ERRATUM

We regret that the article "Controls of Tufa Development in Pleistocene Lake Bonneville, Utah," by Alisa Felton, Paul W. Jewell, Marjorie Chan, and Donald Currey, which appeared in the online edition of our May issue (*Journal of Geology* 114:377-390), failed to appear in our print edition. We note that the online edition, in which it does appear, is the edition of record, but we are including this article here in our July issue for readers who wish to see and use a printed copy.

Controls of Tufa Development in Pleistocene Lake Bonneville, Utah

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ABSTRACT

Prominent tufa localities along the Provo level (~14,000 ^{14}C yr B.P.) shoreline in Pleistocene Lake Bonneville have been characterized in detail. Three types of tufa are recognized: capping tufa, beachrock, and capping tufa over beachrock. Capping tufa and beachrock are end members of a continuum based on variable clastic content. All three types typically occur on headland environments that had stable substrate and little sediment input. Tufa development correlates with bedrock exposure and landform orientation, which in turn are correlated ($R^2 = 0.89$) with the longest fetch directions in the basin. Tufa also tends to be located at major subbasin divides and in the western portion of the basin.

Online enhancements: appendix tables.

Introduction

Calcium carbonate tufa deposits coat the shorelines of Pleistocene Lake Bonneville throughout northern Utah (fig. 1). While King (1878) and Gilbert (1890) described Lake Bonneville tufa and noted the connection between water aeration and tufa development, the bulk of subsequent Lake Bonneville research focused on clastic deposits and shoreline features of the lake. For this reason, the tufa deposits lack detailed characterization and a depositional model.

In the Lake Lahontan basin, the western Great Basin "cousin" of Lake Bonneville, tufa deposits have been more thoroughly examined. Benson (1994) and Benson et al. (1995) describe physical characteristics and paleoclimatic significance of Lake Lahontan tufa deposits, noting several layers of tufa growth with unique morphologies formed when lake levels stabilized. Benson et al. (1995) cite the role of Lahontan subbasin thresholds in controlling the elevation of tufa deposition in the Pyramid subbasin. Benson (1994) identifies several conditions that encourage carbonate deposition, including elevated water temperature, a hydrologically closed basin, proximity to a source of calcium, and a solid substrate. These factors are potentially important to Bonneville tufa deposition as well.

The relative influence of biological and physical factors influencing tufa development is an unresolved issue in the broader field of understanding controls of calcium carbonate formation in terrestrial waters. Kelts and Hsu (1978) present a thorough discussion of carbonate sedimentation in freshwater that includes the chemistry of calcite precipitation as well as a review of biogenic and physical considerations applied to carbonate deposition. Both algae and photosynthesizing cyanobacteria play a role in the biology of many tufas. Pedley (2000) indicates that tufas precipitate in part because of conditions in the physical environment and in part as a result of biological activity. Ford and Pedley (1996) note the connection between tufas, water aeration, and biology by characterizing tufa and travertine deposits according to physical form. The biological aspect of cyanobacteria calcification in relation to availability of CO_2 and phosphate in a water body is reviewed by Merz-Preiß (2000) and Riding (2000).

Two recent studies have examined Lake Bonneville tufa from a geochemical perspective. Hart et al. (2004) used strontium isotopes to understand the sources of water within the lake. In the process of

Manuscript received February 11, 2005; accepted December 15, 2005.

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[The Journal of Geology, 2006, volume 114, p. 377–389] 0022-1376/2006/11403-0008$15.00

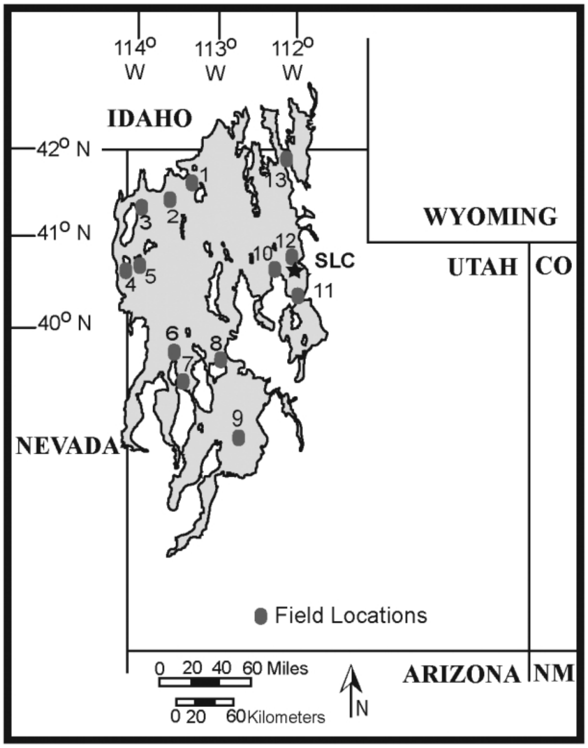

Figure 1. Lake Bonneville at highstand 15,000 ^{14}C yr ago and tufa locations examined in this study. 1 = north end of the Hogup Mountains, 2 = Terrace Mountain, 3 = Lucin Hill and Lion Mountain, 4 = Wendover Knob, 5 = Volcano Peak and Silver Island tombolo, 6 = north end of Fish Springs Range, 7 = Sand Pass, 8 = Table Mountain, 9 = Black Rock Volcano, 10 = north end of the Oquirrh Mountains, 11 = Point of the Mountain, 12 = Beck Street/Wasatch fault, 13 = Cutler Dam; *SLC* = Salt Lake City.

sample collection and analysis, Hart et al. (2004) were able to demonstrate unequivocally the lacustrine nature of the tufas as well as the fact that most of these rocks have undergone minimal subaerial alteration. Nelson et al. (2005) addressed tufa development of Lake Bonneville from a wide-ranging petrographic, field, and geomorphologic perspective and established both the local and basinwide controls of tufa formation.

Tufa Terminology. In order to clarify terms used in this work, it is necessary to distinguish among four often-confused calcium carbonate deposits: tufa towers, waterfall tufa, travertine, and standard tufa. Tufa towers, such as those at Mono Lake in eastern California and the Needles at Pyramid Lake, Nevada, are formed by carbonate-saturated springs flowing into waters (Cloud and Lajoie 1980; Benson 1994). Fluvial waterfall tufas are created by excessive CO_2 degassing in calcium-saturated waters as they flow over a knick point or hydraulic drop (Zhang et al. 2001). Fluvial waterfall tufas often have a biological component to their formation and are also known as tufa dams or barrages. Travertine is calcium carbonate deposited in hydrothermal or warm waters. In contrast, tufa forms in ambient-temperature waters. Both travertines and standard tufas form in freshwaters (Ford and Pedley 1996). Lake Bonneville shore-zone calcium carbonate deposits belong in the standard tufa category because they were deposited in an alternating open and closed basin in relatively fresh, ambient-temperature waters.

Lake Bonneville History and Geologic Setting. Pleistocene Lake Bonneville was a closed-basin pluvial lake that left a detailed record of climate change in northern Utah, eastern Nevada, and southern Idaho in the form of nearshore sediments, shoreline benches, and offshore sediments (Gilbert 1890; Currey 1990). Lake Bonneville began filling around 27,000 ^{14}C yr ago (Oviatt 1997). The pluvial lake rose to the Bonneville highstand around 15,000 ^{14}C yr ago (fig. 2), with a maximum surface area of 50,000 km^2 (Wambeam 2001). Approximately 14,500 ^{14}C yr ago, Lake Bonneville catastrophically flooded through the Red Rock Pass threshold (Gilbert 1890; Oviatt et al. 1992) and stabilized at the Provo stillstand level, about 140 m below the Bonneville highstand elevation. During the Provo still-

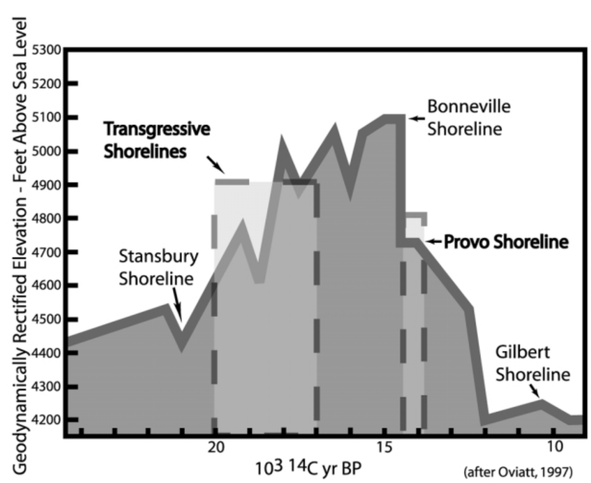

Figure 2. Hydrograph of Lake Bonneville in radiocarbon years B.P. versus lake surface elevation. This study focuses on transgressive (prehighstand) shoreline sequences and Provo shoreline deposits as identified by the highlighted areas in the dashed boxes at elevations between 1420 and 1495 m.

stand, Lake Bonneville had periods of being both hydrologically closed and open (Sack 1999; Godsey et al. 2005). The closed-basin system during the Provo stillstand potentially affected tufa formation in the basin. After the Provo stillstand, the lake continued its regression to the Gilbert level about 10,000 ^{14}C yr ago. The Gilbert lake level marked the end of the Bonneville high-water phase.

Lake Bonneville occupied a large section of the eastern portion of the extensional Basin and Range geologic province. Implications of this setting include numerous lake subbasins, an active tectonic regime with concurrent uplift and erosion, and steep-walled basins creating active sediment supplies and accommodation spaces. These factors worked in conjunction with an arid Holocene climate to produce and preserve the well-defined shoreline and shore-zone sediments exposed today. Bedrock at selected field sites ranges from Precambrian to Tertiary in age and consists primarily of limestones, cherts, granitics, volcanics, and quartzites. The amount and extent of limestone bedrock exposure contributing calcium to the lake water and the isolated subbasins with unique water chemistry were two geologic factors that probably influenced tufa development in the Bonneville basin as discussed in this article.

Methods

Tufa Analysis. Of the original 13 field sites (fig. 1), 10 were mapped on 7.5-min United States Geological Survey quadrangle maps (table 1). Spatial extent, thicknesses, types of tufa, and percentage of tufa-covered area coating a shoreline surface (table 2) were recorded at each field site. In order to understand the petrographic characteristics of the tufas, two samples of tufa were taken from each of the 10 sites for analysis. Samples were slabbed for hand sample analysis and thin sectioned for petrogaphic study. Twenty-two thin sections were point counted (95–158 points per thin section; $n =$ 2882 total points) and categorized as algal filaments, matrix groundmass, shell fragments, clastics, or pore space (table A1 in the appendix, available in the online edition or from the *Journal of Geology* office). The relatively small size of cyanobacteria prevented their identification in standard thin-section examination. It is possible that a certain fraction of the matrix groundmass is composed of calcified cyanobacteria.

The tufa composition was primarily calcium carbonate, but in thin section alone, the difference between calcite and aragonite cannot be distinguished. This is an important distinction because of the different water conditions required for the formation of calcite and aragonite (Kelts and Hsu 1978). X-ray diffraction was performed on nine capping tufa samples to determine calcite and aragonite mineral contents. Specific mineralogical trends could not be established, so the results are not presented here (Felton 2003).

Tufa locations at subbasin thresholds were of particular interest because of the possible chemical differences between subbasins and the main basin. Chemical differences and, hence, mineralogical differences are likely to exist if there was restricted flow between basins. In order to determine if flow was restricted between subbasins, lake surface areas of subbasins were measured using ESRI ArcView software, and constriction cross-sectional area was calculated from digital topographic maps. Lake surface area was compared to constriction cross-sectional area for each subbasin threshold. A large ratio of subbasin to cross-sectional area of the constriction suggests possible chemical difference between the subbasin and the main body of water.

Landform Analysis. The usefulness of process-based landform analyses in interpretation of paleolake dynamics and sediment transport analysis has been known for considerable time (e.g., Gilbert 1890; Adams and Wesnousky 1998). Landform analysis is used to determine local depositional controls on tufa development. For this study, aerial photos and topographic maps were studied from the entire Bonneville basin to locate small (~5 km^2) Lake Bonneville islands where shore processes could be studied from a 360° perspective (fig. 3). At the 10 field locations, aerial photo interpretation and geomorphic mapping were used to understand the spatial relationships between erosional and depositional regimes (table 1). All available paleowave energy indicators (described below) were mapped at the 10 field locations.

Erosional regimes are characterized by exposed bedrock and tufa formation. Bedrock is eroded and exposed by strong and consistent wave energy. Waves, driven by wind, remove and transport sediments from a section of shoreline. The Bonneville basin contains many examples of bedrock exposure on the shoreline. One of these examples is Lucin Hill, where on the eastern side of what was an island in the lake, a majority of shorelines have exposed bedrock. On the opposite western side, a majority of surfaces are covered with lacustrine sediments, and very little bedrock is exposed (fig. 4).

Depositional regimes are characterized by sediment accumulation and constructional landforms such as spits, beach ridges, and tombolos (table 2).

Table 1. Summary of Tufa Localities

Locality	Latitude and longitude	Lake level	Tufa type	Shoreline character[a]	Percentage of slope on shoreface (+/−5%)	Geomorphic setting
Northwestern part of the basin:						
Lucin Hill (west)	41°19′57″N, 113°54′37″W	Provo	Both	Both	19	Lee side of island/tombolo
Lucin Hill (east)	41°19′58″N, 113°54′25″W	Provo	Capping tufa	Erosional	39	Windward side of island
Lion Mountain (west)	41°16′46″N, 113°55′30″W	Provo	Beachrock	Depositional	6	Lee side of island/tombolo
Lion Mountain (east)	41°16′43″N, 113°54′23″W	Provo	Capping tufa	Erosional	40	Windward side of island
Hogup Mountains (north end)	41°35′43″N, 113°11′08″W	Provo	Both	Depositional	18	Spit
Western part of the basin:						
Wendover Knob	40°44′22″N, 114°05′54″W	Provo	Capping tufa	Erosional	27	Windward side of peninsula
Volcano Peak (west)	40°47′19″N, 113°59′31″W	Provo	Both	Erosional	45	Windward exposed headland
Volcano Peak (east)	40°47′17″N, 113°58′45″W	Provo	Both	Erosional	24	Windward exposed headland
Silver Island tombolo	40°53′26″N, 113°52′58″W	4500 ft	Both	Deposional	4	Tombolo
Southern part of the basin:						
Tabernacle Hill	38°55′20″N, 112°31′40″W	Provo	Capping tufa	Both	10	Synprovo volcanic cone
Table Mountain	39°56′54″N, 112°53′46″W	Provo	Both	Both	20	Windward peninsula
Black Rock Volcano	38°48′26″N, 112°29′09″W	4900 ft	Both	Both	20	Volcanic cone
Fish Springs Range (north end)	39°52′29″N, 113°25′45″W	Provo	Both	Both	35	Windward peninsula/headland
Sand Pass (south side)	39°37′14″N, 113°24′05″W	Provo	Both	Depositional	10	Pass between subbasins
Eastern part of the basin:						
Oquirrh Mountains (north end)	40°43′25″N, 112°13′10″W	Provo	Both	Both	60	Exposed headland

[a] "Both" means there are erosional and depositional portions of the shoreline.

Table 2. Summary of Field Criteria for Understanding the Erosional and Depositional Regimes of Lake Bonneville

Process	Field criteria	Indicators
Erosional	50%–100% of surfaces with bedrock exposed, 50%–100% of surfaces with tufa coverage	Bedrock exposure, tufa development
Depositional	Tombolos, spits, beach ridges	Landform orientation

Deposition of sediment occurs when sediments are transported from areas of high energy to areas of low energy (King 1972). Erosional shorelines occur where wave energies are sufficient to remove and transport material and are commonly found on windward slopes. Likewise, where wave energies are reduced or convergent, depositional shorelines develop. Depositional shorelines typically occur in conjunction with the lee sides of slopes. Tombolos, beach ridges, and other constructional shorelines form in areas of decreased wave and wind energy (fig. 3). Wave energies impinge on an island and dissipate while being refracted around the island or headland. This creates an eddylike environment on the lee side of an island, where deposition of sediment occurs (Zenkovich 1967; King 1972). The locations, extents, and trends of spits, beach ridges, and tombolos associated with the islands were recorded as field data (table 2).

Results

Tufa Classification. Tufa deposits occur on various slope profiles and geomorphic settings (table 1). Tufa deposits are located on the basinward edges of Provo shore-zone benches at ~1460 m elevation. Generally, tufa is observed 1 m above to 10 m below mean shoreline bench surface elevation. Distribution of tufa is most common on the break in slope from bench to basin (fig. 5). Three forms of tufa deposits are present in the Bonneville basin: capping tufa, beachrock, and capping tufa over beachrock (fig. 6).

Capping Tufa. Capping tufa is a grayish white, porous foreshore facies that coats exposed bedrock and solidified beachrock (fig. 6*A*). Deposits are commonly 0.2–0.5 m in thickness, with a maximum thickness of 1 m and a minimum tufa film thickness of 2 mm (fig. 7*A*). Capping tufa is calcium carbonate containing less than 10% clastic material (generally quartz, volcanic sand, and clay). Capping tufa has an average porosity of 18%. Porosity increases from the inner portion of the tufa cap to the outer portion (fig. 7*B*). Tufa caps are massive and concentrically accreted around a central nucleus or horizontally laminated on a planar surface. Capping tufa also takes pendulous or draping forms (fig. 7*C*). Contact surfaces between bedrock and tufa are sharp. Encrusting limestones, cherts, volcanics, and quartzites, capping tufa developed on any appropriately stable substrate and is common on headlands that were exposed to unrestricted lake wave energy.

Thin-section counting of 95–158 points for each of 22 samples reveals on average 45% algal filaments, 33% micrite groundmass, 18% porosity, 2.5% clastic fragments, and less than 1% other material, including shell fragments (table A1). Algal filaments range in diameter from 0.5 to 3 mm. Thin sections show an opaque dirty-brown micrite groundmass in plain light. Micrite is commonly banded between algal filaments (fig. 7*D*) at a scale that was not visible macroscopically. Algae genera and species were not identified.

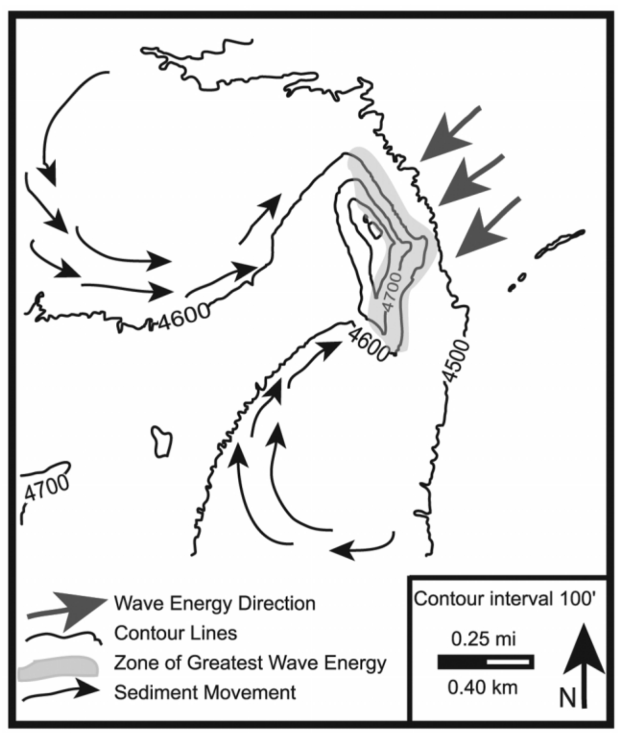

Figure 3. Schematic example of wave energy orienting landforms at Lucin Hill. In this case, a tombolo is formed in the lee of an island, which blocks wave energy and allows a tombolo to form. The windward side of the island shows erosional characteristics as it absorbs the brunt of wave energy.

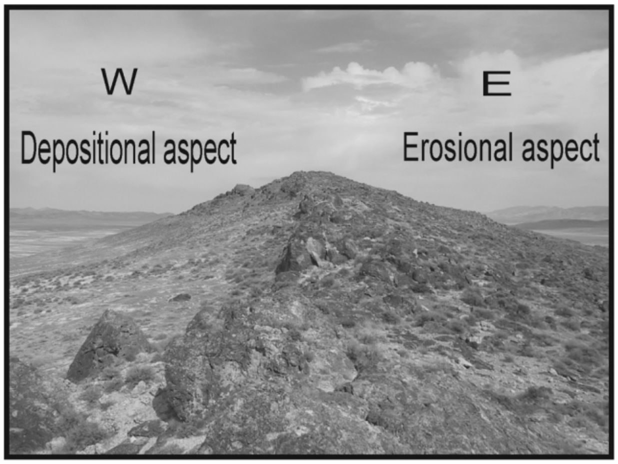

Figure 4. Wave direction indicator of exposed bedrock on Lucin Hill ridge crest looking north, where there is much exposed bedrock on the eastern surface, compared to little bedrock exposure on the western aspect. The east side has erosional character, whereas the west side has depositional character. Camera elevation is 1430 m.

X-ray diffraction analysis of seven samples from erosional regimes shows mineralogy of >70% calcite and <20% aragonite. Tufas from two areas with depositional character rather than erosional character, Sand Pass and Silver Island tombolo, have >50% aragonite mineralogy (Felton 2003).

Beachrock. Beachrock is a clast-supported calcium carbonate deposit (fig. 6*B*). Beachrock contains >90% clasts, which are cemented by tufa (fig. 8*A*). Beachrock contains clasts of varying size. Sandy beachrock (0.06–2 mm), pebble beachrock (2–64 mm), cobble beachrock (64–256 mm), and boulder beachrock (>256 mm) are distinguishable beachrock facies and refer to the size of the majority of clasts cemented by tufa. Beachrock facies are commonly well sorted, which is a consistent feature of high-energy beach foreshore facies. Sandy beachrock is present in embayments and sheltered sides of islands. Cobble and boulder beachrock occurs in reentrant portions of embayments and exposed headlands. Cobble and boulder beachrock consists of locally derived clasts. Outcrops vary in thickness from a 1-cm hard ground to a massive 2-m wall of beachrock.

Capping Tufa over Beachrock. At six of 13 field locations, an encrusting tufa deposit, void of clasts, caps a cemented beachrock (fig. 6*C*). In this deposit, beachrock up to 1–2 m thick can be overlain by up to 0.5 m of capping tufa (fig. 8*B*). This sequence of capping tufa overlying beachrock is well defined at the Volcano Peak field locality near Wendover, Nevada, where a paleobeach surface with a tufa cap is present (fig. 1). Capping tufa over beachrock occurs in transitional sediment transport regimes, where sediment supply diminishes, and tufa development is encouraged by the reduction of clastic input. Capping tufa over beachrock is present in areas that are transitional between depositional and erosional.

The Role of Fetch across Lake Bonneville. Fetch is the distance over water that wind can travel and build wave energy. Because longer fetch distances allow greater wave energy to build, open water exposed to long fetch will produce larger waves. The field areas in this study were generally exposed to waters with fetch distances ranging from 32 to 174 km. Fetch distances correspond to interpreted wave directions for each field area (table A2 in the appendix, available in the online edition or from the *Journal of Geology* office). The longest fetch direction at each field area (table A2) is plotted against the field interpretation of predominant energy direction (fig. 9). Wave direction field interpretations correlated with directions of greatest fetch and yielded an R^2 of 0.89. This implies that the large fetch distances on Lake Bonneville produced large waves that oriented landforms, exposed bedrock, and aided tufa development.

Underlying geologic structures and preexisting topography probably also played a critical role in bedrock exposure. Where strata dip steeply shore-

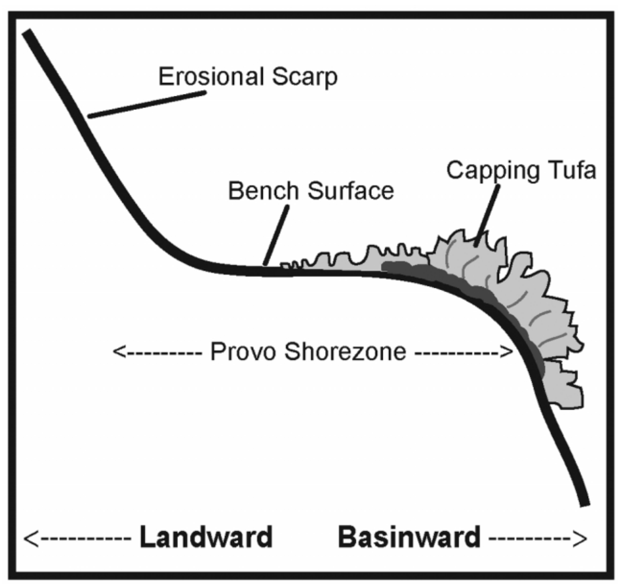

Figure 5. Schematic drawing of tufa locations on Provo shoreline benches. Tufa commonly occurs in patches on the outer edges of benches.

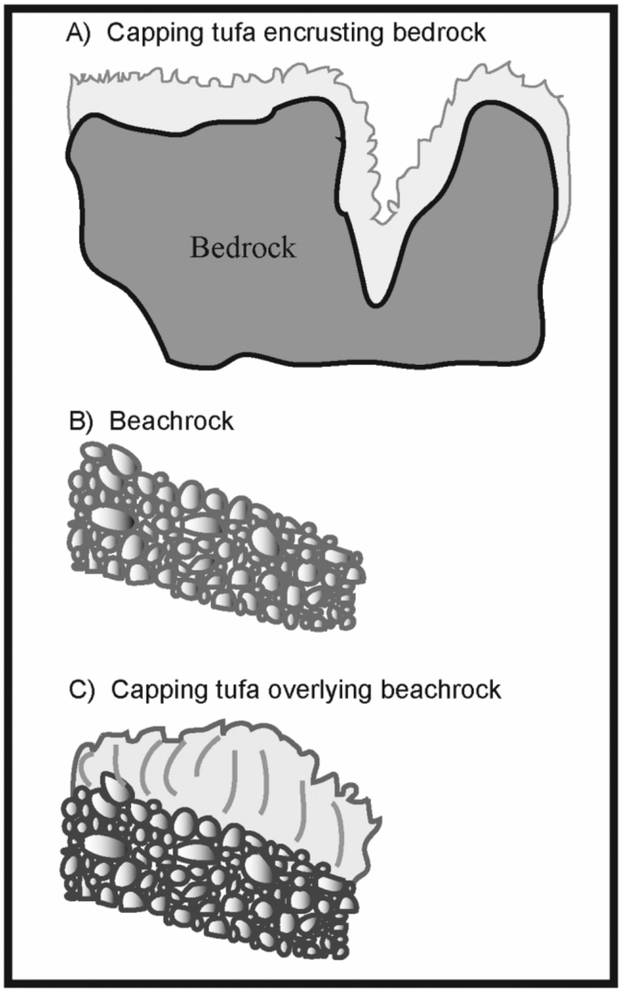

Figure 6. Three major forms of tufa development in the Bonneville basin. *A*, Encrusting tufa, thickness from 2 mm to 1 m, commonly occurs as a crust on exposed bedrock surfaces. *B*, Coated clasts (beachrock). Clast sizes range from sand to boulder, exposed in thicknesses up to 2 m. *C*, Beachrock with a tufa cap.

ward, bedrock is more easily exposed to lake energy. This exposed bedrock is then a good substrate on which tufa can form. As a result, tufa formation is more common on headlands with steeply dipping strata.

Discussion

Tufas are unique features of ambient-temperature waters of western U.S. pluvial lakes such as Pleistocene Lake Bonneville and Lake Lahontan. In the Bonneville basin, calcium carbonate deposits are useful tools for recognizing areas of high hydrodynamic energy. A depositional model for tufa development is presented here that incorporates the interpretation of a tufa continuum as well as local and basinwide controls on tufa formation.

The two end members of beachrock and capping tufa bracket a continuum of shore-zone calcium carbonate deposits (fig. 10*A*). Tufa deposits in the Bonneville basin are present in any ratio along the continuum. The continuum has temporal and spatial elements. The spatial element occurs when facies along a shoreline change from capping tufa to beachrock. This change can take place because of spatial changes in slope angle or wave energy. Capping tufa overlying beachrock adds a temporal dimension to the tufa continuum because it is a transitional facies occurring when a shore-zone system stops depositing beachrock and starts depositing capping tufa. This transition may be caused by a change in the amount of sediment supply or wave energy. The capping tufa over beachrock deposit would be illustrated by a system moving left to right on the continuum over time (fig. 10). When the Provo level lake initially occupied the Provo shore zone, it is suggested that there was excess sediment available as a result of wave action and reworking of highstand material and that these factors caused beachrock formation. As the stillstand progressed, it is possible that in some places, available sediment supply diminished and capping tufa was able to form on top of the stable substrate created by the beachrock.

Local Depositional Controls

Field mapping and laboratory analysis of tufa from around the Bonneville basin provides the basis for interpretation of factors that control tufa development. These factors include local controls (in the shore zone of the particular field locality) as well as larger-scale, basinwide controls based on spatial distributions of tufas around the Lake Bonneville basin.

Chemical Analysis. X-ray diffraction analysis shows predominantly calcite mineralogy for capping tufa samples. There are many factors controlling which carbonate phase precipitates in a lake, including the pH (Friedman 1978; Kelts and Hsu 1978) and the magnesium/calcium (Mg/Ca) ratio of the water. Assuming calcite is a primary product of deposition and not a secondary replacement of original aragonite, partial pressure of CO_2 in shore-zone waters was reduced enough to precipitate calcite at the Provo level of Lake Bonneville but not low enough to precipitate aragonite. This suggests local shore-zone waters with a pH of ~8, sufficient to precipitate calcite ($pH > 7$) but not high enough

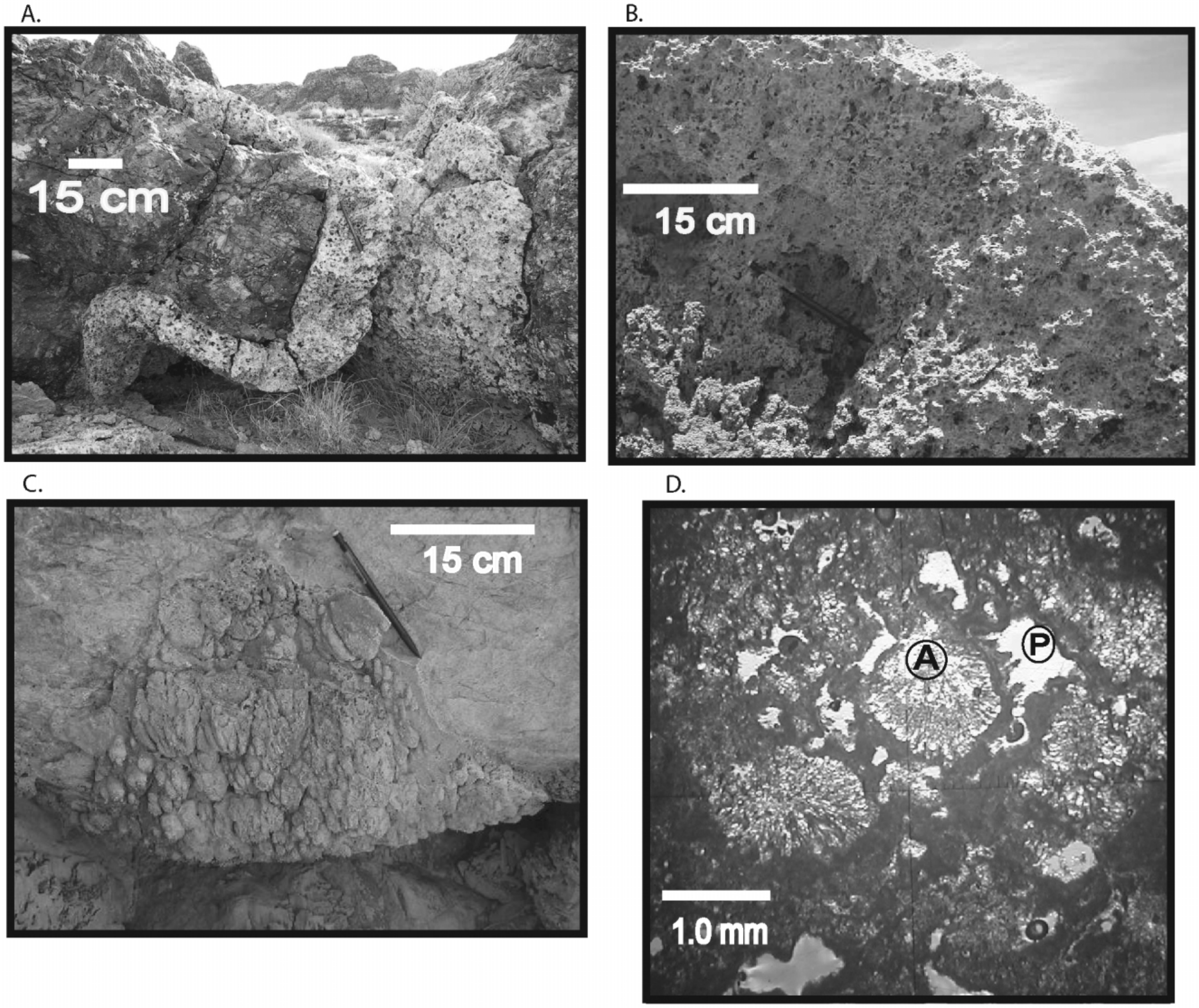

Figure 7. *A*, Capping tufa adheres to chert bedrock at the Lucin Hill locality. Notice coating nature of these porous tufas. *B*, Detail of capping tufa facies at Table Mountain with banded and porous tufas. Tufa shows increased porosity toward the outer edge of the deposit. *C*, Pendulous form of capping tufa coating quartzite at Table Mountain. *D*, Photomicrograph of tufa showing prominent algal filaments (*A*) in the middle and upper middle of the photograph. Light areas are pore space (*P*).

to precipitate aragonite (pH > 9; Friedman 1978). Calcite as the primary precipitate suggests a low (<2) Mg/Ca ratio in the shore-zone waters (Kelts and Hsu 1978) of Lake Bonneville.

Tufa Precipitation. Shore-zone lacustrine calcium carbonate deposition is a function of water temperature, clastic input, calcium concentration of the water body, and local water pH, all of which are influenced by biological factors and water agitation. Both the organic (biological factor) and the inorganic (water agitation factor) presumably affected tufa deposition on the Provo shoreline of Pleistocene Lake Bonneville. Biomediation, solar heating, and wave agitation (degassing) reduced the partial pressure of CO_2 and elevated the local pH of shore-zone waters. As pH of water increases, solubility of calcium carbonate decreases, resulting in calcium carbonate precipitation:

$$Ca^{2+} + 2HCO_3^- \leftrightarrow H_2O + CO_2 + CaCO_3. \quad (1)$$

Release of CO_2 in equation (1) corresponds to precipitation of $CaCO_3$.

In areas where algae and cyanobacteria can flour-

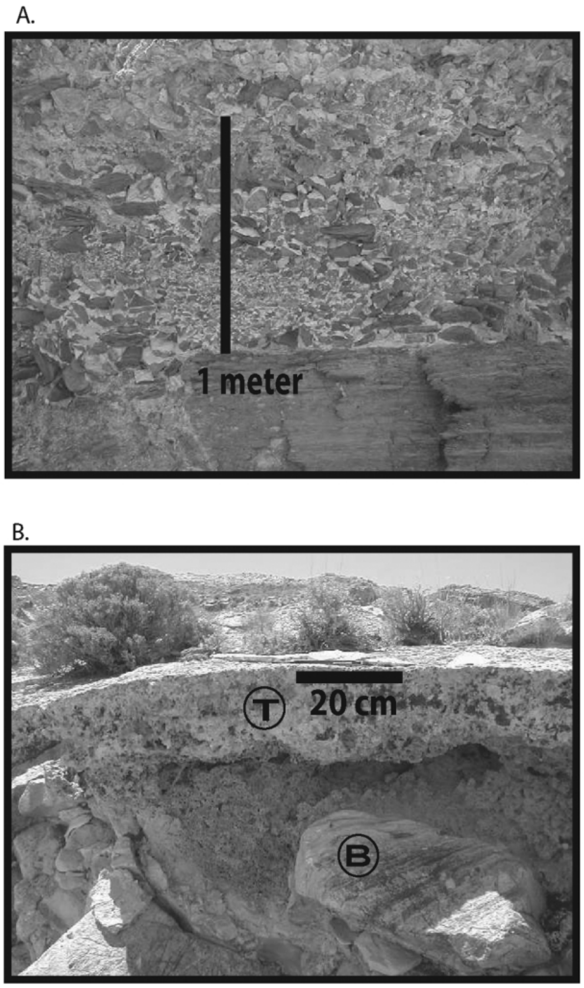

Figure 8. *A*, Beachrock at Table Mountain, with 1.5-m deposit of pebble to cobble calcium carbonate–cemented clasts overlying Cambrian shale. *B*, Capping tufa (*T*) over beachrock (*B*). This deposit is a transitional facies where stabilized beachrock is overlain by capping tufa. This location at Table Mountain contains boulder beachrock of locally derived quartzite clasts capped by 0.4 m of tufa.

ish, such as sediment-limited regimes, local pH rises as a result of biomediation, and tufa can form. It is known that algae played a significant role in the tufa development of Lake Bonneville because thin sections contain an average of 45% algal filaments. In areas where there was water agitation, such as headlands with exposure to large wave energies, local pH rose as a result of degassing, and tufa precipitated largely inorganically. Mapping of tufa localities reveals the most prolific tufa deposits on headlands and areas that were exposed to large fetch distances in the lake. It is herein suggested that algal growth and wave agitation together influenced ambient lake chemistry to create locally massive deposits of capping tufa on steep headlands, where bedrock was exposed and there was little sediment input. In areas where there was some wave action, a less steep slope, and plentiful sediment supplies, beachrock formed (fig. 10).

Basinwide Depositional Controls

Subbasin Thresholds. Subbasin thresholds are a potentially important control of tufa development because reductions of water flow when the lake level dropped may have isolated the waters of subbasins. This may be a major factor in inducing tufa deposition (Kelts and Hsu 1978; Benson 1994). In the Bonneville basin, large deposits of tufa occur at thresholds between subbasins. All four major Provo level subbasin thresholds—Old River Bed, Sand Pass, Point of the Mountain, and Cutler Dam—contain tufa deposits (table 3). One of these divides, Sand Pass, is a predominantly depositional regime at ~4800 ft (1463 m) located on the threshold between the Great Salt Lake main basin and the Tule Valley subbasin in the southwest quadrant of Lake Bonneville. Because the area is predominantly depositional, dense capping tufa like that found at Sand Pass is not expected. In comparison to Sand Pass, the Table Mountain field site contains some of the most laterally extensive and thickest tufa deposits found in the Bonneville basin. This locality is near the Old River Bed, which was the connecting conduit for water flowing from the Sevier subbasin to the Great Salt Lake subbasin of Lake

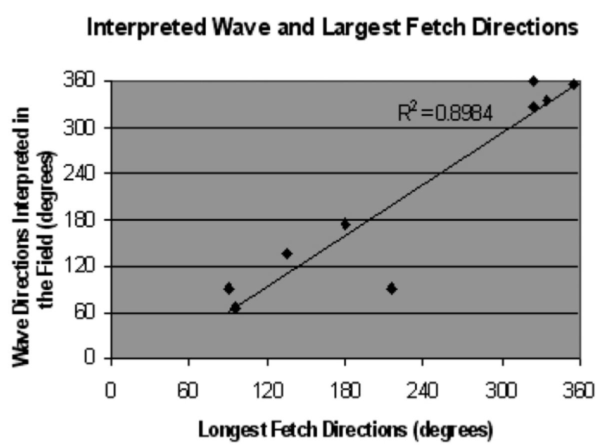

Figure 9. Correlation between longest fetch direction and wave directions ($n = 10$) interpreted from field mapping. This relationship illustrates the important role fetch plays in sculpting landforms in the Bonneville basin.

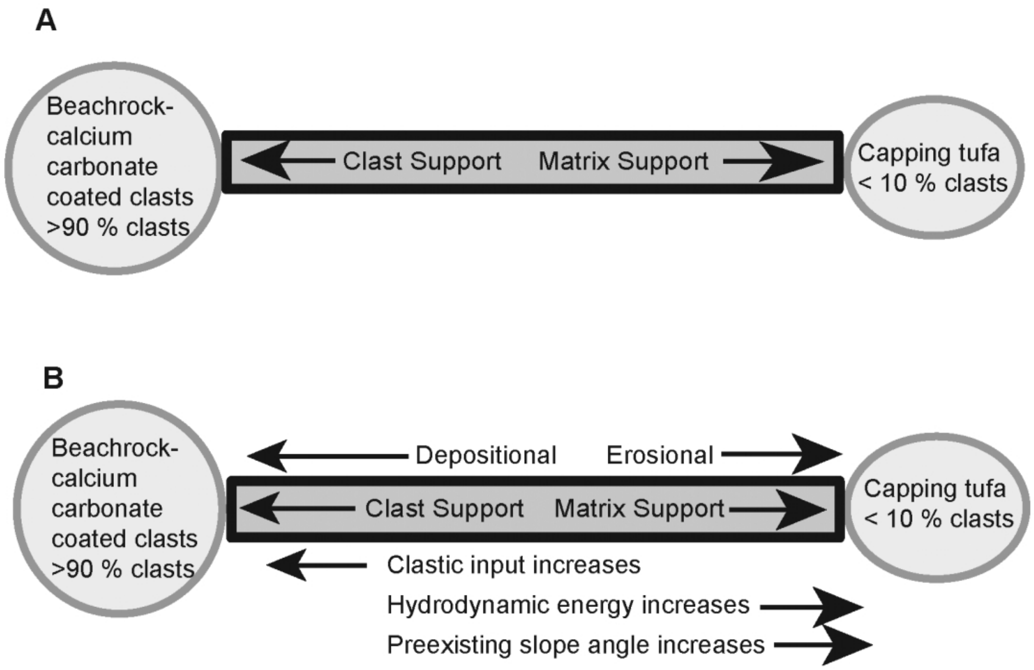

Figure 10. *A*, Field relationships of tufa continuum. In the Bonneville basin, shore-zone calcium carbonate occurs as capping tufa, containing <10% clastic material. Tufa also occurs as the matrix of beachrock, which consists of calcium carbonate–coated clasts. The beachrock end member contains >90% clasts. Calcium carbonate deposits can occur in any concentration along the continuum. *B*, Detailed continuum of the Lake Bonneville beachrock to the capping tufa facies. Beachrock occurs in more depositional regimes where there is adequate sediment input, lower slope angle, and enough wave energy to orient but not transport the clastic material. Capping tufas form where there is sufficient wave energy and slope angle to transport clastic material basinward and allow tufa growth.

Bonneville (Gilbert 1890; Oviatt et al.1992). The Cutler Dam locality is a narrow canyon that carries the present-day Bear River from Cache Valley into the Great Salt Lake basin. Capping tufa coats the walls of this canyon. At Point of the Mountain, which divides Utah Valley and Great Salt Lake Valley, there is beachrock and some capping tufa along the Provo shoreline, especially on the south side of the Traverse Range.

The large size of the subbasins (table 3) and the restricted flow channels imply limited mixing and unique water chemistry for the subbasins as compared to the main water body. It is suggested that tufa development at these sites was initiated by the isolation and chemical concentration of subbasin waters flowing through these constrictions and mixing with less concentrated waters of the main basin. Water flowing between subbasins mixes at these constrictions, encouraging calcite precipitation. An additional factor at the Cutler Dam locality is the watershed runoff from the relatively large Bear River basin that might have contributed a constant supply of calcium to the constriction, promoting calcium carbonate precipitation.

Spatial Distribution of Tufa. The Bonneville basin is flanked on the eastern edge by the Uinta and Wasatch mountain ranges, which both contain large drainage basins. The drainage basins feeding the eastern portion of the Great Salt Lake basin make up 97% of modern-day inflow, with the Bear and Weber Rivers contributing 73% of the total (Arnow and Stephens 1990). During the last glacial maximum, substantially increased inflow is assumed, but the relative size and elevation of the drainage basins and thus the percentage of water entering from the east should have remained equivalent to modern values. Is the spatial distribution of tufa related to the distribution of freshwater in the basin? A majority of large tufa deposits at the Provo level of Lake Bonneville do occur in the western portion of the basin. This skewed distribution could be due to two factors. First, a large amount of water coming out of the Wasatch Mountains could have diluted waters enough to suppress car-

Table 3. Summary of Subbasins of Lake Bonneville

Constriction locality	Locality	Subbasins involved (subbasin → main basin)	Tufa present?	Subbasin water surface area (km^2)	Constriction cross-sectional area (km^2)	Subbasin evaporation with evaporation of .5 m/yr (m^3/s)	Ratio of subbasin area to constriction cross-sectional area[a]
Old River Bed	Table Mountain	Sevier basin → Great Salt Lake basin	Yes	5440	.360	78.8	15,111
Sand Pass	Sand Pass	Tule Valley → Great Salt Lake basin	Yes	971	.0088	15	110,340
Point of the Mountain	Point of the Mountain	Utah Valley → Great Salt Lake basin	Yes	1230	.298	19	4127
Cutler Dam	Cutler Dam	Cache Valley → Great Salt Lake basin	Yes	1036	.056	16	18,500

[a] Subbasin surface areas compared with constriction cross-sectional areas.

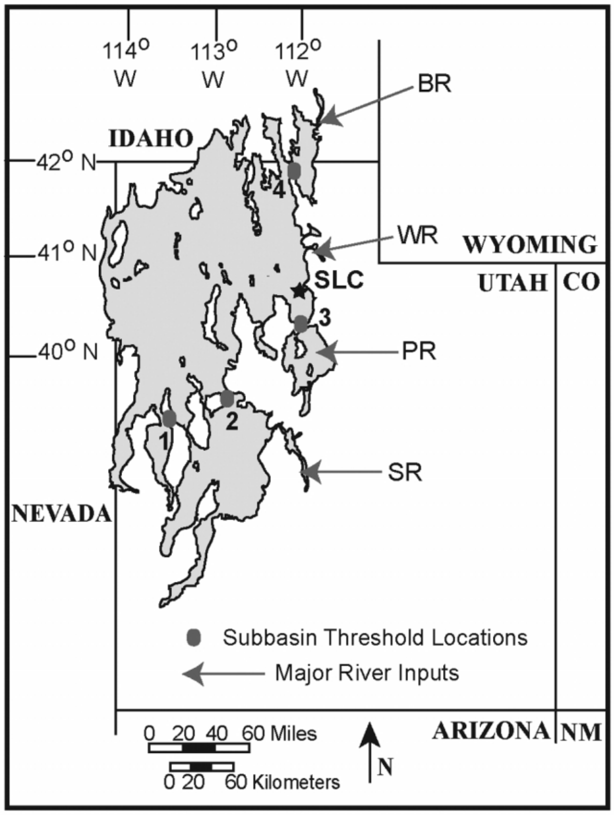

Figure 11. Lake Bonneville at highstand 15,000 yr ago with major river inputs. Note majority of freshwater input is from the eastern half of the basin. This dilution could hinder tufa development in the eastern half of the basin, where larger drainage basins contributed a majority of the water to the lake. *BR* = Bear River, *WR* = Weber River, *PR* = Provo River, *SR* = Sevier River.

bonate formation. Second, large amounts of sediment supply produced by rivers and glaciers in the Wasatch Mountains could have overwhelmed any potential tufa development with clastic material (fig. 11). We suggest that these two factors contributed to the lesser amounts of tufa seen in the eastern portion of the basin.

Conclusions

Three major forms of tufa occur in the Bonneville basin and can be categorized along a continuum with respect to clastic material entrained in the calcium carbonate deposit. Locally, tufas are prevalent on headlands and windward sides of islands that were exposed to high wave energy and contained a solid substrate. Algal growth and wave action degassing played a substantial role in the development of tufa deposits around the Bonneville basin. Calcite mineralogy, rather than aragonite, indicates possible localized shore-zone elevated water pH and Mg/Ca ratio <2.

In terms of basinwide controls, tufa commonly occurs at basin thresholds, where water is moving between a restricted subbasin and the main body of the lake. Tufa deposition may also be limited by the freshwater and sediment input on the eastern side of the Bonneville basin, resulting in a majority of tufa occurring in the western basin.

Identification of tufa deposits in the Bonneville basin demonstrates the importance of paleowater chemistry, wave action, and basin threshold controls. Lacustrine basins are widely recognized as valuable paleoclimate records in Earth history. Although tufa deposits have been typically overlooked even in the Lake Bonneville basin, this study shows the potential for integrating tufa distribution, mineralogy, lake morphometry, and hydrodynamic characteristics in interpreting pluvial lake systems.

ACKNOWLEDGMENTS

H. Godsey, I. Schofield, and M. Gregory assisted in the field and added insightful reviews of this article. Three anonymous reviewers improved the manuscript considerably. This work was supported by Utah Kennecott Copper Corporation and National Science Foundation grants SBR-9817777 and EAR-9809241.

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