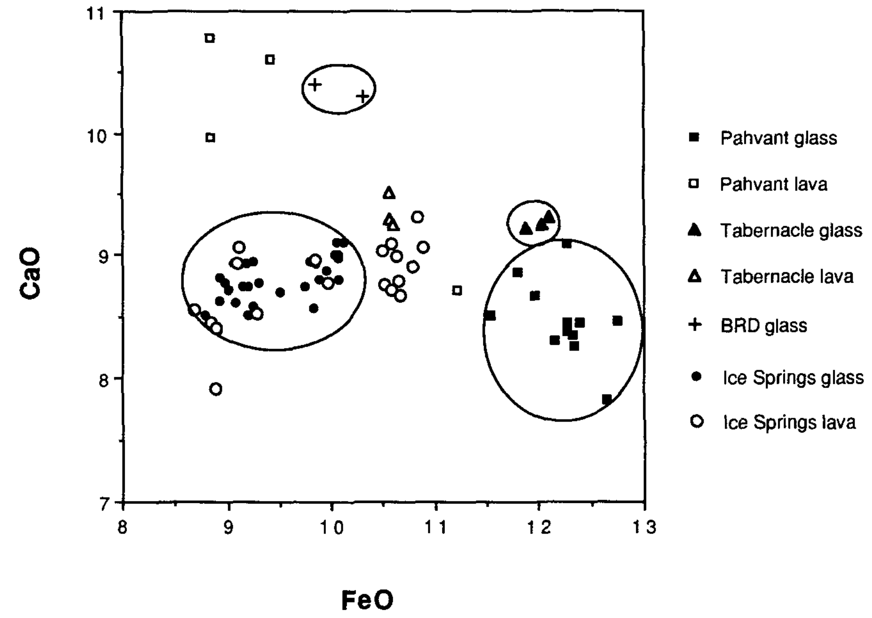


Figure 7. Plots of the results of whole-rock analyses of lavas and microprobe analyses of glass from the Black Rock Desert. BRD glass is basaltic glass from an unidentified vent in the Black Rock Desert. Values are in weight percent.

parts, and abundant ostracodes. The ostracode biostratigraphy is similar to that in other "white marl" sections in the Sevier Desert (Fig. B). A thin sand and gravel bed at the base of the marl marks the basal unconformity and represents the transgression of the lake.

In most parts of the Sevier River delta below the Provo shoreline the upper contact of the marl is abrupt and is overlain by sand containing reworked Pahvant Butte ash, rounded blocks of reworked tufa, and gastropods (BFS in Fig. 4). The sand (BFS) can be traced from localities such as OC-5 (Fig. 4), where it is <1 cm thick and overlies a complete white marl section including untruncated Pahvant Butte ash, to sections such as OC-4, where it is about 1 m thick and overlies Little Valley underflow-fan deposits. At intervening localities, such as OC-1, OC-2, and OC-3, the Pahvant Butte ash and marl are progressively more truncated with distance to the north from OC-5. At OC-4 no marl is present. In the interval between OC-3 and OC-4 small remnants of the white marl <20 cm thick are sandwiched between the basal transgressive sand and the overlying sand that contains reworked ash and blocks of tufa. At localities near OC-4 the sand mapped as BFS is thin and separates stratigraphic units (BRU, LVRU) that are lithologically almost identical, and it is not immediately apparent that the sand marks a major unconformity. Lateral tracing of the sand and other units, however, demonstrates the disconformable relationship. In addition, it is clear that the disconformity is found only at elevations below the Provo shoreline and that at the lowest elevations the thin sand marks the abrupt boundary between the marl and the overlying underflow-fan deposits (BRU; see Fig. 4).

On the basis of the stratigraphic position of the BFS sand and the local disconformity at its base, the sand is interpreted as a deposit laid down during and immediately after the catastrophic Bonneville Flood. During the Flood the lake dropped from the Bonneville shoreline to the Provo shoreline (Fig. 3) in a very short time, possibly on the order of several months, and discharged down the Snake River (Idaho) at a rate as much as 935,000 m^3s^{-1} (Gilbert, 1890; Malde, 1968; Currey, 1982; Jarrett and Malde, 1987; O'Connor, 1993). Strong currents would have been generated in the lake where the Sevier River was lowered to its new level at the Provo shoreline and the river began scouring the surface of the previously submerged delta. In this interpretation, the greatest amount of scour was at places like localities OC-7, where the white marl was completely removed and BFS was deposited directly on the much older Little Valley deposits. As shown by the truncation of the "white marl" described above, the submerged outer slope of the Little Valley delta (between sections

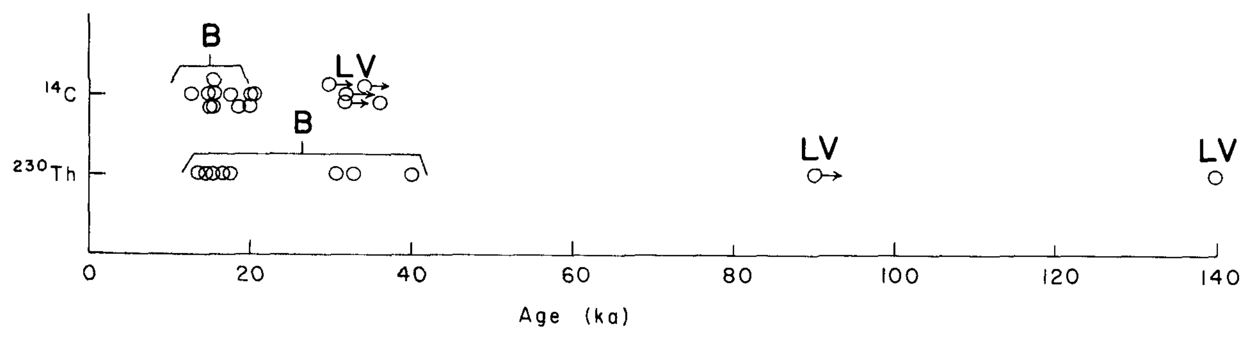


Figure 8. Plot of radiocarbon and ^{230}Th ages from Tables B and C on a time line. Ages are grouped according to stratigraphic interpretations (B, Bonneville; LV, Little Valley). Arrows indicate "greater than" ages.

OC-2 and OC-7, Fig. 4) was also scoured, possibly by sediment-charged density currents. Unit BFS in the Sevier River delta is equivalent in stratigraphic position to the Bonneville Flood marker bed that has been recognized in various forms throughout the Bonneville basin (Fig. B; Oviatt, 1987, 1991c, 1991d).

Pelleted mud overlies the BFS sand bed in the exposures Varnes and Van Horn (1984, 1991) refer to as the Big Gully (Fig. 1). The pelleted mud probably represents reworked underflow-fan sediments derived from river entrenchment caused by rapid base-level lowering.

Fine-grained deltaic (underflow-fan) deposits (BRU), which are lithologically similar to BTU and LVU, overlie the Bonneville marl (BM) and unit BFS in sections downstream from section OC-7 (Figs. 1 and 4). In the past, these deposits have been mapped as Bonneville silt and clay (Varnes and Van Horn, 1951); Alpine Formation sand, silt, and clay (Varnes and Van Horn, 1984); and as silt of "B Unit" (Varnes and Van Horn, 1991). Clearly the deposits labeled BRU (Fig. 4) are of Bonneville age and were deposited during the regressive phase, as shown by their stratigraphic position above the Bonneville marl and Pahvant Butte ash.

The uppermost facies in the Bonneville sequence consist of cross-bedded sand and gravel gradationally overlain by fine sand and silt (BFG, Fig. 4). These upward-fining sediments are virtually identical to the point-bar and overbank alluvium of Holocene age along the Sevier River. The snail fauna in the silt is the same as that in modern and Holocene fluvial/marsh deposits in the Sevier Desert. In addition, the silt overlies strath terraces of the Sevier River cut into the delta surface (primarily into BRU, Fig. 4), or it mantles extensive areas of the delta surface that are marked by well-defined abandoned fluvial channel scars visible on aerial photographs. The silt has been mapped as Provo silt (Varnes and Van Horn, 1951), the Draper Formation (Varnes and Van Horn, 1984; Van Horn and Varnes, 1988), and as silt of "D Unit" (Varnes and Van Horn, 1991). We know of no evidence that would lead to an interpretation of the silt as lacustrine, but there is abundant evidence of a fluvial origin. Its age is late Pleistocene as shown by radiocarbon ages between 12 and 13 ka (Table B). These ages may be minimum ages if the dated shells have been diagenetically altered.

LATE QUATERNARY HISTORY

A brief outline of the late Pleistocene geomorphic history of the Sevier River delta as interpreted from the evidence presented here is as follows.

(1) Prior to the Little Valley lake cycle the Sevier River deposited sandy alluvium (p-LVA in Fig. 4) on a flood plain up to a level higher than the Holocene flood plain. It is possible that the river was graded to a lake in the Sevier Desert at that time, but no direct evidence for such a lake has been discovered. There is evidence at two localities (localities O and OC-3) for more than one episode of calcic soil development at the end of the deposition of the pre–Little Valley alluvium.

(2) The Little Valley lake transgressed possibly as high as ~1,490 m at about 140 ka (Scott and others, 1983). The stratigraphically lowest Little Valley facies in the Sevier River delta exposures is the open-water to deep-water marl facies (LVM), which could not have been deposited directly in the plume of sediment from the river. This suggests that the river was depositing clastic sediment at some locality distant from the exposures shown in Figure 4 during the transgressive phase. A possible location for the river depocenter at that time was in an entrenched valley trending west from Lynndyl, similar to the entrenched valley of post–Little Valley age (Figs. 1 and 9A). During the regressive phase of the Little Valley lake cycle the plume of river sediment was aimed to the south at least part of the time and fine-grained underflow-fan sediments (LVRU) were deposited over the marl.

(3) During and following the regressive phase of the Little Valley lake cycle, the Sevier River entrenched its delta and formed a valley trending west from Lynndyl (Fig. 1). Soils formed in the post–Little Valley alluvium on top of the delta (LVA, Fig. 4).

(4) Lake Bonneville transgressed into the Sevier Desert at about 20 ka (Fig. 3). Within the entrenched Sevier River valley, fine-grained deltaic sediments (BTU) were deposited rapidly in the rising lake (Fig. 9A). On the outer flanks of the Little Valley paleo-delta (such as at OC-1 to OC-5), however, far from the influence of the river, marl (BM) was deposited directly above the basal transgressive sand.

As the lake continued to rise, the deltaic depocenter shifted upstream along the river to Mills Valley on the east side of the Canyon Range (Oviatt, 1992), and marl was deposited over most of the delta area below Leamington (Fig. 9B). Because a plume of turbid water entered the lake at the mouth of the Sevier River, however, the marl in the path of the plume near Lynndyl is rich in mud (as at sections R33, D74, and L-20; Figs. 1 and A).

(5) Pahvant Butte tuff cone erupted into Lake Bonneville at ca. 15.5 ka, when the lake was within 15 m of its highest level, and deposited basaltic ash in the lake over a wide area (Oviatt and Nash, 1989).

(6) The alluvial-fan threshold near Red Rock Pass, Idaho, failed at about 14.5 ka and the lake dropped catastrophically during the Bonneville Flood to a new stable threshold. With its base level lowered ~100 m, the Sevier River downcut rapidly through its deltaic deposits upstream from Lynndyl and reworked those fine-grained sediments offshore (BRU). The lake stabilized at the Provo shoreline, and overflow continued through Red Rock Pass for a period of time, during which the Sevier River deposited alluvium (BFG) at, and upstream from, the Provo shoreline.

(7) With gradual regression below the Provo shoreline, the river, which now had a southward orientation, became entrenched through older deposits (LVU and BRU) and reworked those sediments into the prograding underflow fan (BRU) offshore (Fig. 9C). Strath terraces on the delta surface are overlain by sandy gravel that grades upward into overbank sand and silt (BFG).

(8) Eolian sand and silt (po-BS) were deposited over the delta surface after it emerged at the end of the Bonneville lake cycle.

DISCUSSION

The different facies of the Bonneville Alloformation in the Sevier River delta area are related to changing water depth and geologic time (Fig. 3). Boundaries drawn between facies on the diagram are schematic, but illustrate how most facies contacts are time-transgressive (diachronous), whereas the contact at the base of BFS is approximately isochronous. The Bonneville stratigraphic model is consistent with inferences about the paleogeomorphology, including the paleohydrology of the lake and the river, which determined the physical aspects of the sedimentary environment. For instance, during the Bonneville cycle the Sevier River discharged water and sediment at much greater rates than at present into a deep lake that fluctuated in level during its transgressive phase in the closed basin. In addition, large waves produced by wind in the Sevier arm of Lake Bonneville would have supplied coarse-grained sediment locally and created longshore currents along the mountain front east of the delta. These

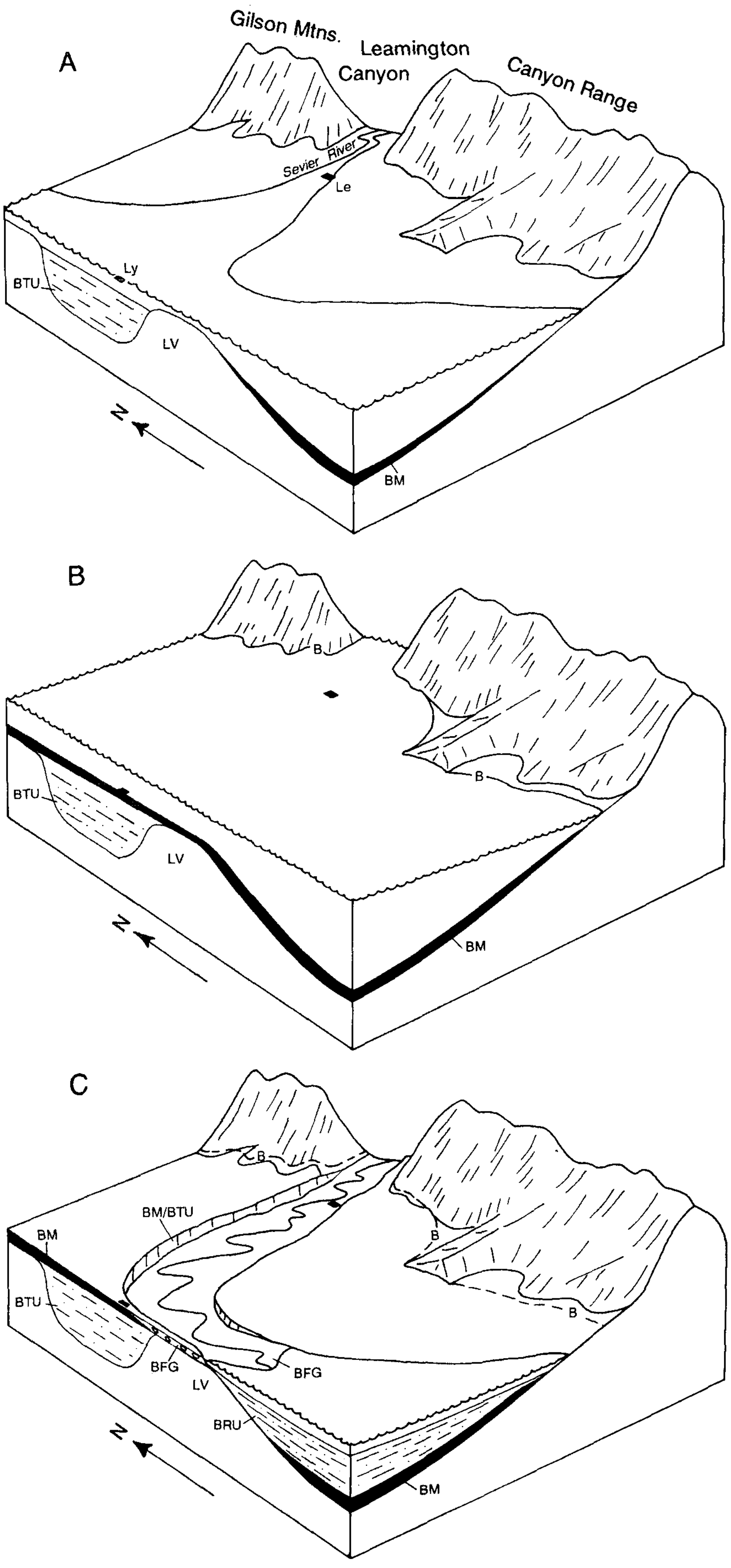


Figure 9. Schematic block diagrams of the Sevier River delta area showing landforms and depositional units at three stages in the Bonneville lake cycle. The relative positions of Leamington (Le) and Lynndyl (Ly) are shown. LV = Little Valley. See Figure 4 for explanation of symbols. A. Transgressive phase; lake at about 1,450 m. Note that the post–Little Valley entrenched valley of the Sevier River is partially flooded, and that deposition of BTU is confined to the submerged paleovalley. Marl (BM) is being deposited on the outer flank of the Little Valley paleodelta. B. Highstand of Lake Bonneville (B is the Bonneville shoreline). Marl is being deposited over the delta surface because the deltaic depocenter of the Sevier River has migrated upstream through Leamington Canyon to Mills Valley and beyond on the east side of the Canyon Range. C. Regressive phase, after development of the Provo shoreline. The Sevier River has begun entrenching a new valley in the delta and is exposing older deposits (BTU, LVRU). Regressive underflow-fan deposits (BRU) are being laid down offshore and the fluvial facies (BFG) is prograding lakeward as the lake level falls.

paleogeomorphic inferences can be made with a high degree of accuracy because the shape of the mountain front and the position of the mouth of the Sevier River have changed little since the Bonneville cycle. A reasonable and necessary inference is that during the period between the Little Valley cycle and the Bonneville cycle the Sevier River was entrenched in a valley similar to the modern river valley (Fig. 9A).

An important conclusion of our study is that the smooth, uniform-appearing external form of the Sevier River delta belies its complex internal structure. The Sevier River delta has been sculpted by a combination of processes, including deposition, wave scour, and river erosion during the Bonneville lake cycle, and eolian deposition during post-Bonneville time. Exposures described in this paper, however, reveal that the delta consists of deposits of at least two major lake cycles, that the unconformity between the stratigraphic units has high relief in places, and that there is no clue to the presence of the older deposits in the external morphology of the delta. Therefore, in parts of the delta distant from the river-bluff exposures, the delta is probably composed of sediment sequences deposited during many Quaternary lake cycles, and each sequence may include both fine- and coarse-grained facies that are arranged in a complex three-dimensional pattern that may include abrupt facies boundaries and the close juxtaposition of sharply contrasting facies. Recognition of this complexity could be important for such applications as exploration and development of ground-water resources, and in the use of Quaternary deltas as models for lacustrine sedimentation in the ancient rock record.

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