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Morphology and paleoclimatic significance of Pleistocene Lake Bonneville spits

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Abstract

Pleistocene Lake Bonneville of western Utah contains a variety of spits associated with shorelines and other features that formed between 21,000 and 12,000 ^{14}C yr BP. Field studies in the low-lying mountain ranges of the central portion of Lake Bonneville identified 17 spits of various types. The spits are connected to small mountain ranges and islands, vary in size from 0.02 to 0.5 km^2, and are composed of coarse-grained, well-rounded, poorly-sorted sedimentary material. Sixteen of the 17 spits have a northeasterly to southwesterly orientation implying that winds were from the northwest to northeast, approximately 180° out of phase with modern winds in the eastern Great Basin. Lake Bonneville spit orientation is best explained as the result of persistent northerly winds caused by the high atmospheric pressure cell of the continental ice sheet and passage of low pressure extratropical storms south of the lake. Similar, strong persistent winds are a common feature of modern continental ice sheets and passing low pressure systems. If so, the North American jet stream tracked south of Lake Bonneville as recently as 12,000 ^{14}C yr BP, well past the height of the last glacial maximum.

Keywords: Spits; Lake Bonneville; Pleistocene climate; Jet stream

Introduction

The integration of detailed field studies with numerical simulations has proven a fruitful combination for understanding the ancient climates of Earth. This is particularly true for the last glacial maximum (LGM), where an abundance of marine and terrestrial paleoproxies serve to constrain the climate models. Although numerical models have been effectively used to understand the large-scale features of the climate of the LGM, substantial gaps and disagreements persist (e.g., Bartlein et al., 1998), particularly for continents where irregular topography and imprecise knowledge of ice sheet morphology test the resolution of most climate models (e.g., Manabe and Broccoli, 1985).

Pleistocene Lake Bonneville (Fig. 1) was the largest of several pluvial lakes that formed in the Great Basin of the western United States during the LGM and over the past century have provided a wealth of paleoclimate information about the continental interior of North America. Detailed descriptions of Lake Bonneville features were first given by Gilbert (1890). During the latter half of the 20th century, a detailed hydrograph of the lake was constructed using radiocarbon dates from a variety of materials (e.g., Currey and Oviatt, 1985; Oviatt et al., 1992; Oviatt, 1997) (Table 1). The lake underwent a transgression that produced the Stansbury shoreline 25,000–20,000 ^{14}C yr BP at an elevation of ~1380 m (Oviatt et al., 1990). Lake Bonneville reached its maximum transgressive level of ~1550 m (Bonneville level) at ~15,600–14,500 ^{14}C yr BP (e.g., Oviatt et al., 1992). The fact that the lake level crested after the peak of alpine glaciation in the North America is taken as evidence that the southern branch of the jet stream was south of the Great Basin and moved gradually northward until it was over Lake Bonneville during the Bonneville high stand (Thompson et al., 1993). The transgressive phase of the lake ended with a catastrophic loss of water due to the cresting of a threshold at Red Rock Pass near the northern-eastern end of the lake (Gilbert, 1890). The flood established the uppermost

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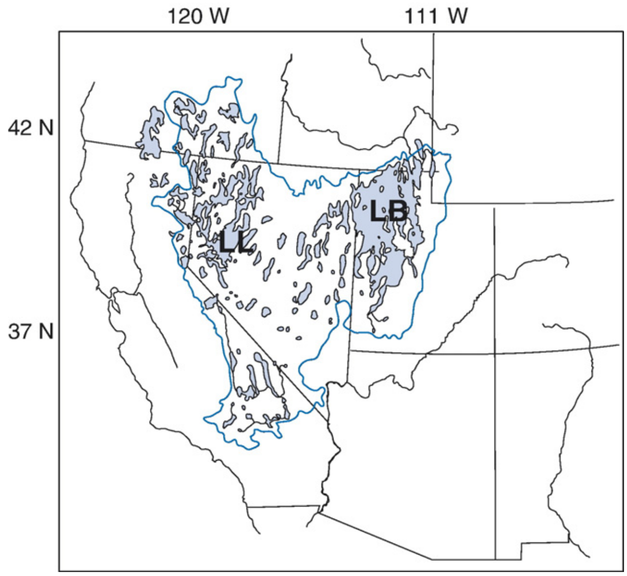

Figure 1. Location map of Great Basin showing location of Pleistocene Lake Bonneville (LB) and Lake Lahonton (LL).

Provo lake level at ~1440 m and ultimately formed a group of shorelines within 15 m elevation of each other (e.g., Burr and Currey, 1988). The Provo group of shorelines appears to have existed for ~2500 years (14,500–12,000 ^{14}C yr BP) (Godsey et al., 2005), although the relative ages of the various Provo shorelines are uncertain. Less prominent shorelines and other features between the Bonneville and Provo levels have long been recognized (the "middle embankments" of Gilbert, 1890) and are believed to be transgressive features that formed between the Stansbury and Bonneville levels from ~20,500 to 17,000 ^{14}C yr BP (Sack, 1999).

Lake Bonneville spit description and geomorphology

Lake Bonneville contains an abundance of landforms that formed as a result of a variety of processes. These include deltas (e.g., Lemons et al., 1996; Milligan and Chan, 1998), baymouth barriers (e.g., Burr and Currey, 1988), and a variety of spits (e.g., Gilbert, 1890). While many of these features have been known for more than a century, studies placing them within the context of the paleoclimate of the Great Basin are relatively few. This paper provides a general field description of spits in the central portion of the Lake Bonneville basin and analyzes their significance within the context of the Pleistocene climate of North America.

Spits are elongate depositional forms that are the result of longshore sediment transport from wave trains approaching a shoreline at an angle <90° (Fig. 2) (Evans, 1942). A variety of spit morphologies, most from marine settings, have been described in the literature (e.g., Horikawa, 1988; Woodruffe, 2003). If other factors such as wind duration and intensity are equal, the amplitude and energy of wave trains in lakes are a function of the maximum fetch (distance over which wave-forming winds blow) of a water body (CERC, 1984). Spit orientation is therefore a general proxy for the direction of maximum wind energy.

Spits are a relatively common feature in Lake Bonneville. Gilbert (1890) discusses spits at some length within the context of other shoreline features such as bay mouth barriers, bars, and hooks. The largest spits described by Gilbert such as the Grantsville spits in the Tooele Valley, Point of the Mountain spit in the southern portion of the Salt Lake Valley, and a large spit near Kelton Butte in the northern portion of the basin are V-shaped features (Gilbert, 1890, p. 57, plate VII) in which sediment transport follows single or bidirectional paths along the two limbs of the "V" that project into lake waters. Some of these relatively large spits have been described in subsequent literature (e.g., Morrison, 1965; Schofield et al., 2004; Gregory et al., 2006). Schofield et al. (2004) demonstrate that sediment-transport direction in the large, V-shaped Fingerpoint and Point of the Mountain spits is not unidirectional in the sense suggested by Gilbert (1890).

The vast majority of Lake Bonneville spits are much smaller than those mentioned above and lack documentation of any sort. As part of a general analysis of the landforms of Lake Bonneville in the late 1990s, a number of spits and other features were

Table 1
Representative age data for prominent levels of Pleistocene, Lake Bonneville

Lake level	Method	Material	Age (^{14}C yr BP)	Calibrated age (cal yr BP)	Reference
Stansbury	Radiometric	Algae rich sediments	20,930±230	n.a.	Oviatt et al. (1990)
	Radiometric	Tufa caprock	20,370±260	n.a.	do.
	Radiometric	Wood	20,390±240	n.a.	do.
Intermediate	Radiometric	Wood	20,500±200	n.a.	Scott, 1988
	Radiometric	Shells	18,860±140	22,460–23,250	Sack (1999)
	Radiometric	Shells	18,700±160	22,270–23,070	do.
	Radiometric	Shells	18,590±140	22,130–22,960	do.
	Radiometric	Shells	17,300±320	20,570–21,560	Sack (1990)
Bonneville	AMS	Charcoal	15,250±160	17,596–18,910	Oviatt, 1991
	Radiometric	Wood	15,100±140	17,455–18,704	Scott, 1988
	Radiometric	Shells	15,080±90	17,484–18,628	Godsey et al., 2005
Provo	Radiometric	Shells	14,420±370	16,301–18,281	do.
	Radiometric	Shells	12,430±50	14,144–15,412	do.

Calibration to calendar years as reported in the references cited.

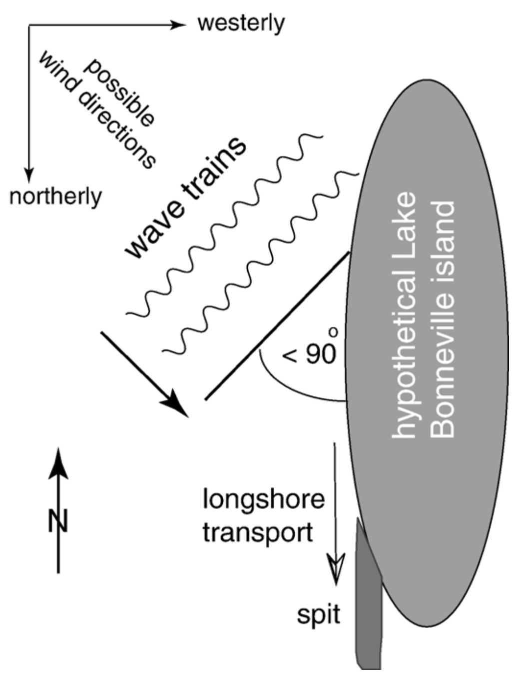

Figure 2. Idealized formation of a spit. Winds from due north to due west cause wave trains to intersect an island or mountain range in Lake Bonneville. Southerly longshore sediment transport occurs where the angle between the wave trains and the shoreline is <90°, leading to the formation of a southerly oriented spit at the south end of the island. Winds that were from due north to due east would also produce a southerly trending spit on the opposite side of the island.

examined. During this work, most of the spits were observed to be oriented in a general southerly direction indicating a north-to-south sediment transport direction. Very large spits (e.g., Draper, Point of the Mountain, Grantsville) in the southeastern portion of the Bonneville basin have a southerly orientation that can be explained as a result of very large fetches to the north. In order to conduct a more systematic analysis of spit geometry, composition, and orientation, the small mountain ranges (Grassy, Lakeside, Silver Island, Newfoundland, and Hogup Mountains and associated islands) in the central part of the Lake Bonneville basin were systematically examined in detail during 2005 and 2006 (Fig. 3). These field localities were chosen because during the highest Lake Bonneville levels significant fetch was present in many directions. Like most mountain ranges in the Basin and Range tectonic province, these small ranges have a north–south orientation. None of the ranges are particularly high and they were mostly inundated by water during the maximum Lake Bonneville trangression.

For each mountain range, all appropriate 7.5′ topographic maps and digital orthophotographs were examined and spit-like features initially identified. These features were then field checked and selected field areas chosen for detailed analysis. The extreme northern portion of the Lakeside Mountains and southern end of the Newfoundland Mountains are military training reservations and thus could not be examined as carefully as the rest of the small mountain ranges. These military areas compose <10% of the total area studied, and photo reconnaissance suggests that they do not contain significant numbers of spits.

In the field, a landform was classified as a spit if: (1) it had the general, elongate topographic shape characteristic of a spit; (2) coarse, well-rounded sediment was observed in the landform; and (3) no rock outcrops were observed on the landform surface. Many landforms that appeared to be spits on the basis of topographic or photo analysis turned out to be abrasion platforms on the basis of bedrock outcrops identified on the surface of these features during field examination. Approximately 10–20% of linear, spit-like features initially identified on topographic maps were actually determined to be spits in the field. Once field examination definitively established the feature to be a spit, it was described and mapped on topographic base maps. The topographic elevation of the spit surface was recorded and correlated with nearby shorelines of known age.

Results

Using the criteria given above, 17 spits were identified in the central areas of Lake Bonneville (Tables 2, 3). The spits tend to be found in clusters in the Hogup and Grassy Mountains. The Newfoundland, Silver Island, and Lakeside Mountains are largely devoid of mappable spits. Five spits are associated with the Stansbury and intermediate (between Bonneville and Provo) shorelines (25,000–17,000 ^{14}C yr BP), seven are associated with the Bonneville shoreline (15,600–14,500 ^{14}yr BP), and five are associated with the Provo shoreline (14,500–12,000 ^{14}C yr BP) (Table 1).

From a geomorphologic point of view, only one spit (Fingerpoint) fits the classification of V-shaped bar given by Gilbert (1890). The Bonneville level of this relatively large

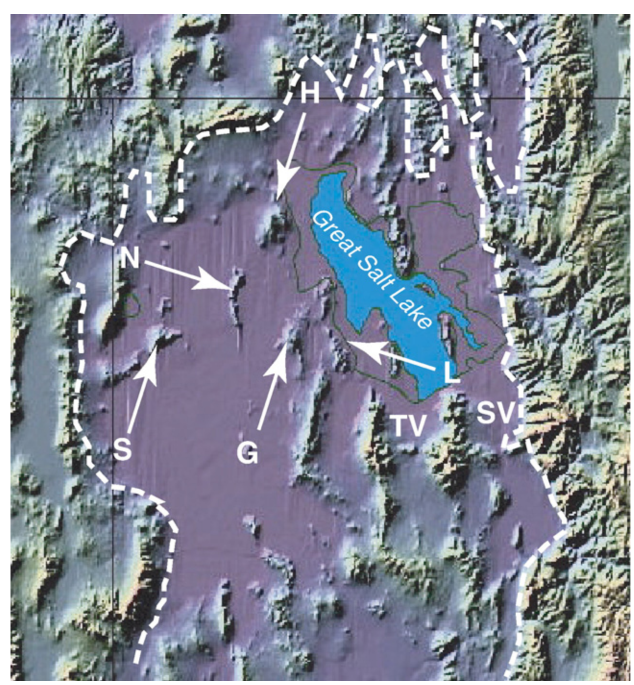

Figure 3. Detailed location map showing the mountain ranges and other localities examined in this study: S = Silver Island Range, N = Newfoundland Range, H = Hogup Mountains, G = Grassy Mountains, L = Lakeside Mountains, TV = Tooele Valley (location of the Grantsville spit), SV = Salt Lake Valley (location of the Draper and Point of the Mountain spits).

Table 2
Summary spit orientation and size discussed in this study

Name	Latitude (N)	Longitude (W)	7.5′ quad	Lake level	Area (km^2)	Orientation	Max. fetch	Adjacent landform
N. Cedar Mts	40°48′	112° 54′	Low	Intermediate	0.04	240°	0°	mountain
Round Mt._1	41° 2′	113° 1′	Round Mountain	Bonneville	0.03	170°	15°	island
Round Mt._2	41° 3′	113° 1′	Round Mountain	Bonneville	0.05	160°	15°	island
Round Mt._3	41°1′	113° 2′	Round Mountain	Provo	0.05	135°	15°	Island
Fingerpoint_1a	41° 26′	113° 6′	Dolphin Island West	Bonneville	0.50	120°	150°	mountain
Fingerpoint_1b	41° 26′	113° 6′	Dolphin Island West	Bonneville	0.50	90°	150°	mountain
Fingerpoint_2	41° 25′	115° 5′	Dolphin Island West	Provo	0.50	120°	150°	mountain
S. Hogup Mts	41°23′	113° 8′	Tangent Peak	Bonneville	0.02	0°	135°	Island
N. Hogup Mts_1	41° 35′	113° 11′	Hogup Bar	Provo	0.02	75°	120°	Island
Hogup Bar	41° 35′	113° 8′	Hogup Bar	Bonneville	0.15	170°	120°	Island
N. Hogup Mts_2	41° 36′	113° 13′	Hogup Bar	Provo	0.05	145°	120°	Island
N. Hogup Mts_3	41° 37′	113° 12′	Hogup Bar	Provo	0.03	190°	120°	Island
Crocodile Mts	41° 38′	113° 7′	Crocodile Mt. NE	Stansbury	0.03	250°	135°	Island
Matlin_1	41° 36′	113° 17′	Matlin	Bonneville	0.15	110°	195°	mountain
Matlin_2	41° 37′	113° 15′	Matlin	Intermediate	0.10	50°	195°	mountain
Ripple Valley_1	40° 46′	113° 1′	Ripple Valley	Intermediate	0.15	70°	210°	island
Ripple Valley_2	40° 49′	113° 1′	Ripple Valley	Intermediate	0.06	140°	210°	Island
Grantsville	40° 39′	112° 28′	Grantsville, South Mountain	Bonneville	0.50	150°	330°	mountain
Draper	40° 32′	111° 59′	Draper	Provo	8.0	190°	340°	mountain
Point of the Mountain	40°27′	111° 54′	Jordan Narrows	Bonneville	0.75	225°	340°	mountain

The first 17 spits represent those studied in central portion of the basin; the Grantsville, Draper and Point of the Mountain spits are included for the sake of comparison.

(0.5 km^2) feature has two demonstrated sediment transport directions (Schofield et al., 2004) (Table 2). While the Provo level at Fingerpoint might also have two slightly different inferred directions, the more narrow, less distinctive field features of this spit led to classifying it as a single feature (Table 2) (Fig. 4a).

The rest of the spits identified in this study are smaller (0.02–0.15 km^2) and have a simple, linear form (e.g., Hogup Bar spit, Fig. 4b) or are composed of short, multiple lobes of sediment (Figs. 4c, d). Length-to-width ratios of the latter are often near unity; in these cases direction of sediment transport was inferred from the relationship of the spit to the adjoining island or mountain range. No hooked or compound spits described from marine settings (e.g., Horikawa, 1988; Woodruffe, 2003) were recognized during the course of this study. Gilbert (1890) documents the composite nature of some large spits however, these spits were not specifically studied in this work.

The internal morphology of spits in this study was impossible to determine due to vegetative cover and lack of post-Lake Bonneville erosion. Examination of surficial exposures revealed spit sedimentary material to be coarse-grained with maximum clast size to be coarse cobble or small boulder in size

Table 3
Summary spits of Bonneville basin discussed in this study

Name	Latitude (N)	Longitude (W)	Elevation (m)	Corrected elevation (m)	Shoreline
N. Cedar Mts	40° 48′	112° 54′	1573	1523	Intermediate
Round Mt._1	41° 2′	113° 1′	1620	1555	Bonneville
Round Mt._2	41° 3′	113° 1′	1610	1555	Bonneville
Round Mt._3	41° 1′	113° 2′	1494	1439	Provo
Fingerpoint_1a, b	41° 26′	113° 6′	1610	1567	Bonneville
Fingerpoint_2	41° 25′	115° 5′	1482	1439	Provo
S. Hogup Mts	41° 23’	113° 8′	1598	1553	Bonneville
N. Hogup Mts_1	41° 35′	113° 11′	1482	1442	Provo
Hogup Bar	41° 35′	113° 8′	1591	1554	Bonneville
N. Hogup Mts_2	41° 36′	113° 13′	1482	1442	Provo
N. Hogup Mts_3	41° 37′	113° 12′	1494	1453	Provo
Crocodile Mts	41° 38′	113° 7′	1421	1381	Stansbury
Matlin_1	41° 36′	113° 17′	1573	1543	Bonneville
Matlin_2	41° 37′	113° 15′	1506	1476	Intermediate
Ripple Valley_1	40° 46′	113° 1′	1527	1472	Intermediate
Ripple Valley_2	40° 49′	113° 1′	1530	1475	Intermediate
Grantsville	40° 39′	112° 28′	1567	1547	Bonneville
Draper	40° 32′	111° 59′	1455	1447	Provo
Point of the Mountain	40° 27′	111° 54′	1567	1552	Bonneville

The first 17 spits represent those studied in central portion of the basin; the Grantsville, Draper and Point of the Mountain spits are included for the sake of comparison. Corrected elevation is from Bills et al. (2002).

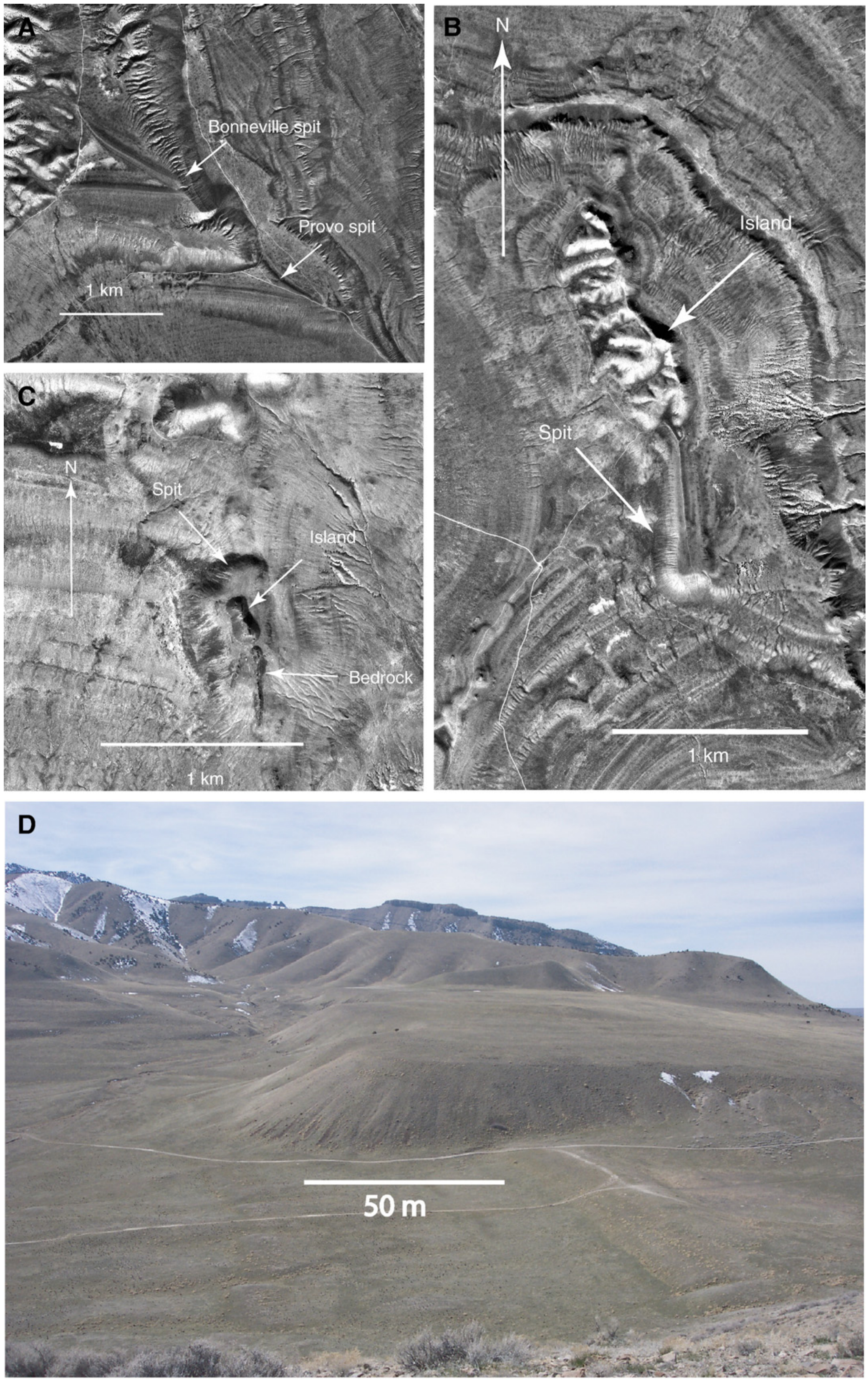

Figure 4. Examples of Lake Bonneville spits. (A) Orthophoto image of the large Fingerpoint Spit, central Hogup Mountains. Spit development occurs at both Bonneville and Provo levels (41°26′, 113°6′; 41°25′, 113°5′). (B) Orthophoto image of a Bonneville level spit in the northern Hogup Mountains, Utah (41°35′, 113°8′). Note the multiple shorelines and beach ridges at elevations below the Bonneville spit. (C) Orthophoto image of a Bonneville level spit in the southern Hogup Mountains (41°23′, 113°8′). Note that this particular spit has a northward orientation. (D) Small spit at the south end of the junction of the southern Grassy Mountains, northern Cedar Mountains looking to the west (40°48′, 112°54′).

(10–20 cm). The material is generally sub-rounded to well-rounded and, in the rare instances where it could be observed, moderately to poorly sorted. The large clast size suggests very strong currents must have been responsible for spit formation. Exact quantification of these currents is the focus of continuing study and numerical modeling of circulation and wave dynamics in Lake Bonneville.

Although all mountain ranges in the interior of Pleistocene Lake Bonneville were technically islands during the highstand of the lake, the spits described in this study can be roughly broken into two categories: those attached to ranges and islands with areas much greater than the area of the spit, and those attached to small islands equal to or smaller than the area of the spit (Table 2). The latter were relatively easy to identify and assign a clear orientation, whereas orientations of the former were often more open to interpretation. Although mountains may have altered the local wind regime in the same way modern mountains do (e.g., Whiteman, 2000), the very strong winds associated with storms that were no doubt responsible for spit formation were probably not greatly affected by the small mountain ranges projecting no more a few hundred meters above the levels of Lake Bonneville.

Spits orientations of this study generally fall within a north-east to southwest hemisphere (45–250°) (Figs. 5a–c). The five spits correlated with the oldest transgressive (Stansbury and intermediate) shorelines have somewhat random orientations,

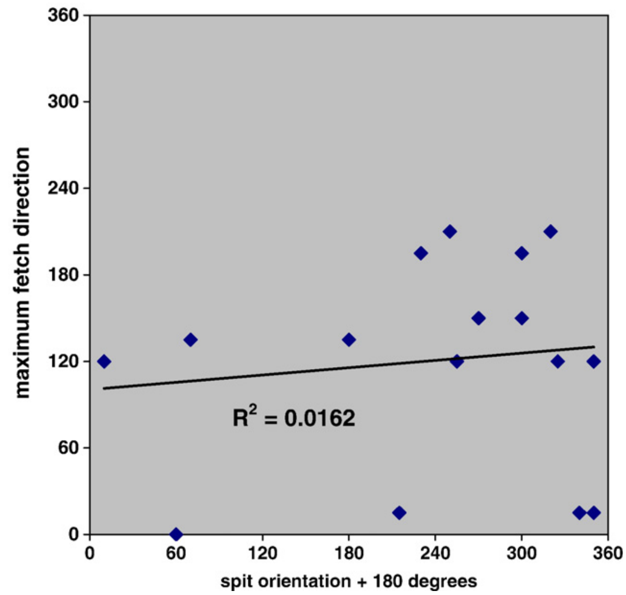

Figure 6. Spit orientation + 180° plotted against direction of maximum fetch for all 17 spits in the central portion of Bonneville basin. The poor correlation between the two indicates that fetch is not an important factor in determining spit orientation.

although none are oriented to the north (Fig. 5a). With the exception of the small (0.02 km^2) compound South Hogup Mountain spit (Table 2, Fig. 4c), the twelve spit orientations

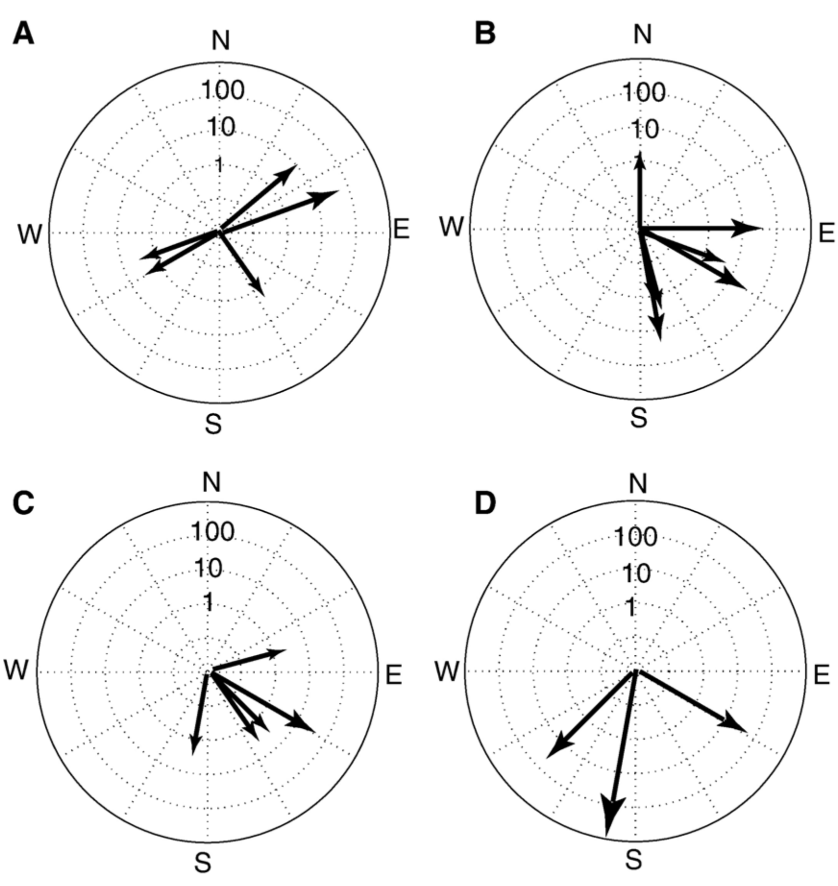

Figure 5. Rose diagram of Lake Bonneville spit orientation. (A) Stansbury and intermediate shoreline spits. (B) Bonneville shoreline spits. (C) Provo shoreline spits. (D) The Point of the Mountain, Draper, and Grantsville spits. Circles represent the size of spits in hectares.

associated with the Bonneville and Provo shorelines have orientations fall in an easterly to southerly quadrant (90–190°).

As mentioned previously, the field localities for this study were chosen in a manner so as to negate the importance of fetch, which in turn is known to control the magnitude of the wave energy that forms spits and other geomorphic features in large lakes. Indeed, there is no significant correspondence between direction of maximum fetch and spit orientation (Fig.

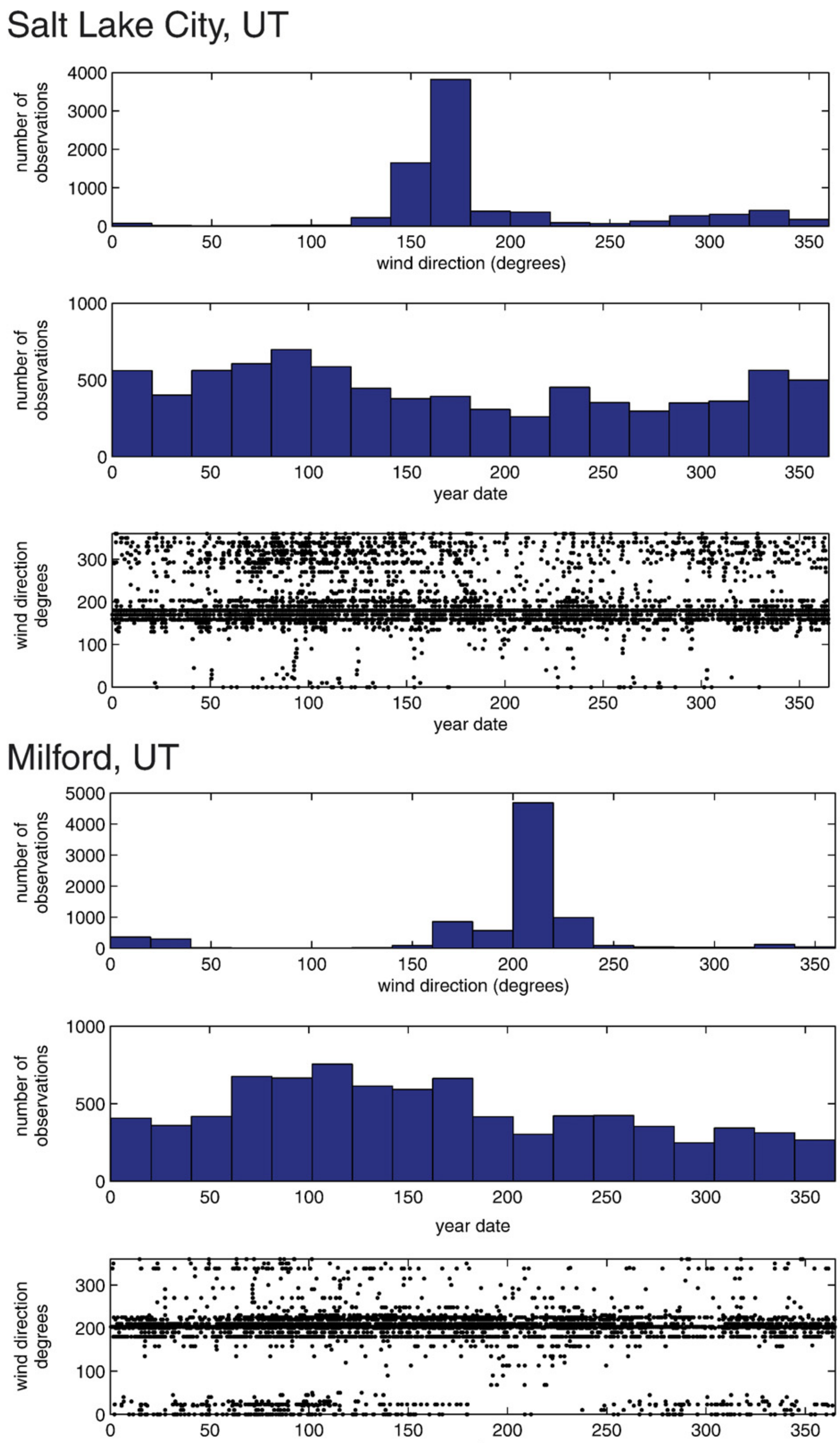

Figure 7. Summary of strong modern winds at Salt Lake International Airport and Milford, Utah. Data are winds >10 m/s for a period in which the 12-h average wind was >5 m/s. The period analyzed was 1946–1993.

6) for the identified spits in this study in the central portion of the basin.

It is interesting to further note that three very large spits (Point of the Mountain, Draper, and Grantsville) in the southern portion of Lake Bonneville are also oriented in a southern direction (Table 2; Fig. 5d). While these spits can be explained as the result of very large fetch directions to the north, similar large spits in the northern portion of Lake Bonneville (e.g., the Fingerpoint spits), which might indicate strong fetch controlled southerly winds, have not been documented.

Discussion

Most wave energy in water bodies at middle latitudes is derived from extratropical cyclones, namely low-pressure weather systems steered by the jet stream that produce significant winds and precipitation (e.g., Whiteman, 2000). In the northern hemisphere, the passage of these low-pressure systems is typically marked by warm southerly winds that shift around to colder westerly or northerly winds that bring the bulk of the precipitation in the storm. While this general picture of extratropical cyclogenesis has been known for decades, it has also long been recognized that local or regional topographic features can exert a strong influence on the magnitude and direction of the surface winds that would form waves that do the most geomorphic work on lake shoreline features.

In his analysis of modern winds in the central Great Basin, Wells (1983) showed that the strongest winds associated with these low-pressure systems tends to be from the west or southwest. More systematic analysis of strong winds in the modern Great Basin and surrounding area has recently been undertaken by the author. Hourly records of wind magnitude >10 m/s for periods in which the 12-h moving average wind speed was >5 m/s were recorded for the period of 1946–1993 (Fig. 7). The results for the Salt Lake City International airport (located on the eastern side of the Bonneville basin) and Milford, Utah (located on the southern edge of the Bonneville basin) clearly demonstrate that the strongest modern winds come from the southeast to southwest. Similar analyses of long-term wind records from the central Great Basin by the author corroborate the conclusions of Wells (1983) that the strongest winds are westerlies.

A comprehensive theoretical and observational study of cold fronts and frontogenesis in the Great Basin by meteorology researchers at the University of Utah offers an explanation for these observations (Shafer and Steenburgh, in press). Extra-tropical cyclones entering the Great Basin from the west are often enhanced by southerly flow around the southern end of the Sierra Nevada mountains. The result is convergent circulation that produces very strong southerly winds that tend to be channeled northward along the Wasatch Front as the cold front traverses the Great Basin. Westerly and northerly winds in the eastern Great Basin are relatively weak.

The strongest modern winds in the eastern Great Basin are thus from the south-southeast to southwest. These winds are the result of the geographic position of major mountain ranges (the Sierra Nevada and Rocky Mountains) that alter surface winds associated with low-pressure systems entering the Great Basin and are not related to the modern regional climate regime. The strongest winds of the modern Bonneville basin are 90–180° out of phase with the Pleistocene wind direction suggested by the spit analysis of this study.

An alternative to formation of the spits by extratropical cyclonic winds can be found by considering how the continental ice sheets of Pleistocene North America may have affected surface winds in the eastern Great Basin. Virtually all computer simulations of climate during the LGM indicate that the continental ice sheet produced a persistent zone of high pressure in much the same fashion that high pressure is observed over the modern Greenland and Antarctic ice sheets (e.g., Kutzbach and Guetter, 1986, Thompson et al., 1993; Bush and Philander, 1999). The continental ice sheet is also believed to have split the polar jet stream into a northern component and a southern component that steered extratropical cyclones across the mid-latitudes of the continent (e.g., Bush and Philander, 1999). These mid-latitude storms and associated precipitation are considered the most likely cause of the enhanced precipitation that lead to the formation of pluvial lakes such as Lake Bonneville in the Great Basin.

The wind field between a persistent high pressure system over the continental ice cap and extratropical cyclones steered by the jet stream may explain the unidirectional nature of the Lake Bonneville spits. If low-pressure extratropical cyclones and their associated storms were routinely passing south of Lake Bonneville, the strong north-to-south pressure gradient might have produced very strong, unidirectional northerly or northwesterly winds capable of overwhelming the southerly

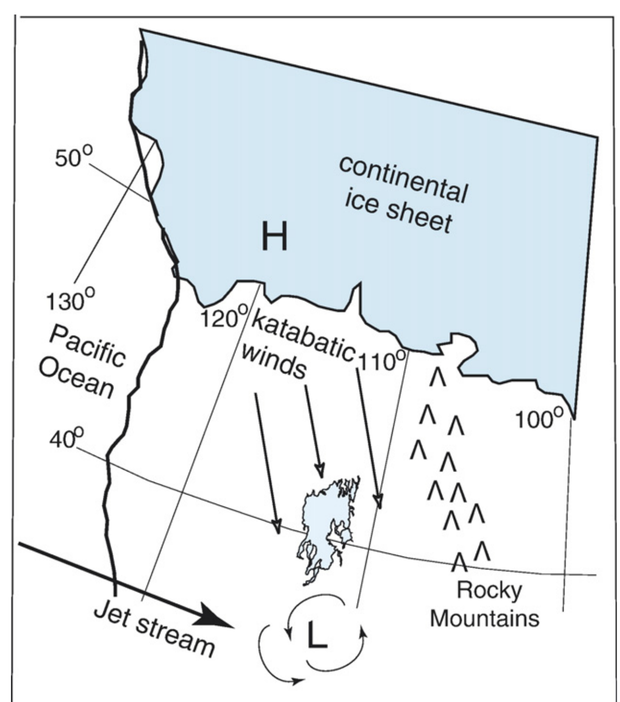

Figure 8. Diagram of Pleistocene North America, showing the location of the continental ice sheet, Lake Bonneville, and wind circulation as a result of transitory low-pressure systems south of the lake.

winds that today are characteristic of the eastern Great Basin. These in turn would have caused north-to-south wave trains and sediment transport observed in the Lake Bonneville spits (Figs. 2, 5).

Precise geographic analogs for this scenario of Pleistocene North America are not readily available in the modern world. The modern Antarctic and Greenland ice sheets are surrounded by oceans unlike the North American Pleistocene ice sheet, which had a large landmass to the south. Even so, detailed meteorological and climatological studies of modern polar regions shed light on what might have led to formation of the Lake Bonneville spits.

The persistent high pressure atmospheric cell over continental ice sheets leads to katabatic winds: persistent strong winds that move downslope off of the high pressure over the ice sheet perpendicular to the land-ice margin. Over the interior of the ice sheet of Greenland and Antarctica, katabatic winds are remarkably persistent, whereas farther out in the ocean the wind fields tend to be more variable and prone to the influence of offshore weather dynamics (Rasmussen et al., 2003). Topography can play a significant role in channeling katabatic winds (Parish, 1982). For instance, the Transantarctic Mountains result in very strong winds over the adjacent Ross Ice Shelf of Antarctica (O'Conner et al., 1994; Parish and Bromwich, 1998).

The interaction of katabatic winds and the storms that develop offshore of continental ice sheets has been studied from both an observational and modeling perspective, although logistical difficulties make detailed studies more difficult than those in mid-latitudes. In general it appears that extratropical cyclones have little effect on the katabatic winds directly over the ice sheet. As would be expected in the southern hemisphere (where storms associated with low pressure cell circulate in a clockwise direction), the katabatic and synopitic winds associated with the storms reinforce each other on the western side of the low pressure and tend to counteract each other on the eastern side of the low pressure (Parish and Bromwich, 1998; Parish and Cassano, 2003).

A similar scenario of ice sheet high pressure, extratropical storms, and mountains may have been a factor in the wind regime of North America during the Pleistocene. In this case, the north-northwest to south-southeast trending axis of the Rocky Mountains may have steered katabatic winds from the western portion of the ice sheet in southerly and southeasterly directions in a similar fashion to the modern Transantarctic Mountains (Fig. 8) (O'Conner et al., 1994). The passage of storms to the south of Lake Bonneville would have reinforced the katabatic winds on the western side of the storm while weakening them on the eastern side. In either case, the winds would have been from the north and would have caused the predominant spit direction to be to the south or southeast (Fig. 8).

Recognition that the Late Pleistocene jet stream was steering most storms south of Lake Bonneville places specific constraints on numerical climate models of the LGM. Of particular importance is the possibility that the jet stream maintained this position as late as the Provo level of the lake (14,500–12,000 ^{14}C yr BP) (Fig. 5c), well past the LGM peak. This result appears to be somewhat at odds with GCM models, which place the jet stream almost directly over the Great Basin during this time period (e.g., Thompson et al., 1993), although it does appear to correspond to detailed paleolake studies to the south in the Mojave desert (e.g., Enzel et al., 2003).

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References

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb III, T., Whitl, C., 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17, 549–585.

Bills, B.G., Wambeam, T.J., Currey, D.R., 2002. Geodynamics of Lake Bonneville. In: Gwynn, J.W. (Ed.), Great Salt Lake: An Overview of Change. Utah Geological Survey Special Publication, pp. 8–32.

Burr, T.N., Currey, T.N., 1988. The Stockton bar. Utah Geological Survey Miscellaneous Publication 88-1, 66–73.

Bush, A.B.G., Philander, S.G.H., 1999. The climate of the last glacial maximum: results from a coupled-atmosphere general circulation model. Journal of Geophysical Research 104, 24,509–24,5245.

Currey, D.R., Oviatt, C.G., 1985. Durations, average rates, and probable causes of Lake Bonneville expansions, stillstands, and contractions during the last deep-lake cycle, 32,000 to 10,000 years ago. Geological Journal of Korea 10, 1085–1099.

CERC, 1984, Shore Protection Manual. Coastal Engineering Research Center, Waterway Experiment Station, US Army Corps of Engineers.

Enzel, Y., Wells, S.G., Lancaster, N., 2003. Late Pleistocene lakes along the Mojave River, southeast California. In: Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts. Geological Society of America Special Paper, vol. 368, pp. 61–77.

Evans, O.F., 1942. The origin of spits, bars, and related structures. Journal of Geology 50, 846–965.

Gilbert, G.K., 1890. Lake Bonneville. U.S. Geological Survey Monograph, vol. 1. 438 pp.

Godsey, H.S., Currey, D.R., Chan, M.A., 2005. New evidence for an extended occupation of the Provo shoreline and implications for regional climate change, Pleistocene Lake Bonneville, Utah, USA. Quaternary Research 63, 212–223.

Gregory, M., Chan, M., Currey, D., Schofield, I., 2006. Transgressive landforms and lithofacies models of Pleistocene Lake Bonneville, Utah in Geology of northwest Utah. In: Harty, K.M., Tabet, D.E. (Eds.), Utah Geological Association Publication, p. 34.

Horikawa, K., 1988. Nearshore dynamics and coastal processes: theory, measurement, and predictive models. University of Tokyo Press, Tokyo (522 pp.).

Kutzbach, J.E., Guetter, P.J., 1986. The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. Journal of Atmospheric Sciences 43, 1726–1759.

Lemons, D.R., Milligan, M.R., Chan, M.A., 1996. Paleoclimatic implications of late Pleistocene sediment yield rates for the Bonneville Basin, northern, Utah. Paleogeography, Paleoclimatology, and Paleoecology 123, 147–159.

Manabe, S., Broccoli, A.J., 1985. The influence of continental ice sheets on the climate of an ice age. Journal of Geophysical Research 90, 2167–2190.

Milligan, M.R., Chan, M.A., 1998. Coarse-grained Gilbert deltas: facies, sequence stratigraphy, and relationships to Pleistocene climate at the eastern margin of Lake Bonneville, northern Utah. Relative Role of Eustacy, Climate, and Tectonism in Continental Rocks. SEPM Special Publication, vol. 58, pp. 177–189.

Morrison, R.B., 1965. Lake Bonneville Quaternary stratigraphy of eastern Jordan Valley, south of Salt Lake City, Utah, US. Geological Survey Professional Paper 477 (80 pp.).

O'Conner, Bromwich, D.H., Carrasco, J.F., 1994. Cyclonically forced barrier winds along the Transantarctic Mountains near Ross Island. Monthly Weather Review 122, 137–150.

Oviatt, C.G., 1991. Quaternary geology of the Black Rock Desert, Millard County, Utah. Utah Geological and Mineralogical Survey Special 73.

Oviatt, C.G., 1997. Lake Bonneville fluctuations and global climate change. Geology 25, 155–158.

Oviatt, C.G., Currey, D.R., Miller, D.M., 1990. Age and paleoclimatic significance of the Stansbury shoreline of Lake Bonneville, northeastern Great Basin. Quaternary Research 33, 291–305.

Oviatt, C.G., Currey, D.R., Sack, D., 1992. Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA. Paleogeography, Paleoclimatology, and Paleoecology 99, 225–241.

Parish, T.R., 1982. Surface flow over East Antarctica. Monthly Weather Review 110, 84–90.

Parish, T.R., Bromwich, D.H., 1998. A case study of Antarctic katabatic winds interaction with large-scale forcing. Monthly Weather Review 126, 199–209.

Parish, T.R., Cassano, J.J., 2003. The role of katabatic winds in the Antarctic katabatic wind on the Antartic surface wind regime. Monthly Weather Review 131, 317–333.

Rasmussen, E.A., Ninomiya, K., Carleton, A.M., 2003. Climatology. In: Rasmussen, E.A., Turner, J. (Eds.), Polar Lows: Mesoscale Weather Systems in the Polar Regions. Cambridge University Press, pp. 52–149.

Sack, D., 1990. Quaternary geology of the Tule Valley, west-central Utah. Utah Geological Survey 124.

Sack, D., 1999. The composite nature of the Provo level of Lake Bonneville, Great Basin, western North America. Quaternary Research 52, 316–327.

Schofield, I., Jewell, P.W., Chan, M.A., Currey, D., Gregory, M., 2004. Longshore transport, spit formation, and surface wave modeling, Pleistocene Lake Bonneville, Utah. Earth Surface Processes and Landforms 29, 1675–1690.

Shafer, J.C., Steenbrugh, W.J., in press, Climatology of strong intermountain cold fronts: Monthly Weather Review.

Scott, W.E., 1988. Transgressive and high-shore deposits of the Bonneville cycle near North Salt Lake, Utah. Utah Geological and Mineralogical Survey Miscellaneous Publication 88-1, 38–42.

Thompson, R.S., Whitlock, C., Bartlein, P.J., Harrison, S.P., Spaulding, W.G., 1993. Climatic changes in the Western United States since 18,000 yr B.P. In: Wright, H.E., Kutzbach, J.E., Webb, T., Ruddiman, W.F., Street-Perrott, F.A., Bartlein, P.J. (Eds.), Global Climates Since the last Glacial Maximum. University of Minnesota Press, Minneapolis, pp. 468–511.

Wells, G.L., 1983. Late glacial circulation over central North America revealed by aeolian features. Variations in the Global Water Budget: Street Perrott et al. D. Reidel Publishing Company, pp. 317–330.

Whiteman, C.D., 2000. Mountain Meteorology: Fundamentals and Applications. Oxford, 355 pp.

Woodruffe, C.D., 2003. Coasts: form, Process and Evolution. Cambridge, 623 pp.