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SHORELINE DEVELOPMENT, LONGSHORE TRANSPORT AND SURFACE WAVE DYNAMICS, PLEISTOCENE LAKE BONNEVILLE, UTAH

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ABSTRACT

Point of the Mountain spit and Fingerpoint spit are two of the largest geomorphic features of Pleistocene Lake Bonneville of the western Great Basin, USA. The spits and their associated shorelines show distinctly different geomorphic expression and genesis; this is a function of their positions within the lake and the dynamics of the waves and storms that formed them. Mapping of geomorphic features, geometry of erosional features, and detailed lithologic analysis of shoreline deposits are used to determine dominant modes of sediment erosion and deposition. The Point of the Mountain spit, located in the eastern portion of the basin, was formed as a result of highly fractured bedrock in a salient of the Wasatch Front being exposed to wave trains that approached from the north-northwest causing north-to-south longshore sediment transport. Shoreline development and sediment transport on the southern portion of the spit were minimal. The Fingerpoint spit, located on an island in the northwest portion of the basin, was formed by bidirectional longshore sediment transport as the result of waves that approached from both the north-northeast and the south-southwest. Spit development is a function of surface wave energy and direction which in turn is the integrated result of wind direction, wind intensity, and fetch. Wave transport direction determined from field measurements at Point of the Mountain spit corresponds very well to the direction of maximum fetch (*c*. 200 km). For the Fingerpoint spit, the hypothesized wave transport direction from the south corresponds with the direction of maximum fetch (*c*. 350 km). However, wave energy transport from the north had limited fetch (*c*. 100 km), implying that wind intensity from the north was relatively large. The geometry of the two large Bonneville spits suggests the predominant wind direction from storms during the Pleistocene was from the north and points the way for future studies that can aid in further understanding the nature of Pleistocene wind fields in the Great Basin.

KEY WORDS: spits; longshore transport; hydrodynamics

INTRODUCTION

Pleistocene Lake Bonneville in the eastern Great Basin of the western United States is one of the world's best-exposed and most well-studied palaeolimnologic archives. The lake was the largest of several large late Pleistocene lakes in North America (Figure 1). Although considerable research addresses the geochronology and geomorphology of Lake Bonneville, little detailed work has been conducted on the physical and palaeoclimatic controls of the lake's prominent shoreline features. The lake is an excellent natural laboratory for this type of investigation because of outstanding exposure and minimal post-Bonneville erosion of geomorphic features. In this paper we report on field investigations of two large spits in Lake Bonneville and on geometric relationships between the observed transport directions in the spits and the waves that formed them. In addition, we discuss how these features are related to the storm dynamics that formed both the waves and spits.

The first important work on the Bonneville basin was G. K. Gilbert's classic studies of the geomorphology and landforms of Lake Bonneville in the late 1800s (Gilbert, 1882, 1890). Throughout the following century, new geochronologic and stratigraphic tools established a robust hydrograph of Lake Bonneville. Four prominent

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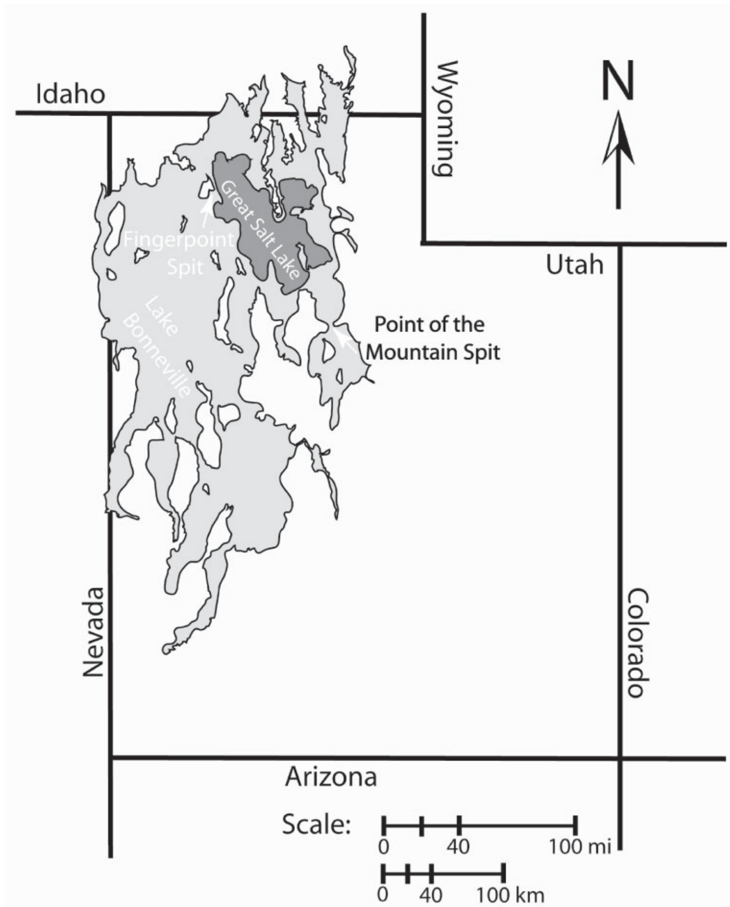

Figure 1. Location of Lake Bonneville, the Point of the Mountain and Fingerpoint spits

shorelines (Stansbury, Bonneville, Provo and Gilbert) developed between 30 000 and 12 000 ^{14}C years before the present (Figure 2). A relationship between climate and lake elevation has long been postulated (e.g. Anteves, 1938). More recent interpretations between lake level and climate are described in Oviatt *et al*. (1990, 1992, 1994) and Oviatt (1997). Chan and Milligan (1995), Lemons *et al*. (1996) and Lemons and Chan (1999) investigated Lake Bonneville deltas and other sedimentological features and their possible relationship to palaeoclimate of the Bonneville basin.

Lake Bonneville formed when estimated precipitation in the Great Basin was ten times that of modern values (Mifflin and Wheat, 1979; Morrison, 1991; Benson *et al*., 1990). Global climatic models suggest that the Laurentide ice sheet split the jet stream and thus caused the drastically different precipitation over North America and the Great Basin during the last glacial maximum (Barnosky *et al*., 1987; Thompson *et al*., 1993; Kutzbach *et al*., 1993). During the time of Bonneville shoreline development (representing the lake's maximum transgression) (Figure 2), the southern portion of the jet stream is believed to have traversed the southern edge of the ice sheet although its exact position is not certain. Inasmuch as the jet stream is considered to be the primary steering mechanism for extratropical cyclones and accompanying storms, the position and orientation of the jet stream may have influenced the behaviour of storms and hence the development of Lake Bonneville shoreline features.

Understanding the nature of storms that may have existed in the eastern Great Basin during the late Pleistocene requires reliable palaeowind proxies. Considerable effort has been aimed at developing proxies such as sand dunes (Wells, 1983) and fallen trees (Allen, 1998). Lacustrine geomorphic and sedimentologic features are also potential palaeowind proxies. For instance, the orientation of lacustrine and marine spits is a direct function of

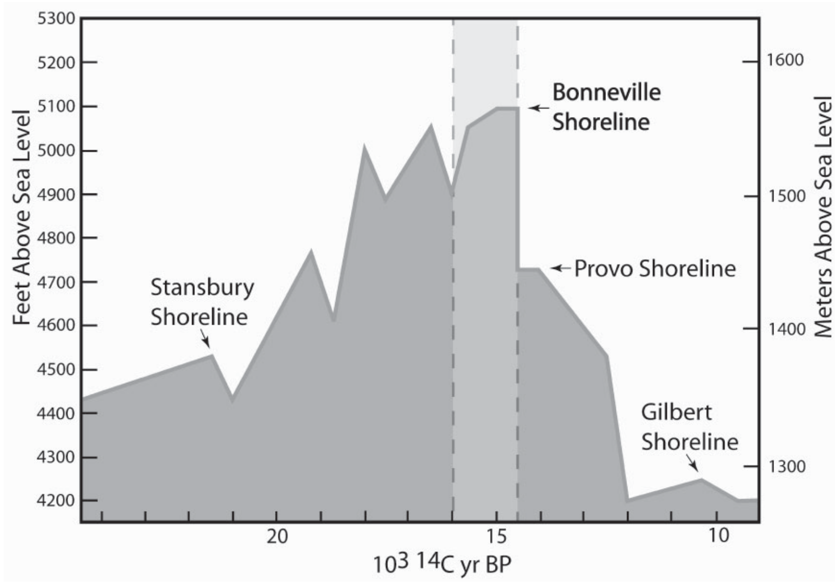

Figure 2. Hydrograph of Lake Bonneville showing location of prominent shorelines. The time frame of the present investigation is shown

surface wave energy and direction (Swift, 1976) which in turn is a function of wind direction and magnitude (CERC, 1984). This study represents a first attempt to use detailed analysis of spits in a large, well-studied palaeolake to understand generalized palaeowind direction and storm dynamics.

METHODOLOGY

Lake Bonneville's large fetch (distance over which wave-forming winds blow) in conjunction with the widely varying Basin-and-Range topography produced a wealth of wave-dominated erosional and depositional geomorphic features. Prominent sedimentary and geomorphic features in Lake Bonneville include shorelines, deltas, wave-cut cliffs, bayhead barriers and spits.

Spits are appropriate geomorphic features for this study because their formation can be directly related to the hydrodynamic forces that form them. The term 'spit' has been formally defined as 'a ridge or embankment of sediment attached at one end and terminating in open water at the other' (Evans, 1942). In the context of this study, the term spit is used to include not only ridges of sediment but also the underlying bedrock and any erosional and depositional features associated with the bedrock. In reality, the two Lake Bonneville spits described here, Point of the Mountain spit and Fingerpoint spit, are complex features that were formed not only during the late Pleistocene lake cycle but also during the older lake cycles that are known to have existed in this portion of the Great Basin.

Field research was conducted over a 12-month period beginning in the summer of 2000. Laboratory and geometric analyses were conducted in concert with the field work. Aerial photographs from the National Aerial Photography Program (NAPP) 1997 series at a scale of 1:40 000 were used to initially examine the spit morphologies. The lithology of clasts within the shoreline deposits was traced to geologically mapped units. United States Geological Survey (USGS) 7·5-minute quadrangle maps were used for general field orientation and for making geomorphic interpretations based on topography.

Gravel samples were collected in order to characterize the sedimentary texture and lithology of the shoreline deposits. Samples were collected wherever Bonneville shoreline deposits where not obscured by post-Bonneville alluvium. Vertical outcrop exposures of shoreline gravels were limited. Shoreline benches contained numerous angular to subangular clasts which were assumed to be Holocene alluvium from mountain scarps above the Bonneville shoreline. Angular clasts having at least one polished face were collected for this study on the assumption that the polished surface was the result of shoreline transport processes and subsequent post-depositional

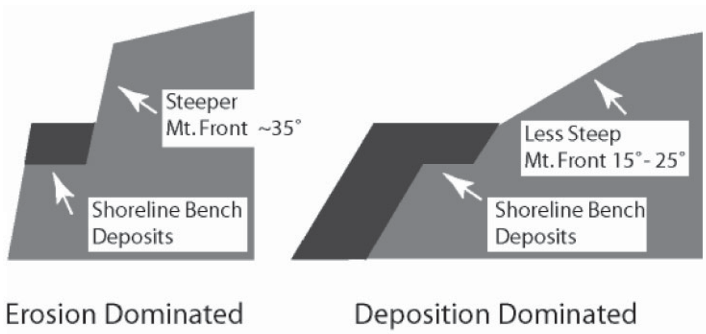

Figure 3. Idealized cross-sections of erosion- and deposition-dominated Lake Bonneville shorelines. Thickness of shoreline deposits are exaggerated in order to more clearly show their horizontal distribution

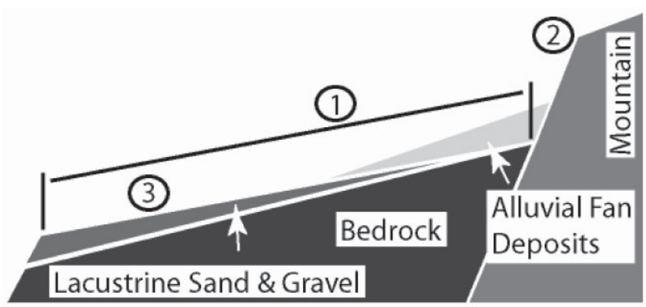

Figure 4. Idealized shoreline profile of a Bonneville shoreline bench. (1) Total measured width of the bench, (2) mountain scarp, and (3) lacustrine sands and gravels

fracturing. At each sample location a minimum of 100 clasts was collected over a 1 m by 1 m area. Longest axis diameter of the clasts was >1 cm.

Bedrock lithologies adjacent to Bonneville shorelines were matched to beach gravel lithologies in order to determine directions of longshore transport. Bedrock composition is generally uniform for hundreds of metres along the shoreline, so particular attention was given to shoreline beach gravel compositions on either side of bedrock contacts.

Geomorphic features associated with the spits were examined in detail. Small spits were mapped as directional indicators of longshore transport with the termini of spits indicating predominant longshore transport direction. The shoreline widths were measured from topographic maps, aerial photographs and field observations.

The shape and width of the shorelines were examined in detail and placed within the context of erosional and depositional features of the spits (Figure 3). Very steep mountain fronts associated with the shorelines indicate erosion while more gentle mountain front angles are more characteristic of a depositional setting. Similar observations have been noted in the marine realm (Pethick, 1984). In Lake Bonneville, where sediment erosion, transport and deposition take place over relatively short (<10 km) distances, narrow bench width was considered to be an erosional environment while a relatively wide bench represents deposition (Figure 3). These relative widths are taken to represent localized redistribution of sediment. Absolute values of bench width as proxies for erosion and deposition have not been established in this study.

Mountain slope and shoreline bench width data were collected with a laser range finder and a surveyor's rod with prism. The mountain front slope above the shoreline bench was determined with a minimum of three points (Figure 4). These average slopes were then compared to mountain scarp slopes measured from USGS 7.5-minute topographic maps.

Average shoreline bench slope and width determination was more complicated. Holocene alluvial fan deposits commonly cover the original shoreline benches near the edge of the mountain front. As a result, recorded distances were slightly smaller than actual width of the shoreline. True shoreline bench widths were computed by measuring the slope angle of the shoreline bench, the slope angle of the mountain front, and the measurements from the edge of the bench to the base of the mountain scarps to extrapolate beneath post-Bonneville alluvium (Figure 4).

Widths of shoreline benches were also determined from stereoscopic analysis of aerial photographs. The edges of the shoreline benches were manifested as erosional channels at the break in slope by shadows on the photos. Shoreline bench contacts with the mountain front were defined as the point where alluvial fan deposits met the mountain front. Alluvial fan deposits in the aerial photographs were distinguished by changes observed in the slope and vegetation between the mountain fronts and the shoreline benches.

The field observations, aerial photographs, and map analysis were combined to classify the shoreline benches as being dominated by erosional, depositional or transport processes. Erosion-dominated areas were defined as those exhibiting steep mountain scarp slopes above the shorelines and lacking a shoreline bench of significant width. Deposition-dominated areas were defined as those exhibiting a shoreline bench with significant width and lacking slopes significantly modified by Lake Bonneville (Figure 3). Some sections of shoreline exhibit a combination of erosional and depositional characteristics and were thus classified as transport-dominated.

Shoreline analysis

Surface wave mechanics at Point of the Mountain and Fingerpoint spits were analysed with two data sets: predominant direction of longshore transport determined through the analysis of shoreline gravel clasts, and the geometries of the shorelines. Longshore current direction and hence sediment transport is a function of cross-shore shear stress (S_{xy}) produced by energy (E) and incidence angles (α) with the shoreline (Komar, 1998):

$$S_{xy} = E \times n \times \cos \alpha \times \sin \alpha \tag{1}$$

Energy (E) is a function of wave amplitude and other wave parameters and n is an empirically based parameter. Neither parameter is evaluated in this study. Instead, Equation 1 is used to establish the relative direction of shear stress (and hence sediment transport) as a function of wave incidence angles (α). Wave incidence angles of 0° or 90° produce no cross-shore shear or longshore current whereas wave incidence angles of 45° maximize shear.

POINT OF THE MOUNTAIN SPIT

Point of the Mountain spit is located at the intersection of the Wasatch Range and Traverse Mountains on the eastern side of the Salt Lake Valley southeast of Salt Lake City (Figures 1, 5). Emphasis was placed on the Bonneville shorelines (i.e. those formed at the maximum lake level) north of the spit on the southwestern end of the Traverse Mountains (Figure 6). The southern side of Point of the Mountain displays little geomorphic expression or shoreline development. This is assumed to be due to limited wave energies in the small sub-basin immediately to the south.

Geologic constraints

The Wasatch Range marks the easternmost extent of the Basin-and-Range geologic province, a series of north–south trending, normal fault-bounded half grabens. Although faults along the Wasatch Mountains have been seismically active since the Pleistocene, field examination in this study suggests that Bonneville deposits and shoreline features in the Point of the Mountain area have not been significantly influenced by seismic activity.

Four bedrock units were identified in outcrop and from samples along the Bonneville shoreline bench north of Point of the Mountain spit (Personius and Scott, 1992; Davis, 1983). Bedrock north of Bear Canyon is low- to high-grade Archean to Proterozoic metamorphic rock of the Big Cottonwood Formation (Figure 5). Primary lithologies are quartzites with lesser amounts of interbedded shales and siltstones. Only a small fraction of shales and siltstones were identified within the shoreline samples. Between Bear Canyon and Corner Canyon bedrock consists of Oligocene porphyritic quartz monzonite of the Little Cottonwood stock. Southeast of the mouth of Corner Canyon bedrock consists of Neogene volcanic flows, tuffs and breccias of andesite, latite and quartz latite. Although these rocks are exposed well above the highest elevation of the Bonneville shoreline, they have

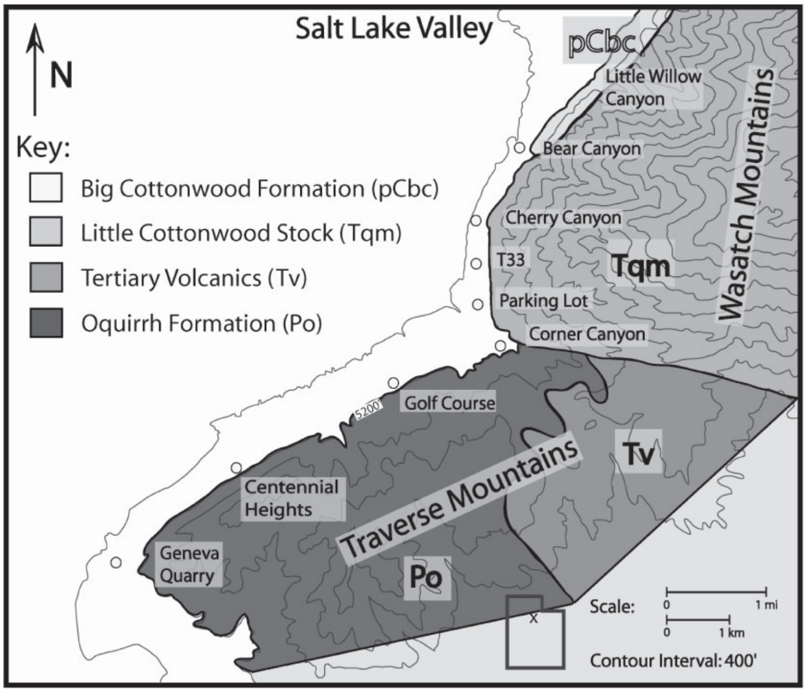

Figure 5. Bedrock geology map of Point of the Mountain spit and the area immediately to the north (adapted from Davis, 1983)

been transported to the Bonneville shoreline by the Corner Canyon drainage, the largest drainage in the area. The volcanic rocks are important for determination of longshore transport direction because they comprise a significant portion of the Traverse Mountains bedrock. The bedrock along the Traverse Mountains between the southern side of Corner Canyon and Point of the Mountain spit is Pennsylvanian Oquirrh Formation consisting of limey or indurated sandstone, and cherty limestone. This formation is also primarily manifested in Bonneville shoreline deposits as quartzite. While it was difficult to distinguish between individual quartzite samples from the Big Cottonwood and indurated sandstone of the Oquirrh Formations, the fact that the formations were on opposite ends of the study area (Figure 5) and that the percentage of material from these two formations changes very rapidly away from their sources (Figure 6) allowed them to be distinguished in the field.

The surface of the Bonneville shoreline bench is composed of Holocene alluvium as well as late Pleistocene beach gravel and sand. Alluvial channels have also locally eroded through the shoreline bench to form small gullies where a few outcrops of bedrock are exposed.

Big Cottonwood Formation clasts steadily decrease from *c*. 80 per cent at Bear Canyon south to *c*. 50 per cent at Corner Canyon (Figure 7). The presence of Big Cottonwood Formation clasts south of their southernmost bedrock exposure indicates some component of longshore transport from north to south. However, there were no suitable collection sites north of Bear Canyon and it is not known whether there was northward transport or whether one primary direction of transport was greater than another. The Big Cottonwood Formation quartzite is not recognized in shoreline deposits south of Corner Canyon although this lithology is difficult to distinguish from the Oquirrh Formation indurated sandstones. There may be some overlap of Big Cottonwood Formation and Oquirrh Formation clasts near Corner Canyon. This overlap is assumed to be minimal, however, because the shales and siltstones of the Big Cottonwood Formation are not present south of Corner Canyon.

Clasts of Little Cottonwood quartz monzonite increase from *c*. 20 per cent at Bear Canyon south to >40 per cent at Corner Canyon indicating north-to-south longshore transport (Figure 7). South of Corner Canyon gravel-sized clasts of Little Cottonwood stock quartz monzonite significantly decrease and then cease to exist south of the Golf Course site. The sand-sized fraction of the deposits along the Traverse Mountain section of the Bonneville shoreline contains minor amounts of Little Cottonwood stock material. The disappearance of clasts

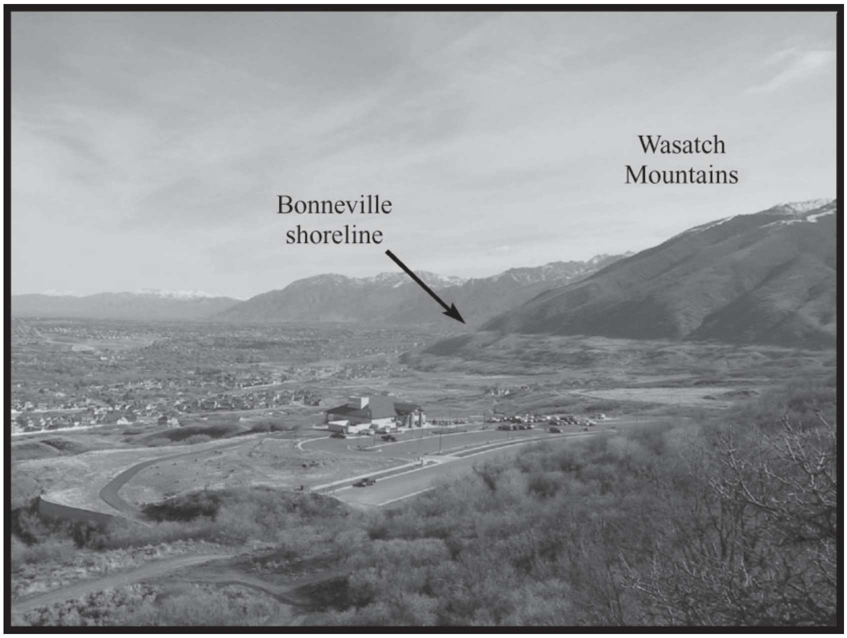

Figure 6. Overview of the Bonneville shoreline bench along the Traverse Mountains viewed to the northeast. The area shown is north of Corner Canyon

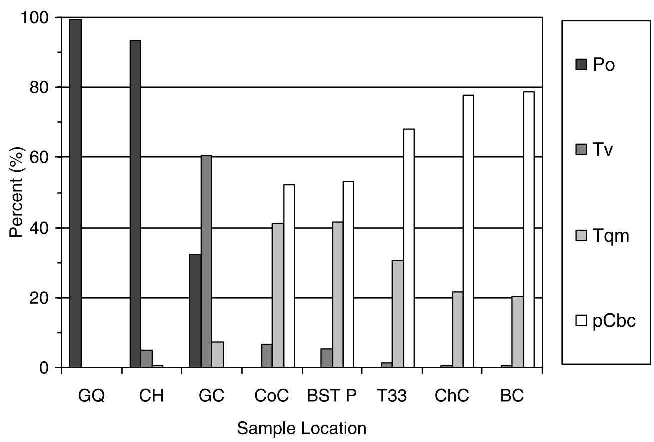

Figure 7. Lithologic trends of Bonneville shoreline beach gravels north of Point of the Mountain spit. Sample locations from south to north are: GQ, Geneva Quarry; CH, Centennial Heights; GC, Golf Course; CoC, Corner Canyon; BST P, Bonneville Shoreline Trail Parking Lot; T33, Township 33 corner; ChC, Cherry Canyon; BC, Bear Canyon (see Figure 5 for lithology abbreviations)

larger than a few millimetres south of the Golf Course site could result from the partially grusified nature of the granitic material and may explain why these materials never exceed 50 per cent of any of the samples collected north of Corner Canyon.

Corner Canyon is located at the intersection of the Wasatch Mountains and the Traverse Mountains. Because it was the only major drainage for Tertiary volcanic material from the Traverse Mountains into Lake Bonneville it can be considered a point source for sediments derived from this lithology. Furthermore, the Corner Canyon drainage basin area is as great as all the other significant drainage basin areas in the field area combined. Analyses of shoreline deposits to the north and southwest of Corner Canyon should therefore be a key indicator of predominant longshore transport direction along the Wasatch and Traverse Mountains.

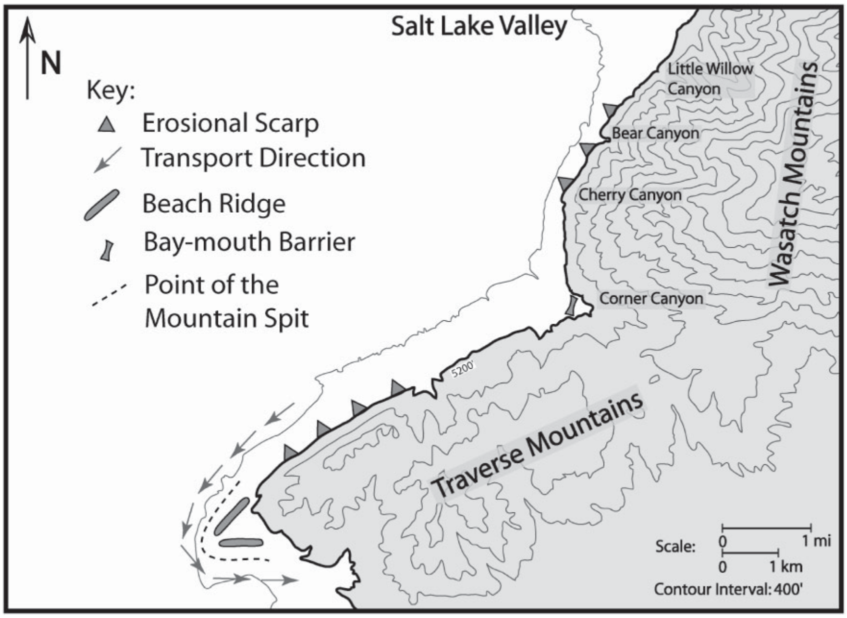

Figure 8. Key geomorphic features of Bonneville shoreline beach gravels north of Point of the Mountain spit. Small arrows indicate inferred direction of transport as shown by small spits on top of the Bonneville shoreline

Volcanic clasts increase linearly from Bear Canyon (*c*. 2 per cent) to Corner Canyon (*c*. 6 per cent) (Figure 7). Southwest of Corner Canyon there is a dramatic increase in the percentage of Tertiary volcanic clasts (60 per cent) at the Golf Course sample location. Southwest of the Golf Course location Tertiary volcanic clasts decrease to fewer than 10 per cent and are not present within the samples from Point of the Mountain spit. These trends indicate that sediments were transported both north and south along the Bonneville shoreline near Corner Canyon, although the primary sediment transport direction was south.

Oquirrh Formation indurated sandstone clasts increase from negligible amounts in the Corner Canyon sample to nearly 100 per cent of the Geneva Quarry sample (Figure 7). The highly fractured nature of the Oquirrh Formation in the Traverse Mountains makes it susceptible to erosion and incorporation into the shoreline deposits. The large amount of Oquirrh Formation sediment entering the Lake Bonneville shoreline may have swamped input of other rock types from the north. Furthermore, widths of the Bonneville shoreline bench increase from Corner Canyon to the south along the Traverse Mountains. This increase could be due to the large volume of sediment available from the Oquirrh Formation and the ease by which Lake Bonneville waves eroded into the side of the mountain. Implications of shoreline widths are discussed below.

Shoreline characterization

Select geomorphic features are used to determine whether erosion or deposition dominates a given section of the Bonneville shoreline (Figure 8). Steep scarps on the ends of mountain ridges just above the shorelines are used as indicators of erosion (Figure 3). Prominent erosional scarps were identified and mapped along the southern end of the Traverse Mountains and the region north of Cherry Canyon along the Wasatch Mountains (Figure 8). Angles of the erosional scraps are *c*. 55°. These steep erosional scarps are distinct from other mountain ridgelines that intercepted the Bonneville shoreline in this study area.

Several spits, smaller in scale than Point of the Mountain spit, were identified and mapped for aid in general shoreline classification (Figure 8). These geomorphic features served as both indicators of deposition and directionality of sediment transport. A bayhead barrier, an extension of the shoreline bench that extends across an embayment created by a drainage entering the lake, was identified at the mouth of Corner Canyon and classified as both a depositional and transport feature. If longshore transport had not existed at Corner Canyon, a delta would have formed at the contact with the lake rather than a bayhead barrier.

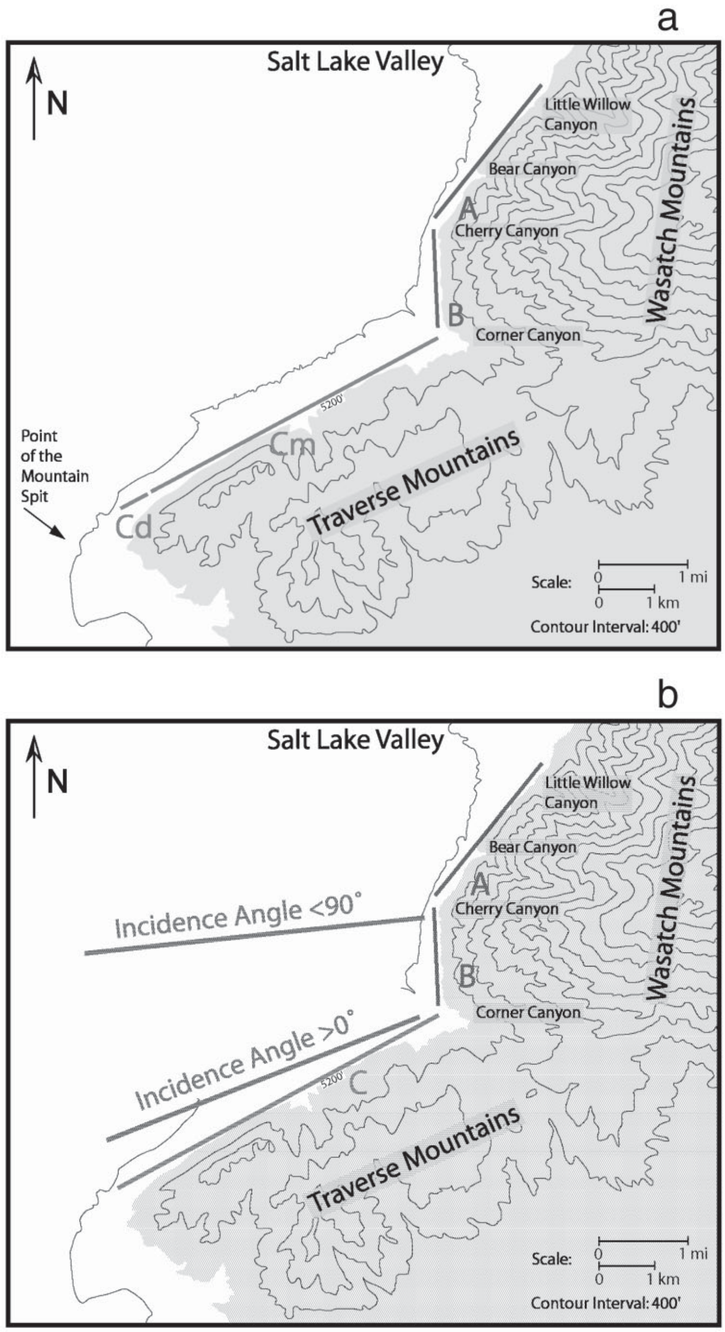

Figure 9. (a) Shoreline segments north of Point of the Mountain spit. (b) Hypothetical wave approaches to shoreline segments; arrows represent the wave approach angles

The Point of the Mountain Bonneville shoreline is divided into four sections based on the geometric orientations of the mountain fronts to aid in the interpretation of surface wave dynamics (Figure 9a). The angles of shoreline sections A, B, Cm and Cd are expressed as angles that are clockwise from 0° north. Section A is dominated by erosional processes. Energies from waves along section A of the shoreline eroded large amounts of material from the Wasatch Mountain front creating steep (*c*. 35°) scarps. Section A of the Bonneville shoreline exhibits bench widths on the order of 50 m.

Widths of section B of the Bonneville shoreline bench are *c*. 50 m, similar to those in section A, although mountain scarp slope angles are less steep (*c*. 25°). Section B exhibits moderate amounts of deposition and erosion, although because neither process was dominant it is characterized as a mixed system.

Depositional and erosional processes also dominate section Cm of the Bonneville shoreline from Corner Canyon to the southern extent of the Traverse Mountains (Figure 9a). The mountain scarp slope angles along this portion of the shoreline increase from *c*. 20° to *c*. 35° in a southward direction. The shoreline bench along section Cm is also significantly wider than either section A or B of the shoreline and is mapped as a mixed setting, because both depositional processes and erosional processes are indicated.

Depositional processes dominate section Cd of the Bonneville shoreline at the southernmost end of the Traverse Mountains south to Point of the Mountain spit. Sediments eroded in regions to the north were deposited as the longshore currents entered deeper waters at the end of Point of the Mountain spit. This portion of the shoreline has the largest measured bench width in the entire field area with shoreline widths an order of magnitude larger than those seen in sections A and B. The Point of the Mountain spit itself extends *c*. 200 m from the Traverse Mountains westward into the valley (Figure 9a).

Geometric surface wave analysis

Equation 1 makes it possible to understand the direction of the current produced by a given wave incidence angle with the shoreline. Incidence angles are considered to be perpendicular to the crests of the wave travel direction. First, we consider the wave incidence angles of waves constrained by the geometry of shoreline section C (combined from subsections Cm and Cd) (Figure 9b). On the basis of clast distribution data it is assumed that sediment was transported from northeast to southwest along this shoreline section. Therefore the wave incidence angle with this section of shoreline must be >0°. This wave incidence angle also produces positive cross-shore shear stresses and north-to-south sediment transport along sections A and B of the shoreline (Figure 9b). If the incidence wave angle with section C of the shoreline is increased in a clockwise direction, at some point the wave incidence angle with section B of the shoreline is >90° and north-to-south transport of sediment along this section would not have been possible.

A limited range of wave incidence angles with the shorelines thus produces north-to-south longshore currents that fit the field data. The angle of wave approach (defined as the azimuth direction perpendicular to the incidence wave angle) must be >152° in order to have transport along section C of the shoreline, and the angle must be <177° in order to have transport of sediment along section B of the shoreline (Figure 9b).

In summary, the northern portion of Point of the Mountain spit shows shoreline features that indicate sediment erosion to the north and deposition to the south and southwest. These geomorphic interpretations are backed up by lithologic trends of the shoreline sediments. The southern portion of the spit lacks distinctive shoreline features. Orientation of the depositional and erosional features on the northern part of Point of the Mountain indicates that waves approached from the north-northwest.

FINGERPOINT SPIT

The second field area consisted of Bonneville shoreline deposits on the eastern side of the Hogup Mountains on the northwestern shores of the Great Salt Lake (Figure 1). Although faults have been mapped in this area (Figure 10), Bonneville shoreline deposits do not appear to have been significantly influenced by post-Pleistocene tectonic activity. Bedrock geology in this area is dominated by three Permian formations (Figure 10). The Upper Oquirrh Formation of Wolfcampian age outcrops at the northernmost and southernmost portion of the Hogup Mountains whereas the Diamond Creek Formation and Loray Formation of Leonardian age make up the central portion of the range. Lithologies of the three formations include interbedded dark grey blocky limestone; fine-grained, thin-bedded, lavender weathering limestone; calcareous sandstone and dark grey bioclastic limestone; local conglomeratic units; and interbedded to massive sandstones and orthoquartzites with local crinoidal, fusulinid-bearing limestone (Doelling, 1980). The lack of distinctive lithologies for individual formations prevented investigation of longshore transport based on tracking the source area of clasts in a manner similar to that used at Point of the Mountain.

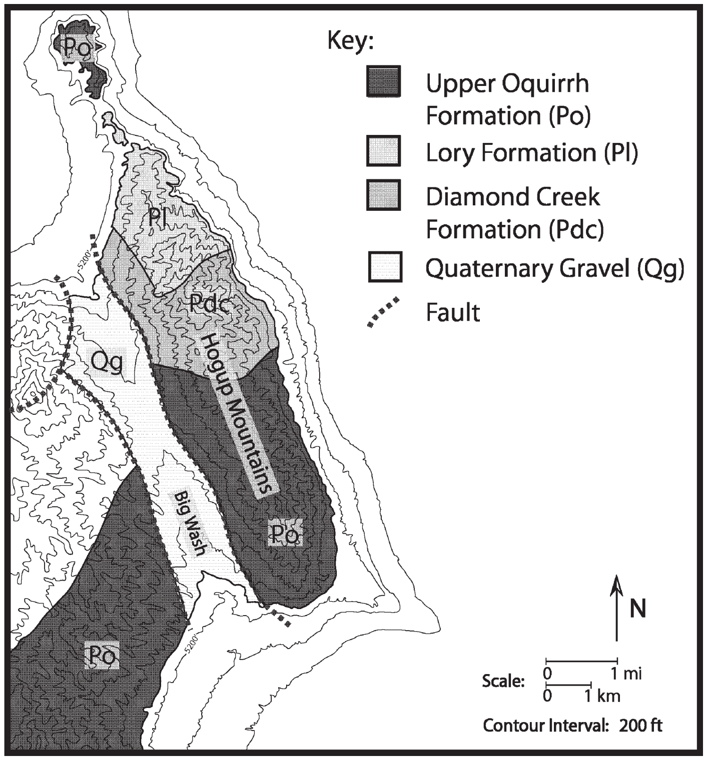

Figure 10. Bedrock geology map of the Fingerpoint spit and the area immediately to the north (adapted from Doelling, 1980)

Shoreline characterization

Bench erosion and depositional features were mapped and bench widths measured to determine how deposition and erosion varied near the Fingerpoint spit and which process dominated a given section of shoreline. Geomorphic features such as spits, pocket barriers and erosion scarps were used to determine the erosional or depositional character of a given section of the shoreline. High-angle scarps on the ends of mountain ridges just above the shorelines are used as indicators of erosion. Spits and bayhead barriers are used as indicators of deposition. These data are used to develop a map of erosion and deposition along the Bonneville shoreline bench (Figure 11).

Prominent erosional scarps were identified and mapped in regions north and south of Fingerpoint spit along the Bonneville shoreline (Figure 11). The erosional scarps were produced by wave action eroding mountain ridgelines that intercepted the Bonneville level of the lake. These were considered significant because they were not present on all of the mountain ridgelines that intercepted the Bonneville lake level. Several spits and beach ridges, smaller in scale than Fingerpoint spit, occur at the end of the Fingerpoint spit and were mapped to aid in general shoreline classification (Figure 11). These small features serve as both indicators of deposition and of directionality of sediment transport. The Bonneville shoreline bayhead barrier at the mouth of Big Wash, an embayment southwest of Fingerpoint spit, was identified and classified as a depositional and transport feature (Figure 11).

The Bonneville shoreline of Fingerpoint spit is divided into four linear sections (Figure 12a). Section A of the shoreline is subdivided into sections Ae and Am. Section Ae is erosion-dominated because of the presence of steep mountain scarps above a narrow shoreline bench. The mountain scarp angles above section Ae as shown on USGS topographic maps are *c*. 34°. The mountain scarp angles above section Am of the shoreline measured from quadrangle maps are *c*. 20° and so the section is characterized as mixed with neither erosion nor deposition dominating.

Section B of the Bonneville shoreline bench has also been subdivided into two parts (Bm and Bd). Section Bm is characterized as mixed because neither process of erosion nor deposition dominates. The mountain scarp

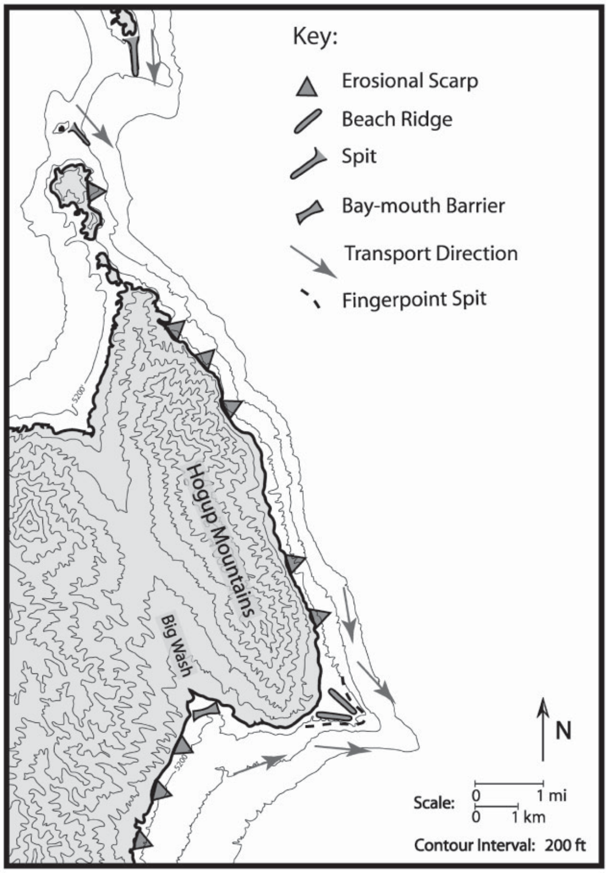

Figure 11. Key geomorphic features of Bonneville shoreline beach gravels north of Fingerpoint spit. Small arrows indicate inferred direction of transport as shown by small spits on top of the Bonneville shoreline

angles above section Bm are *c*. 27°. Section Bd is depositional because of the extreme increase in width of the shoreline bench towards the tip of Fingerpoint spit. The mountain scarp angles above section Bd are *c*. 10°.

Section C of the Bonneville shoreline bench is characterized as mixed on the basis of scarp angles and geomorphic features. Mountain scarp angles above section C of the shoreline are *c*. 14°. The end of Fingerpoint spit along this portion of the shoreline supports the mixed characterization. Assuming that the geomorphic features to the north of Fingerpoint spit suggest north-to-south longshore transport, then only one characterization of section C is plausible: sediment built the spit southward. Longshore transport from south to north in the southern embayment interrupted the southward deposition of sediment by transporting sediments east into deeper portions of the basin.

Section D of Fingerpoint spit shoreline exhibits several erosional scarps as well as depositional benches with widths that are average for this area. On this basis, section D is tentatively characterized as mixed.

Measurements from aerial photographs were found to be consistent with measurements made in the field with the laser range finder and prism. Using both techniques, the Bonneville shoreline benches exhibit greater widths in areas characterized as deposition-dominated (300–900 m wide) than in areas characterized as erosion-dominated. The portions of the Bonneville shoreline benches characterized as mixed exhibit slightly larger widths (125–200 m) than erosion-dominated benches (25–75 m).

Geometric surface wave analysis

Field evidence suggests that there were two dominant directions of longshore transport along the Bonneville shoreline near Fingerpoint spit. Longshore currents converged from north and south to produce the Fingerpoint

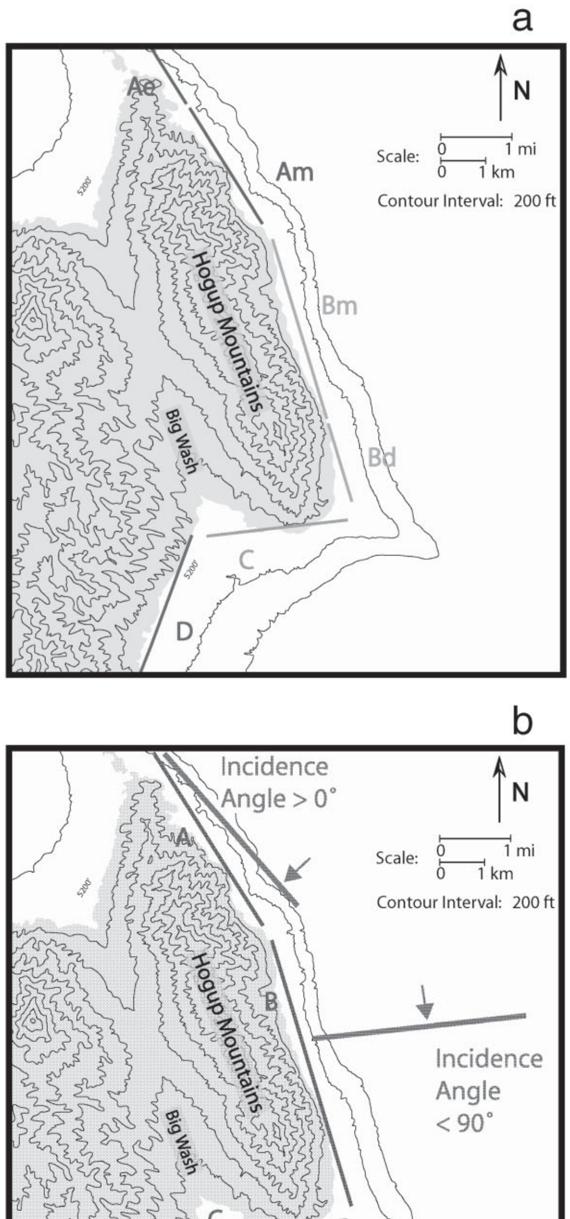

Figure 12. (a) Shoreline segments of the Fingerpoint spit. (b) Hypothetical wave approaches to shoreline segments; arrows represent the wave approach angles

spit. Two directions of sediment movement based on the limitations of Equation 1 for the four segments of Bonneville shoreline near Fingerpoint spit are depicted in Figure 12b.

For north-to-south transport to occur north of the Fingerpoint spit, wave incidence angles with section A of the shoreline must be >0° whereas wave incidence angles with section B must be <90°. Similarly, for transport to occur from south to north, wave incidence angles with section C of the shoreline must have been >0° and maximum wave incidence angles with section D of the shoreline must have been <90°. For the sections of shoreline north of Fingerpoint spit, the wave approach angle had to be between 148° and 238° for sediment to be transported along section A and between 163° and 253° to allow sediment transport along section B of the shoreline (Figure 12b). The wave approach angle from the north therefore had to be between 163° and 238°. For the sections of shoreline south of Fingerpoint spit the wave approach angle must have been between 353° and 83° for sediment to be transported along section C and between 310° and 20° to allow transport of sediment along section D of the shoreline. The range of wave approach angles south of the Fingerpoint spit thus had to be between 353° and 20°.

In summary, the Fingerpoint spit shows bidirectional sediment transport from the north-northwest and south-west that converges to form the prominent southeast-trending end of the spit. This interpretation is supported by a variety of geomorphic features including the angles of scarps and minor features such as beach ridges and small spits on the benches. Orientation of these features indicates that wave energy for the Fingerpoint spit was from the north to northeast and south-southwest.

DISCUSSION

Processes of shoreline erosion and deposition on spits and their application to Point of the Mountain and Fingerpoint spits in Pleistocene Lake Bonneville have been explained within the context of erosional, transport and depositional features. In addition to the constraints provided by wave angles to the shorelines (Figures 9b, 12b), the amount of wave energy plays an important role (Equation 1). The amount of wave energy is proportional to the square of the wave height. Wave height in turn has long been recognized as being a function of surface wind intensity, wind duration and fetch (length over which the wind blows). Although considerable research remains to be done, empirical relationships between wind strength, fetch and wave height have been constructed (e.g. CERC, 1984.) For a given wind strength, wave height is proportional to the square root of fetch and thus directly proportional to wave energy.

The range of wave fetch direction is determined for the lake using a generalized map of the lake shorelines (Figure 13). For Point of the Mountain spit, the geometric contraints on wave angle closely match the direction of maximum fetch (*c*. 200 km). Significant wave erosion and sediment transport are not recognized south of Point of the Mountain, an observation that is not surprising considering the limited fetch from that direction. Direction of maximum fetch for the south-to-north transport direction in the southern portion of the Fingerpoint spit corresponds to the direction of maximum fetch (*c*. 350 km). However, the north-to-south transport on the northern portion of the spit corresponds to a relatively limited fetch direction (*c*. 100 km) (Figure 13). The fact that significant sediment transport was recognized from the north at the Fingerpoint spit but not from the south at Point of the Mountain, despite these two localities having similar fetch length, suggests that the most energetic storms were those that came from the north. This supposition is not surprising because modern winter storms in this portion of North America tend to be steered by the jet stream from the northwest.

Analyses similar to those carried out on the Fingerpoint and Point of the Mountain spits hold the promise for better understanding a variety of physical processes. Additional fieldwork in the Lake Bonneville basin is currently underway and should eventually provide a complete picture of predominant wind directions. Once this is accomplished, specific storm scenarios could be tested using standard numerical models (e.g. Schwab *et al*., 1984) in order to understand the nature of Pleistocene storms in the Great Basin. These models could in turn shed light on a variety of palaeoclimate phenomena, such as the role that continental ice sheets play in influencing wind fields and thus the orientation of the jet stream over the Great Basin during that period of time.

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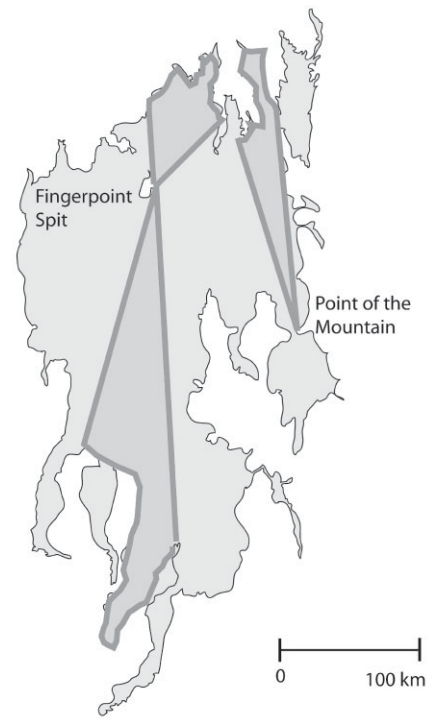

Figure 13. Outline of Lake Bonneville showing arcs of maximum fetch for the two field localities analysed in this study. The directions of wave angles determined at Point of the Mountain and Fingerpoint spits closely correspond to these zones of maximum fetch

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