SHORELINE SUPERELEVATION

Evidence of Coastal Processes of Great Salt Lake, Utah

by Genevieve Atwood

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2006

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Cover photo: Shoreline evidence of Great Salt Lake, Utah, view of Unicorn Point, the southernmost tip of Antelope Island, looking to the east.

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10/06

PREFACE

The research of this dissertation is part of a larger research effort given impetus by the rise of Great Salt Lake in the 1980s. In 1984, while I was State Geologist and Director of the Utah Geological and Mineral Survey (UGS), the survey published Donald R. Currey's mapping of major levels of Great Salt Lake and Lake Bonneville to provide timely information to the public and to decision makers about past and, therefore, potential future lake fluctuations (Currey and others, 1984). As the lake rose, the State of Utah called upon earth scientists and hazards specialists, including Currey, for advice concerning the magnitude of fluctuations of Great Salt Lake (Currey and Oviatt, 1985; Karl and Young, 1985; Riebsame, 1985). In 1986, I assisted Don R. Mabey and Currey in a study that compared elevations of still-water lake level and highstand shoreline expressions of 1986 along the east shore of Antelope Island with those of the 1860s-70s estimated by Grove Karl Gilbert (1890). It was found that the highstand of the 1860s-70s equaled that of 1986 within the margin of error of hand-leveling equipment (Mabey, 1986). This 1986 field work with Currey and Mabey began my research into the relationships of shoreline expressions and coastal processes of Great Salt Lake (photo on p. iv). During the 1980s, I investigated evidence on Antelope Island of Holocene fluctuation of Great Salt Lake as part of Currey and colleagues investigations of the Holocene history of lake fluctuations in the Great Basin and in response to the need for the State of Utah to understand recurrence intervals of lake flooding (Atwood and Mabey, 2000).

Specific questions concerning shoreline superelevation, the topic of this

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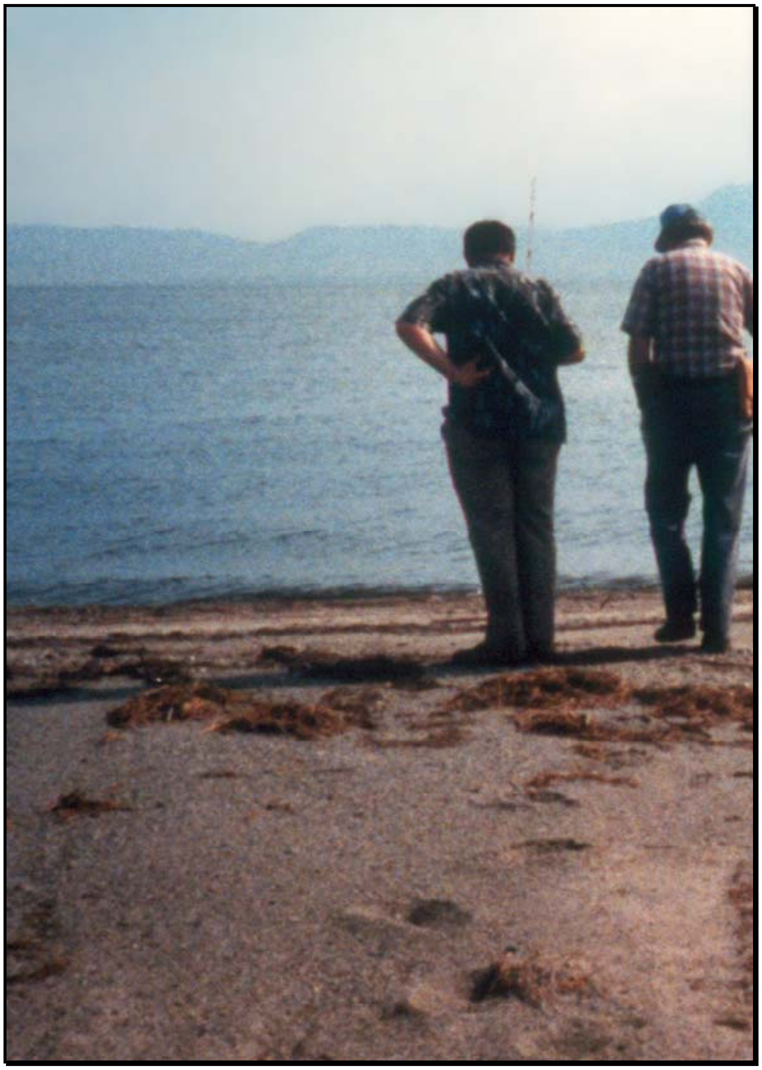

In the footsteps of Gilbert, Currey, and Mabey. Highstand shoreline evidence is examined by Donald R. Currey and Don R. Mabey along the east side of Antelope Island in June 1986. We repeated Grove Karl Gilbert's elevation survey of evidence of the 1860s-70s highstand, but for 1986 evidence (Gilbert, 1890; Mabey, 1986). This 1986 hand-level survey began the research of this dissertation. Note fresh accumulations of organic debris and wash-over sheets of sand that document wave action of early June 1986 when the lake was near its historic highstand elevation.

dissertation, developed with the growing recognition that (1) shoreline expressions related to a single still-water lake elevation formed over a range elevations, (2) prehistoric shorelines of Great Salt Lake could not be correlated based on elevation alone, and (3) shoreline superelevation might be useful for defining storm-related inundation hazards of Great Salt Lake (Atwood, 1994).

This dissertation has been completed with abundant help and encouragement of many people and support from several organizations. I wish to thank not only those individuals and organizations mentioned in the following paragraphs, but also those I have unintentionally omitted.

First, I thank Don R. Mabey, retired U.S. Geological Survey geophysicist, friend, colleague, and spouse. Don was the instrument person for the more than 2000 surveyed locations of the Antelope Island and Great Salt Lake data sets that are the quantitative evidence underpinning this dissertation. Although the Antelope Island research approach did not follow an efficient, traditional, USGS project-oriented trajectory, Don participated from start to finish.

Second, I am thankful to Donald R. Currey, deceased, mentor and former dissertation committee chair. I worked with Don for almost three decades, beginning in the 1970s, field checking his air photo identifications of Lake Bonneville shorelines. Don's commitment to understanding the histories of lakes of the Bonneville Basin and love of field work inspired me to return to school to better understand processes of Great Salt Lake. Don had an amazing ability to see spatial, temporal, and process relationships among exposures of lake sediments. His generosity, enthusiasm, and collegiality as well as his encyclopedic knowledge of Great Basin places and environments are missed by me and many other of his students.

I thank present and former members of my dissertation committee: Katrina A. Moser, chair; Marjorie A. Chan; Thomas J. Cova; Paul W. Jewell; Roger M. McCoy (retired); and Harvey J. Miller. Each contributed to the substance of the dissertation. Katrina's ethic to complete projects and publish research results has inspired me to finish this phase of research. I thank Roy Adams, Donald J. Easterbrook, Lehi F. Hintze, Don R. Mabey, William J. Neal, Charles G. (Jack) Oviatt, and Dorothy A. Sack for reading versions of the dissertation and improving it.

Several individuals assisted in the field with contributed time, ideas, and observations of shore debris. I thank Roy Adams, Katie Andrews, Amanda Atwood, Vickie Backus, Tim Edgar, Alisa Felton, Holly Godsey, Art Hantla and family, Paul Jewell, Matthew Mabey, Linda Martinez, Mark Milligan, Vicki Pedone, Pamela Poulsen, Jack Oviatt, Janet Roemmel, and Catherine Spruance for their ideas and observations of shore debris. I thank Mark Finco, Matthew Mabey, and Tamara Wambeam for GIS advice, and Julia Reid for assistance with SPlus statistical software.

Several organizations provided logistical and/or financial support. For 8 years (1981-1989), I served as State Geologist and Director of the Utah Geological and Mineral Survey, an organization whose mission is to make the State of Utah richer, safer, and better understood geologically. The rise of Great Salt Lake during the 1980s focused diverse talents and resources of the survey on coastal hazards of Great Salt Lake. This dissertation benefits from field investigations led by Hellmut Doelling and conversations with William Case, Gary Christenson, Suzanne Hecker, and William Mulvey. Salt companies and private landowners allowed access to their properties around Great Salt Lake for elevation surveys. Specifically, I thank Lee Brown and Dan Tuttle of US Magnesium, Jim Huizingh and Nathan Tuttle of Morton Salt, Eric Beaumont and Tom Burton of Great Salt Lake Minerals, the Bleazard brothers of Stansbury Island, and Bill Hopkins of Deseret Land and Livestock.

A USGS Data Grant for Land Process Research provided MSS remote satellite images for change analysis of lake extent for 12 dates during 1986-1987. National

Science Foundation grant DEB-9817777 to Chan and Currey funded research that included incorporating concepts of shoreline geoantiquities into teacher workshops.

I am especially grateful to present and former managers and rangers of Antelope Island State Park. They gave access to all parts of the island, provided logistical support, and shared insights about the island's terrain. Specifically, I thank Mitch Larsson (Park Manger, 1978-1993), Tim Smith (Park Manager, 1994-1999), and Jim Fillpot (Assistant Park Manager, 1984-2000).

In summary, I have benefited from copious assistance and abundant suggestions. I take full responsibility for errors and omissions of this dissertation.

I thank the Utah Geological Survey for making this dissertation available through their Miscellaneous Publications series. Kimm Harty, Deputy Director, shepherded it through the publication process. Liz Paton designed the cover graphics.

My address is: Genevieve Atwood, 30 North U Street, Salt Lake City, Utah, 84103, USA. I appreciate your comments.

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ABSTRACT

The rise of Great Salt Lake to its historic highstand in 1986 and 1987 left shoreline expressions that can be identified by their debris, surveyed relative to known still-water lake elevation, and studied as evidence of coastal processes of shallow closed-basin lakes. Shoreline superelevation, the difference between still-water lake level and shoreline expressions, was quantified for the 64-km shoreline of Antelope Island, the largest island in Great Salt Lake. Elevations surveyed at 1228 locations around the island define a surface that is neither essentially horizontal nor at still-water lake elevation. Elevations range from 0.5 ft (0.2 m) below still-water lake elevation to 12.2 ft (3.7 m) above still-water lake elevation and average 2.9 ft (0.9 m) above still-water lake elevation. One-third of the elevations are more than 3.4 ft (1 m) above still-water lake elevation. Relative magnitude of shoreline superelevation is evidence of relative wave energy. Higher shoreline superelevation on Antelope Island is associated with longer fetch, shores that face to the west and northwest, steeper shorezone slope, and erosional coastal landforms.

Research findings on Antelope Island were tested around Great Salt Lake. Superelevation patterns around Gunnison Bay for pairs of shorelines with equal fetch show higher elevations along downwind shores that face into storm winds and lower elevations in the lee of land along the northeast shores of the bay. The contribution of wind strength to superelevation is explained by Great Salt Lake's fetch-limited size, with wave-generating areas sufficiently small that wave environments do not develop into fully arisen seas. For Great Salt Lake, contrasting patterns of eroding versus

accreting coastal landforms and steep versus gentle shorezone slope are associated with shoreline superelevation and are evidence of wave energy and direction of storm winds.

CHAPTER 1

INTRODUCTION

Great Salt Lake is located at the eastern edge of the Great Basin near major metropolitan communities of Utah's Wasatch Front (Figure 1.1). Great Salt Lake is the Holocene, shallow, highly saline, interglacial lake that presently occupies the lowest areas of the Bonneville Basin. Shoreline evidence of Great Salt Lake and its late Pleistocene, 1000-ft (300-m) predecessor, Lake Bonneville, are well exposed on Antelope Island, the largest island of Great Salt Lake. Coastal landforms of Lake Bonneville and Great Salt Lake are evidence of coastal processes, and elevation differences of shorelines document changes of climate and postdepositional deformation (Gilbert, 1890).

The past century and a half of historic lake fluctuations of approximately 20 ft (6 m) have caused dramatic changes in the extent of the lake (Figure 1.2). During 1982-1987, the lake rose approximately 12 ft (4 m) to almost 4212 ft (1283.8 m) above sea level (a.s.l.), increased water depth in deep portions of the lake by about 50 percent, increased the lake's surface area by more than 33 percent, and resulted in more than $350 million of damages and public expenditures to control flooding (Arnow and Stephens, 1990).

U.S. Geological Survey (USGS) hydrographs summarize historic lake fluctuations (Figure 1.3). The lake reached its 1980s highstand level of approximately 4212 ft (1283.8 m) a.s.l. in both 1986 and 1987. This approximately equivalent highstand of both 1986 and 1987, referred to as 1986/87, also approximately equaled

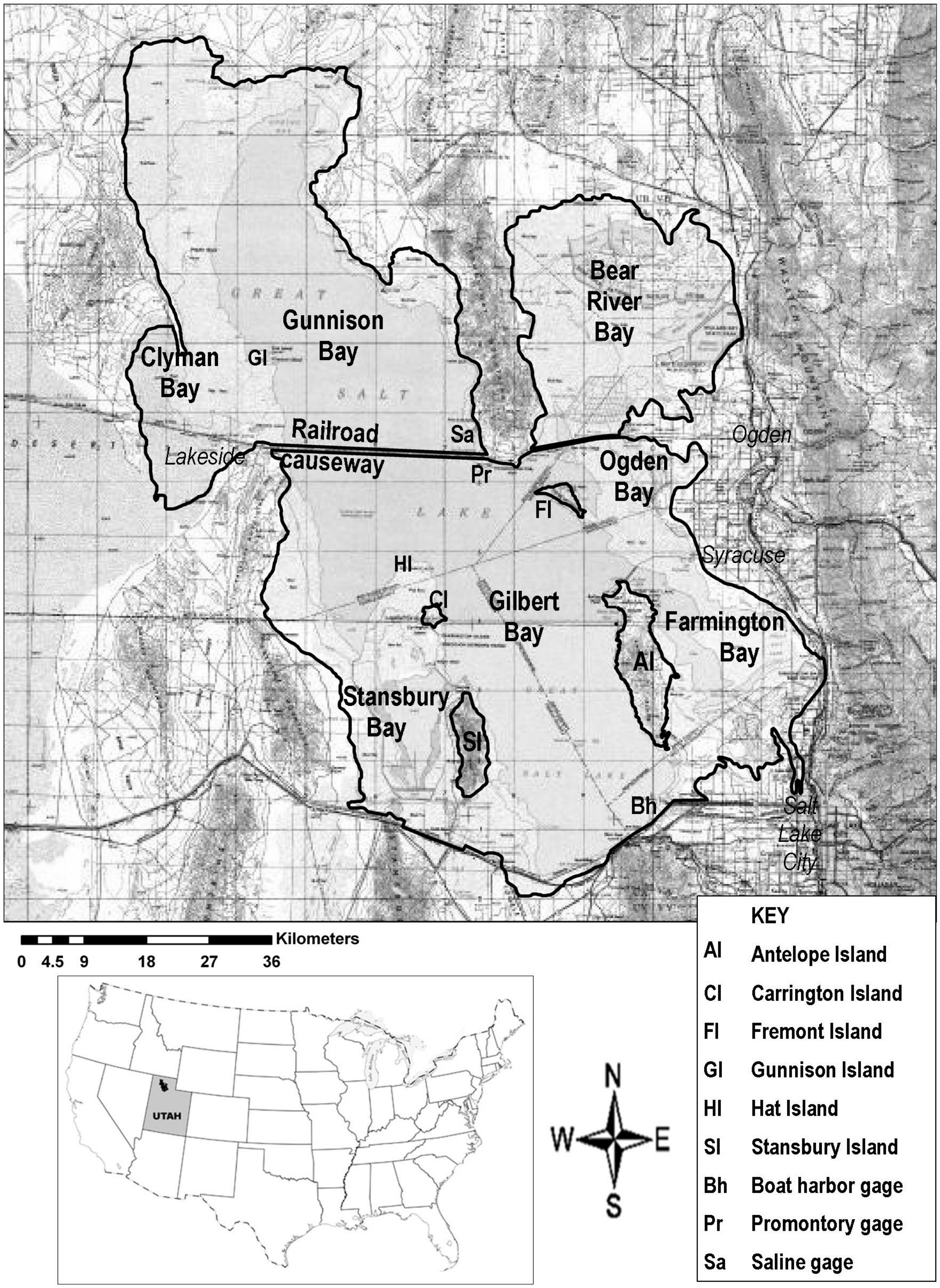


Figure 1.1. Index and location maps of Great Salt Lake, Utah.
Place names include bays of Great Salt Lake, major islands, and locations of lake-level monitoring gages. Names of communities are shown in italics. Dark line indicates extent of 1986/87 highstand flooding. Source of index and base maps: USGS, 2004c.

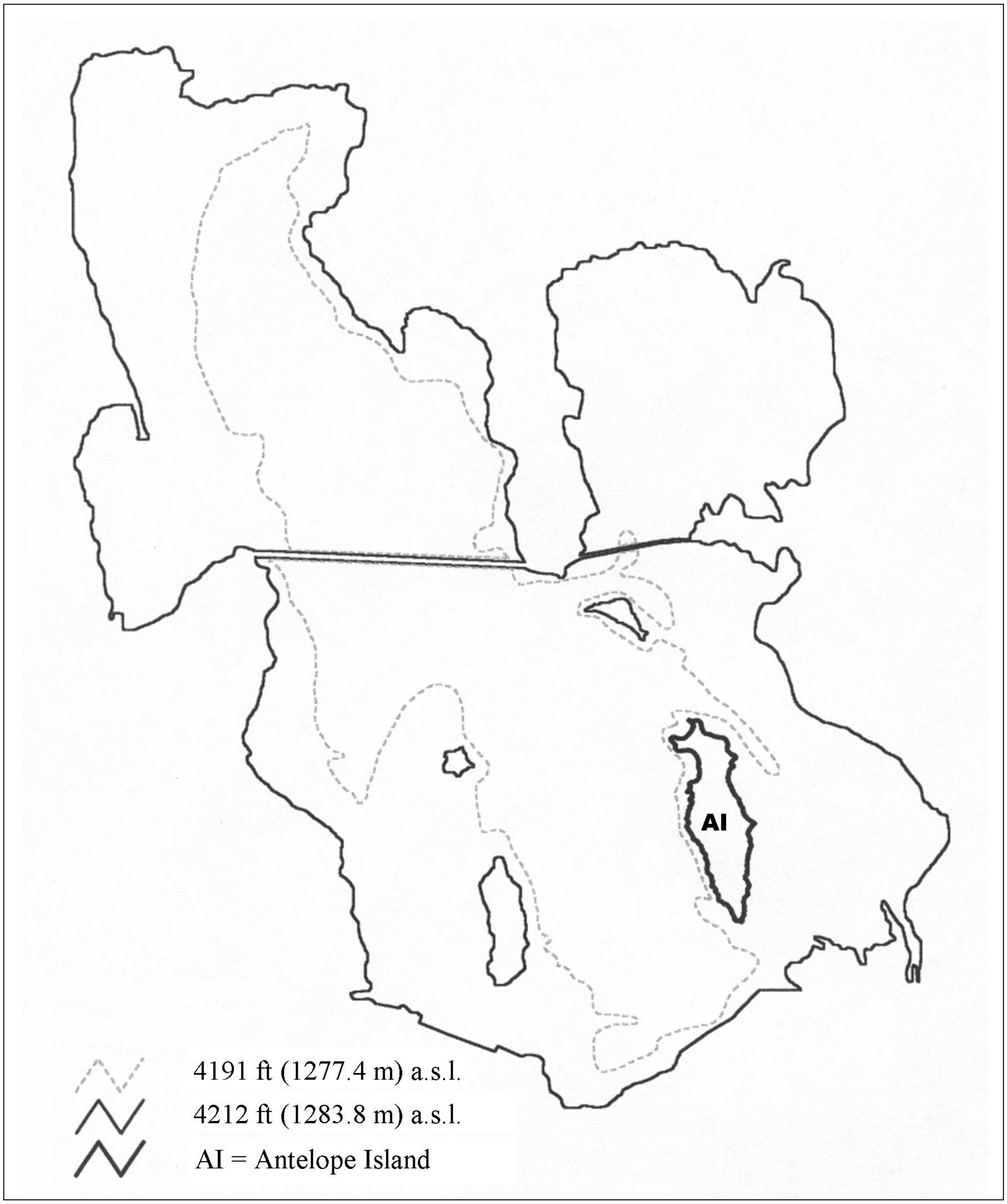
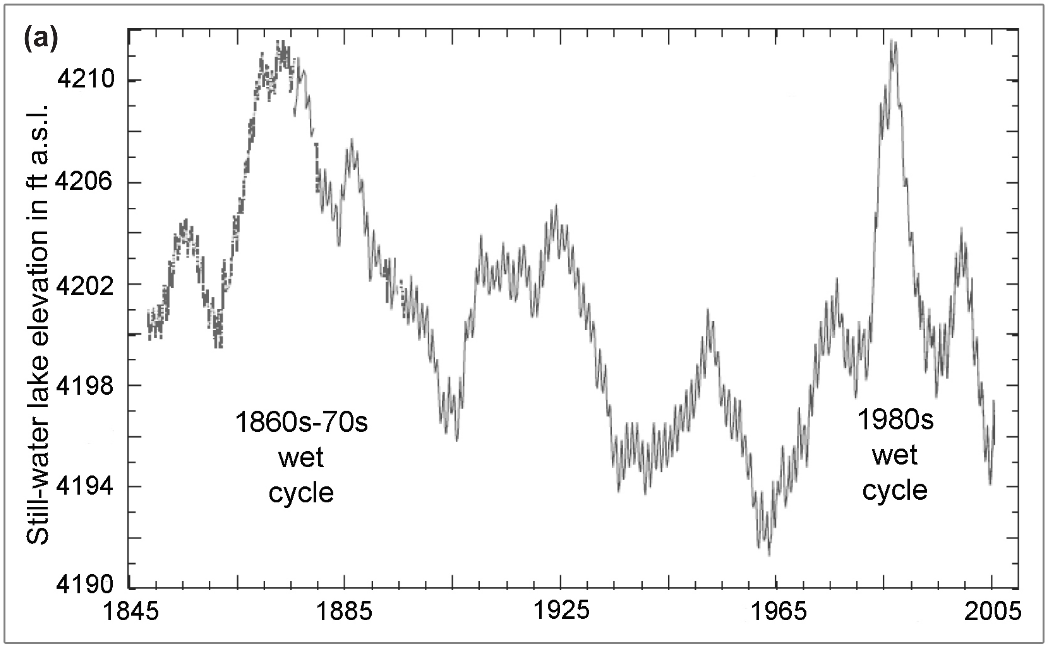


Figure 1.2. Historic extent of Great Salt Lake.
The shape and surface area of Great Salt Lake change dramatically with lake-level fluctuations. Great Salt Lake's historic lowstand of 4191.3 ft (1277.5 m) a.s.l. occurred in November 1963. The June 3, 1986, highstand of 4211.6 ft (1283.7) a.s.l. approximately equaled the highstand of the 1860s-70s.



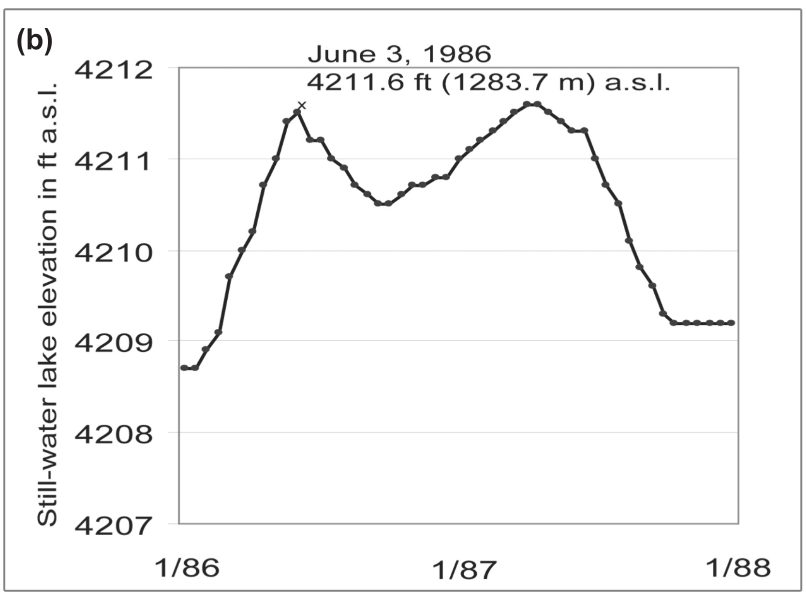


Figure 1.3. Hydrographs of historic fluctuations of Great Salt Lake, Gilbert Bay. Hydrograph (a) shows USGS 160-year record including two wet cycles, both of which peaked close to 4212 ft (1283.8 m) a.s.l. Pale portion of line indicates traditional data sources in contrast to dark line of gaged elevations. Detailed hydrograph (b) shows twice-monthly readings during 1986-1987 (dots and connected line) and the official highstand level (x) of 4211.6 (1283.7 m) recorded June 3, 1986. Lake elevation data have been adjusted for 2001 datum corrections. Data sources: USGS, 2004a, 2004b.

that of the 1860s-70s (Mabey, 1986).

Research of this dissertation examines two widely used working assumptions: (1) elevations of shoreline expressions are accurate evidence of still-water lake level, and (2) shoreline expressions can be used as horizontal datums. Elevations of shoreline expressions of 1986/87 on Antelope Island were surveyed relative to the highstand still-water lake elevation monitored by the USGS. Main features of Antelope Island are shown in Figure 1.4. Formal and informal names of locations of surveyed shorezone stretches are shown in Figure 1.5. The U.S. Army Corps of Engineers (USACE) defines still-water elevation as the elevation of the water surface "if all wave and wind action were to cease" (USACE, 2003, p. A-75). The difference in elevation between the still-water surface of a water body and the elevation of shoreline evidence created by that water body is shoreline superelevation, a term used, for example, by Currey (1982), and shown schematically in Figure 1.6. Coastal-process terms are defined later in this chapter (see Terms).

Shoreline superelevation of 1986/87 was analyzed in the context of coastal processes, such as wave runup and lake set-up, and in the context of coastal conditions, including wave-energy environments. Specifically, elevations of shoreline expressions, such as barrier beaches and strand lines of sediments, were examined for evidence of the storm conditions that were recorded, witnessed, photographed, or otherwise known to have occurred during the highstand years. If 1986/87 storm conditions, such as relative wave energy or direction of storm winds, left recognizable evidence specific to 1986/87 storm conditions, then similar features of paleoshorelines could have potential as useful indicators of paleostorm conditions.

Determining the magnitude and patterns of shoreline superelevation is important to research that uses absolute or relative lake level because superelevation is a potential source of error for these types of research. For example, understanding

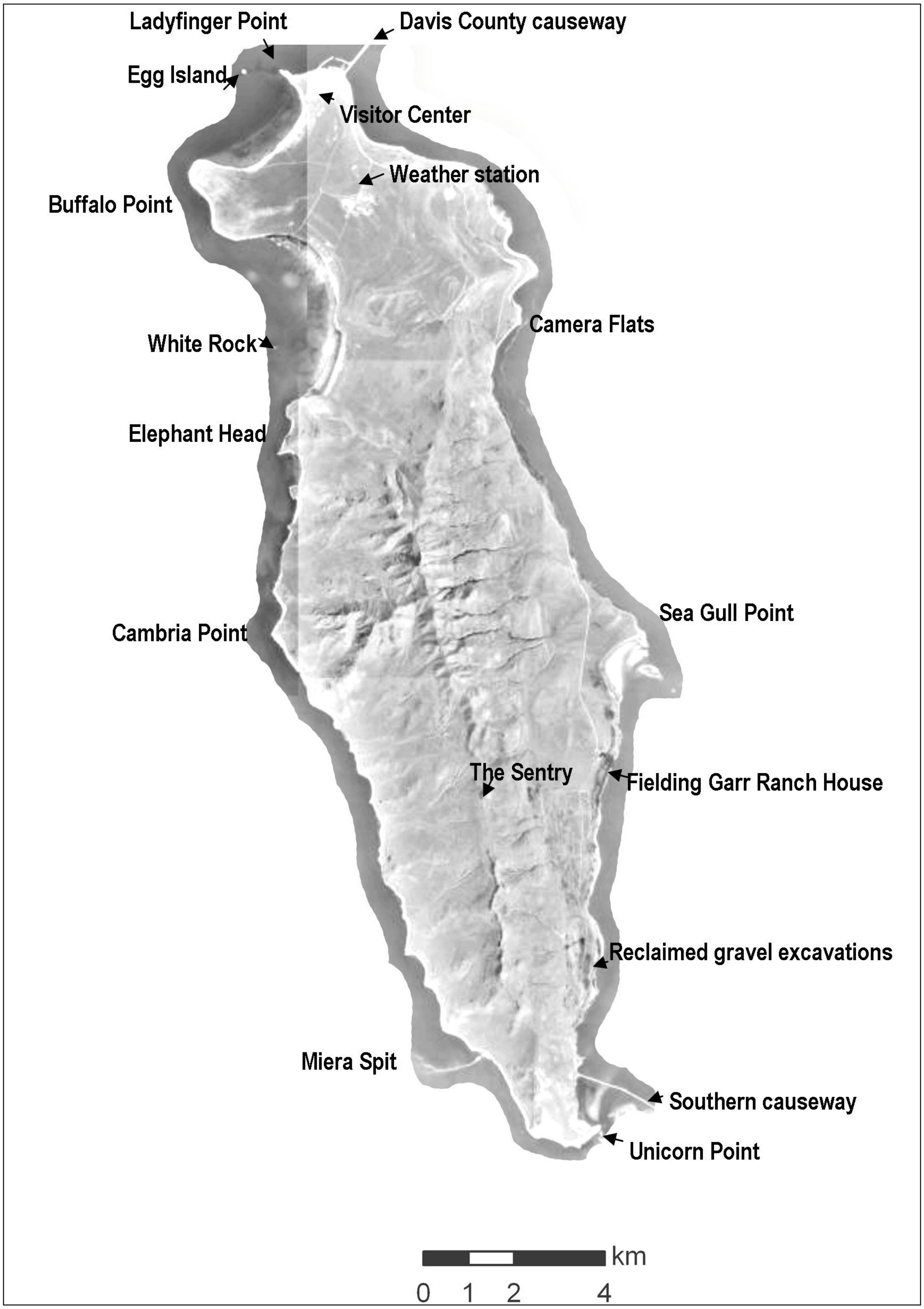


Figure 1.4. Photo-mosaic of Antelope Island showing main features.
Source of photo-base: USGS, 2004c.

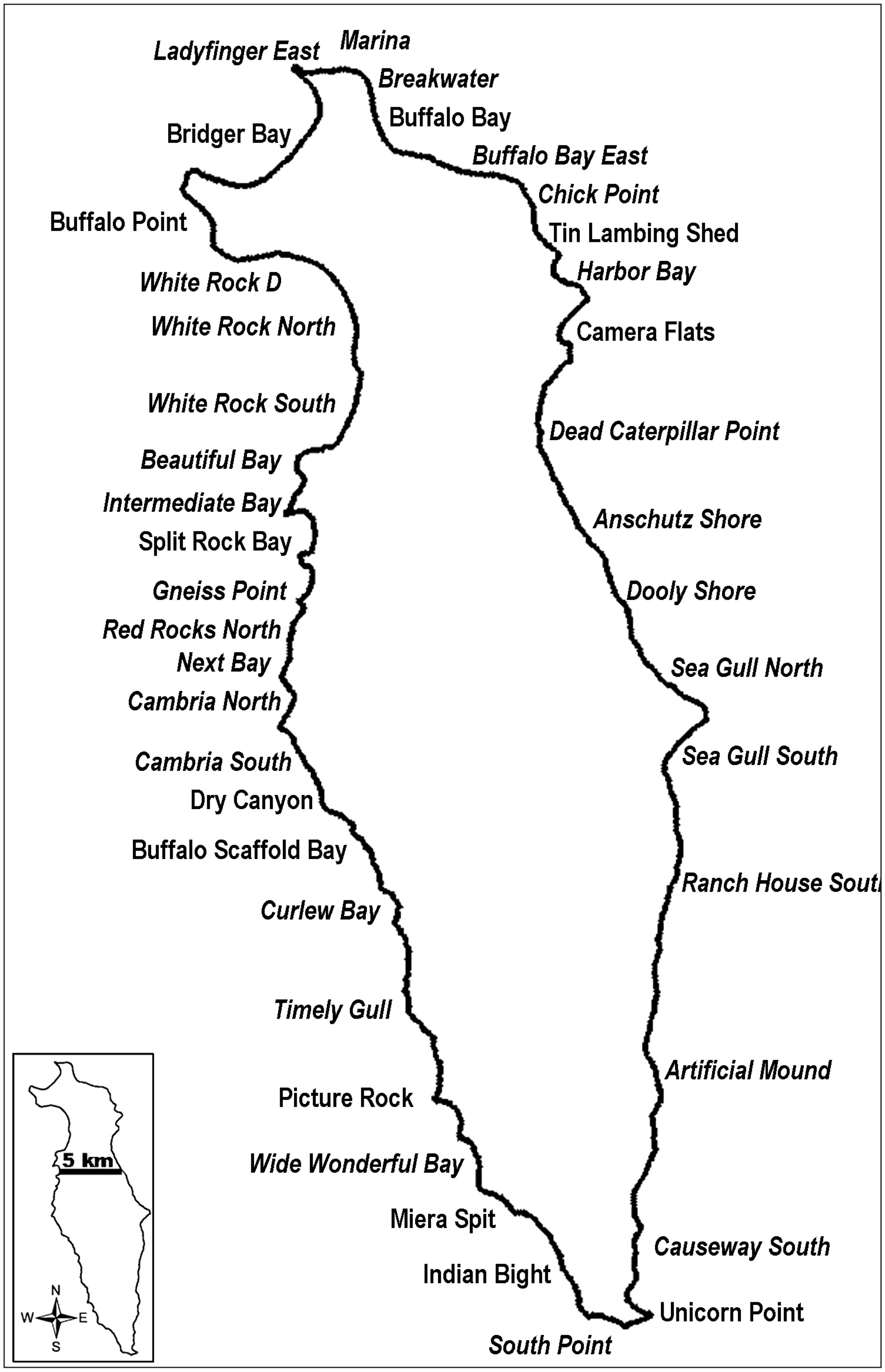


Figure 1.5. Shorezone stretches surveyed for shoreline superelevation.
Formal and informal names (in italics) identify stretches of Antelope Island's shore.

(a)

(b)

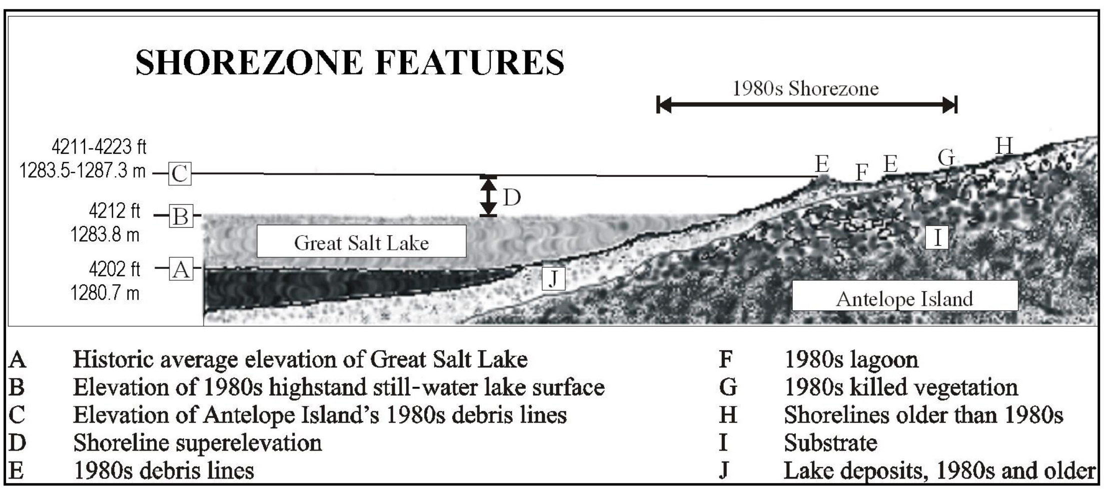


Figure 1.6. Superelevation of shoreline expressions.
Photograph (a) taken in 1998 looking east from Ladyfinger Point shows a 1986/87 shoreline expression, foreground, with anthropogenic debris strewn across the beach zone. Contrasts in vegetation patterns, upper center of photograph, are still evident a decade after flooding. Person on ridge provides scale. Lower sketch (b) illustrates shoreline superelevation (D), the difference between elevations of shoreline expressions and still-water lake elevation.

the magnitude of shoreline superelevation may contribute to more accurate modeling of lake processes because local differences in lake-surface elevation instigate lake currents (Lin and Wang, 1978; Imboden and Wuest, 1995), lake currents influence lake chemistry (Naftz and others, 2005), and lake chemistry impacts biota (Baxter and others, 2005). Accurate identification of shoreline superelevation provides direct evidence of extent of coastal flooding for risk management (Atwood, 1994).

In other research, determining the relationships among coastal processes, patterns of shoreline superelevation, and coastal features may improve hindcasts of paleolake conditions. For example, paleoshoreline elevations are the basis for calculations of paleolake surface area and volume (Mifflin and Wheat, 1979; Benson and Paillet, 1989). If not accounted for, shoreline superelevation can introduce potential error into calculations of lake morphometry. A 12-ft (3.6-m) difference in elevation of Lake Bonneville at the Bonneville level from 1552 to 1555.6 m a.s.l. (5092 to 5104 ft a.s.l.) changes calculated lake surface area by only about 0.5 percent (Wambeam, 2001). However, a 5-ft (1.5-m) difference from 4212 to 4217 ft a.s.l. (1283.8 to 1285.3 m a.s.l.) changes calculated surface area of Great Salt Lake by 55 percent (Currey and others, 1984; Wambeam, 2001).

Finally, differences in elevation along paleoshorelines of Great Salt Lake, Lake Bonneville, and other Great Basin paleolakes have been used to calculate the magnitude and recurrence of faulting (Caskey and Ramelli, 2004), magnitude of tectonic tilt (McCalpin and others, 1992), effects of crustal loading (Gilbert, 1890; Tackman, 1993; Lillquist, 1994; Bills and others, 2002), surface deflection associated with volcanism (Oviatt, 1991), and surface displacement due to ground failure (Personius and Scott, 1992). All of these studies are based on the assumption that the paleoshorelines were once essentially horizontal and, therefore, can be used as horizontal datums for determining postdepositional change (Smith and Dawson, 1983). Distinguishing patterns of paleoshoreline superelevation from patterns of postdepositional deformation is important for calculations of rates and direction of postdepositional deformation. Minor adjustments of measurements of paleoshoreline elevations can change interpretations of postdepositional deformation. For example, a repeat-survey of paleoshoreline elevations in Dixie Valley, Nevada, reduced estimates of Holocene fault slip rates by half (Caskey and Ramelli, 2004).

Historical Perspectives on Shoreline Superelevation

Grove Karl Gilbert observed superelevation of shorelines of Great Salt Lake during his late-1870s field investigations:

> All about the lake shore there is a storm line marking the extreme advance of the water during gales in the summers of 1872, 1873, and 1874. It is indicated by driftwood and other shore debris and is especially distinguished by the fact that it marks a change in vegetation. In some places vegetation ceases at this line, but usually there is a straggling growth of herbaceous plants able to live on a saline soil. Above the line, on all the steeper slopes not subjected to cultivation, the sage and other bushes flourish, but below the line they are represented only by their dead stumps. The height of this storm line above the contemporaneous still-water surface varies with the locality being much greater on a shelving coast, over which the water is forced to a considerable distance by the winds, and especially small upon the islands. On the east side of Antelope Island it was found by measurement to be three feet above the summer stage of the lake in 1877, or about one foot above the winter stage in 1872. (Gilbert, 1890, p. 242)

Gilbert also noted superelevation of paleoshorelines of Lake Bonneville and recognized that shoreline superelevation introduced potential error into estimates of paleolake still-water levels:

> The discovery that the old water line is no longer of uniform height, and the fact that its variations of altitude afford a means of measuring the recent differential movements of the earth's crust within the basin, give occasion for great regret that the exact identification of the highest water stage is so difficult a matter. In a majority of instances the range of uncertainty, after all allowances have been made, amounts to five or six feet. (Gilbert, 1890, p. 125)

In the appendix of that same monograph, elevations of paleoshorelines of Lake Bonneville are accompanied by estimates of uncertainty that include "estimated allowance for the difference in altitude between the topographic feature measured and the high water level… being based upon considerations arising from Mr. Gilbert's general study of the subject" (Webster, 1890, p. 416).

Gilbert investigated superelevation of Lake Bonneville paleoshorelines as potential evidence of paleowind direction and strength:

> At an early stage of the investigation, the writer thought that the coasts facing in certain directions gave evidence of exceptional amounts of wave work, and imagined that he had discovered therein the record of prevalent westerly winds or westerly storms in ancient times. This belief was dissipated by further study; and he discovered, as students of modern shores long ago discovered, that there is a close sympathy between the magnitude of the shore features and the 'fetch' of the efficient waves. The greater the distance through which waves travel to reach a given coast, the greater the work is accomplished by them. The highest cliffs, the broadest terraces, and the largest embankments are those wrought by the unobstructed waves of the main body; and opposite coasts appear to have been equally affected. (Gilbert, 1890, p. 107)

Among the "students of modern shores" (above) was Douglas Wilson Johnson whose *Shore Processes and Shore Development* summarizes much of coastal geomorphic knowledge of the early 20th century. Johnson (1919) reports that prevailing winds are not necessarily the winds that most influence shore features because wind waves associated with storms are more effective agents of shorezone change, and that long fetch, rather than direction of strong wind, determines sediment transport direction for large lakes, such as for the Great Lakes:

> The direction of the greatest stretch of open water is likewise important, since weak winds blowing over a long stretch of water may develop larger waves than strong winds which cross a limited water area. A good example of the effect of "length of fetch" is found in the beach drifting along the sand spit which encloses Toronto Harbor on Lake Ontario. Here the movement of the beach material is westward against the prevailing westerly winds, because the greatest stretch of water over which westerly winds can blow is 40 miles, whereas easterly winds cross 180

> miles of the open lake surface. Failure to recognize the important relation of beach drifting to the direction of greatest expanse of open water has led many authors to unsound conclusions…. (Johnson, 1919, p. 99)

A century after Gilbert's field investigations of the 1870s-1880s, little progress had been made in quantifying and understanding superelevation of paleoshorelines. Currey provided the following guidelines for estimating still-water lake elevation from paleoshoreline expressions:

> The mean position of a formative water plane, the perimeter of which theoretically constitutes an isochronous shoreline, may not be reflected unequivocally in the geomorphology of a shore zone. In their geomorphic development, shorelines clearly can be superelevated, coincident, or sub-elevated with respect to mean water levels (e.g., Rose, 1981, table 5.6). In the present study most of the shoreline altitudes have been determined at the crests of depositional shoreline forms. On spits, as well as on barriers and berms that are weakly or moderately developed, crests are likely to have been approximately tangent to formative water planes. However the crests of barriers and berms that are strongly developed are likely to have formed in superelevated positions. In selecting shoreline altitude localities and in estimating shoreline altitudes, a consistent effort has been made to detect and avoid crestal positions that are likely to be of unusually superelevated origin. In coastal geomorphic terms, drift-aligned beaches were selected in preference to swash-aligned beaches (Davies, 1980). No geomorphic correction factors have been invoked to somehow adjust altitudes to "true" values, but if such adjustments were feasible it is probable that they would seldom exceed the ± error estimates associated with the crestal altitudes themselves…. Each identifiable and dateable shoreline of Lake Bonneville can be viewed as coplanar (lying or occurring in the same plane with reference to a plane projection of the NGVD) at the time of its formation. Any subsequent departure of a shoreline from coplanarity is clearly relevant to analysis of post-shoreline crustal deformation. (Currey, 1982, p. 21-22)

Currey's discussion (above) is referenced in Caskey and Ramelli (2004) as a basis for using paleoshorelines as horizontal datums with precision of ±1 m. Phrased differently, the practice of assuming the horizontality of shorelines has been explained as follows:

> Because the static surface of a lake is essentially level, landforms created at the lake margins form at basically the same elevation throughout a basin. If coastal landforms are not level throughout a basin, subsequent neotectonic deformation in the form of

> seismotectonic displacement or isostatic deflection has likely occurred. (Lillquist, 1994, p. 143)

The possibility of error associated with initial nonhorizontality was recognized by these and other researchers; however they did not have evidence with which to quantify the magnitude and patterns of shoreline superelevation. In practice, it was assumed that shoreline superelevation could be ignored as negligible for research concerning neotectonics, isostasy, and climate change. Because Great Salt Lake shoreline expressions of 1986/87 are exceptionally continuous and are precisely dated, they can be used to test those assumptions.

Literature Specific to Great Salt Lake Coastal Processes

Great Salt Lake has been the subject of scientific investigation from the 1843 investigations of Fremont (Jackson and Spencer, 1970) to the present. Considerable recent research concerning the biota, chemistry, limnology, processes, resources, and history of Great Salt Lake is summarized in Gwynn (1980) and Gwynn (2002). Recent research directly related to the cause and effects of shoreline processes includes study of circulation patterns of the lake (Rich, 1991); determination of chemical distributions in the lake (Naftz and others, 2005); and periods and magnitude of seiches on Great Salt Lake (Lin and Wang, 1978; Wang, 1978). Recent related work at the University of Utah concerning coastal processes of Lake Bonneville includes research by Chan, Currey, Jewell, and several of their past and present students (Godsey and others, 2004; Schofield and others, 2004; Sack, 2005). Similar research questions have been pursued in the Lahontan Basin (Adams and Wesnousky, 1998; Adams and others, 1999).

Engineering studies have examined flooding hazards along shores of Great Salt Lake. Shoreline superelevation is evidence of storm-related inundation hazard. Probable maximum water levels and wave runup for proposed dikes of Great Salt Lake were calculated by Rollins, Brown, and Gunnell, Inc. and Creamer and Noble

(1987) based on USACE guidelines (1986). These calculations include estimates for two locations in Gilbert Bay offshore of Antelope Island. Davis County communities contracted with USACE (1996) to map inundation potential at five shoreline locations along the eastern mainland of Great Salt Lake.

Specific Research Objectives

Shoreline expressions of the 1986/87 highstand on Antelope Island provide opportunities to study a broad array of coastal processes and geomorphic expressions of shallow closed-basin lakes. Four research topics are addressed in the following four dissertation chapters:

(1) Pattern and magnitude of shoreline superelevation. Chapter 2 examines the nature of shoreline evidence of the 1986/87 highstand of Great Salt Lake, reports magnitudes of superelevation, and explores whether shoreline superelevation is random or has spatial patterns indicative of coastal processes.

(2) Shore processes of shallow closed-basin lakes. Chapter 3 explores the relative contributions of coastal processes of wind set-up and wave runup to superelevation and whether patterns of shoreline superelevation on Antelope Island support a tilted lake-surface model of wind set-up.

(3) Coastal environments. Chapter 4 examines associations of shoreline superelevation with fetch, wind strength, shorezone slope, shorezone materials, and coastal landforms.

(4) Applicability beyond Antelope Island. Chapter 5 examines whether relationships of shoreline superelevation, coastal processes, and coastal environments observed on Antelope Island can be generalized to shore areas around Great Salt Lake and, potentially, to other shallow closed-basin lakes and paleolakes.

The following statements grouped into the four categories discussed above and summarized in Table 1.1 were explored for their validity using empirical evidence of

Table 1.1. Coastal processes issues.

Issue explored	Chapter
Pattern and magnitude of shoreline superelevation.	2
• Shoreline expressions document still-water lake elevation precisely.	
• Shoreline expressions describe a horizontal plane.	
• Shoreline superelevation is random and inconsequential.	
Shore processes.	3
• Changes in lake surface due to wind set-up resemble lake seiche.	
• Wave runup explains shoreline superelevation.	
• Shoreline superelevation represents wave energy.	
Coastal conditions.	4 and 5
• Strong storm winds result in shoreline superelevation.	
• Long fetch alone explains high shoreline superelevation.	
• Steep shorezone slope is associated with high shoreline superelevation.	
• Shallow offshore slope is associated with low shoreline superelevation.	
• Coarse beachzone materials indicate high-energy wave environments.	
Applicability.	5
• Antelope Island shores represent shores of Great Salt Lake.	

the Antelope Island and Great Salt Lake data sets.

(1) With respect to the pattern and magnitude of shoreline superelevation:

- Shoreline expressions document still-water lake elevation precisely.
- Shoreline expressions describe a horizontal plane.
- Differences in elevations of shoreline expressions are random and inconsequential.

(2) With respect to shore processes:

- Changes in lake surface due to wind set-up resemble the changes of lake surface due to lake seiche.
- Wave runup explains patterns, magnitude, and variability of shoreline superelevation.
- Relative shoreline superelevation is evidence of relative wave-energy environments.

(3) With respect to coastal environments:

- Shores facing into strong storm winds have high shoreline superelevation.
- Long fetch alone, not strong storm winds, explains high shoreline superelevation.
- Steep shorezone slope is associated with high shoreline superelevation.
- Extensive, shallow, offshore slope is associated with low shoreline superelevation.
- Coarse shorezone materials indicate high-energy wave environments.

(4) With respect to applicability beyond Antelope Island:

- Shorezones of Antelope Island are representative of conditions of mainland shores and shores of other islands of Great Salt Lake.

Criteria for Determining Shoreline Superelevation

Patterns of absolute shoreline superelevation, the difference between still-water lake elevation and the elevation of a shoreline expression, can be determined when three conditions are met: (1) shoreline expressions with different exposures and geomorphic conditions are known to be the same age, (2) the elevation of the still-water surface of the water body is known, and (3) elevation differences between the shoreline expressions and still-water lake elevation can be determined with precision. Relative shoreline superelevation can be quantified when the precise elevation of still-water lake level is not known so long as shoreline expressions are the same age and can be surveyed with precision.

For most marine shores, the second of the three conditions cannot be met. Mean sea level, the still-water elevation of marine water bodies, is not a precise datum from which to measure the effects of waves (Smith and Dawson, 1983). Mean sea level is an average of levels monitored in diverse locations and averaged over time (USACE, 2002). Fluctuations of sea level, such as tides, that occur during storms can result in exceptional sea surface elevations (Komar, 1998). Marine sea surface processes, such as the storm surge of hurricanes, associated with superelevated shoreline evidence are hostile environments to monitor in real-time (Birkemeier and others, 2001). For these reasons it is difficult to associate specific storm-wave conditions with specific shoreline expressions.

All three conditions necessary to determine absolute shoreline superelevation are difficult to meet for most paleoshorelines. First, it is difficult to determine that shoreline expressions at diverse locations are the same age. Second, associating shoreline expressions of paleolakes with their still-water elevation is not possible by direct observation. Third, vertical survey control for some field areas is problematic. For example, western portions of the Bonneville Basin have a dearth of first-order, stable benchmarks for vertical survey control (Crittenden, 1963; National Geodetic Service, 2005). Advances in global positioning technology (GPS) may diminish this third concern by providing alternative, precise, vertical survey control (Caskey and Ramelli, 2004).

Lake processes that cause shoreline superelevation have been studied on modern lakes, such as Lake Erie (Platzman, 1963; Csanady, 1972; Croley, 1987). Even for modern shores, such as Lake Erie, patterns of relative shoreline superelevation are challenging to determine unless distinctive, datable evidence that has not been reworked by shore processes positively identifies various shoreline segments as contemporaneous.

Evidence of Shoreline Superelevation and Great Salt Lake

Shoreline superelevation can be quantified for 1986/87 shoreline expressions of Great Salt Lake on Antelope Island because the three conditions necessary for determining shoreline superelevation are met. First, expressions of 1986/87 around the island can be distinguished from older and younger shoreline expressions. They are distinguished from younger shoreline expressions because 1986/87 expressions are farther inland or higher. They are distinguished from older, higher, shoreline expressions by distinctive anthropogenic materials, such as lumber and plastic, and by organic debris of vegetation from the island and lake detritus including windrows of brine fly pupae cases (Figure 1.6). Furthermore, some shore segments are known to be from 1986/87 because they were documented and photographed during 1986-89 (Atwood and Mabey, 2000).

Second, still-water lake elevation of 1986/87 is known. A lake gage at the boat harbor on the south shore of Gilbert Bay monitors daily, seasonal, and annual lake elevations (Arnow and Stephens, 1990). The official, published, USGS-adjusted, highstand elevation of Great Salt Lake's 20th-century wetcycle is 4211.6 ft (1283.7 m) a.s.l. recorded June 3, 1986 (Tibbetts and others, 2004). During 1987, the lake peaked at 4211.5 ft (1283.7 m) a.s.l., virtually the same highstand elevation as in 1986. By the end of 1987, the still-water level of the lake had fallen over 2 ft (0.6 m). The rapid drop in lake level left evidence of the 1986/87 highstand shoreline high, dry, and above subsequent wave action.

Third, differences in elevation between still-water lake elevation and elevation of shoreline expressions around the island can be determined with sufficient precision to quantify relative shoreline superelevation. Survey control will be discussed in detail in Chapter 2.

In addition to meeting the necessary conditions for quantifying shoreline superelevation, Antelope Island has other positive attributes for coastal processes research. First, unlike some islands of Great Salt Lake, such as Stansbury Island, Antelope Island during 1986-1987 was surrounded by water uninterrupted by causeways and dikes. During the highstand years, the lake around the island flooded causeways that, at lower lake levels, separate Farmington Bay from the main parts of the lake. Second, the island's approximately 64-km 1986/87 shoreline represents diverse examples of Great Salt Lake's shorezone environments. Geomorphic conditions on the island are exposed to a wide range of wind velocities, wind directions, and fetch. Third, because Antelope Island is a state park, its shores are protected from most development and, with park permission, accessible for research. Fourth, two contrasting geologic units dominate the island's exposed bedrock: the generally light-colored Cambrian Tintic quartzite and the typically dark-colored Early Proterozoic Farmington Canyon Complex. The contrasting lithologies provide opportunities to study transport directions. Fifth, the island is spatially isolated from mainland riverine processes, and no perennial streams drain the island. This simplifies examinations of coastal processes. Sixth, the lake, including Farmington Bay, did not freeze over during 1986-1987 and ice-related shore processes can be dismissed as causing 1986/87 shoreline expressions. Seventh, the island is a study area sufficiently compact to be surveyed in its entirety. Vertical survey control can be carried around the island using monitored lake elevations as a consistent datum. Eighth, because only a decade passed between formation of the shoreline evidence and elevation surveys of this research, tectonic displacement and isostatic deflections are ruled out as causes of shoreline nonhorizontality.

Empirical Research Approach

The research approach has been field-oriented. Techniques and criteria to map shoreline expressions and characterize the shorezone were tested during 1995-1997. Types of shorezone materials, abundance of materials, and shorezone evidence, such as largest particles moved, were characterized in a 1998 field survey. A second field investigation, also completed in 1998, surveyed elevations of inundation shoreline expressions at 1228 locations using total station, electronic distance measuring equipment. The survey team consisted of Don R. Mabey at the instrument station and me as rodperson.

Field work was designed to capture ephemeral evidence, such as vegetation changes, as well as longer-lasting evidence of 1986/87 shorezone processes, whether or not the evidence related directly to shoreline superelevation. The guiding principle was to document shorezone characteristics that would have been useful to 19th- and 20th-century geomorphologists had the information been collected during and after the lake's 1860s-70s highstand. The 1986/87 shoreline expressions can be considered a geoantiquity, a record of recent Earth systems history endangered by natural processes and human disturbances as defined in Chan and others (2003a) and as used in teacher workshops (Atwood and others, 2004).

Field investigations mapped shoreline evidence of 1986/87 and surveyed elevations of shoreline evidence. Additional geomorphic, topographic, and geologic information was derived from maps. The data, combined into the Antelope Island data set, were used to examine shoreline evidence, including questions concerning the magnitude and patterns of shoreline superelevation (Chapter 2); lake processes that cause superelevation (Chapter 3); and associations of shoreline superelevation with coastal characteristics, including fetch, aspect, shorezone slope, and coastal landforms (Chapter 4). In 2003, findings of the Antelope Island shoreline superelevation research were investigated at 10 shore areas around Great Salt Lake that represent 20 contrasting shore exposures (Chapter 5).

Terms

Terminology for lacustrine coastal research has its roots in four bodies of literature: (1) marine coastal process research on storm surge and sea surface set-up, (2) marine, reservoir, and Great Lakes research on wave energy, (3) research on lacustrine coastal environments, and (4) research associated with shore protection. Coastal process terms used in this dissertation and summarized in Table 1.2 are defined based on usage by Komar (1998), Masselink and Hughes (2003), and USACE (1984; 2002). Discussions in later chapters reference these three sources as representing present understanding of coastal processes and geomorphology.

Shoreline superelevation is the difference in elevation between still-water lake-surface elevation and the elevation of an expression of its highstand shoreline (Figure 1.7). Still-water lake level is the elevation of the lake surface undisturbed by wind, seiches, or currents. For Great Salt Lake, still-water lake elevation is the official USGS record of lake-level monitoring at two (and, for some years, three) locations on Great Salt Lake. Relative shoreline superelevation refers to variations of superelevation, such as the contrast between Antelope Island's west and east shores. Absolute superelevation ties elevation differences to a still-water lake elevation datum. USGS has adjusted official still-water elevations of Great Salt Lake during 1986-1987 to account for

Table 1.2. Coastal processes terms and usage.

Shorelines and paleoshorelines.

Shoreline: the interface of the surface of a water body and the shorezone. The active shoreline of Great Salt Lake is not a landform; it is the hypothetical junction of the lake surface and land.

Shoreline expression: the physical and geomorphic evidence of a shoreline. The 1986/87 highstand shoreline created several shoreline expressions on the shores of Antelope Island, including barrier beaches, lagoons, and erosional surfaces.

Historic shoreline: as narrowly used in this dissertation, historic shorelines of Great Salt Lake are shoreline expressions of lake-level fluctuations from 1850s to the present and include evidence from highstands of the 1860s-70s and of 1986/87.

Paleoshorelines: physical and geomorphic evidence of shoreline of paleolakes. Prehistoric shoreline expressions of Great Salt Lake and Lake Bonneville are paleoshorelines.

Shorezone: the general term for the area of the shore where waves encounter land. During the highstand of Great Salt Lake, the shorezone included areas nearshore and onshore from approximately 4205 ft (1281.7 m) a.s.l. to the inundation shoreline expression.

Beach zone: the wave runup portion of the shorezone, the beach face.

Shoreline evidence.

Inundation expression of the 1986/87 shoreline: the farthest inland evidence of flooding associated with the 1980s wet cycle.

Shoreline debris: natural and anthropogenic materials incorporated in shoreline expressions of a shoreline.

Bedload or terrigenous debris: materials entrained and transported at wave base that are incorporated in expressions of a shoreline. Materials consist primarily of nonfloating materials, such as sand, gravel, and anthropogenic materials denser than lake water including pottery, asphalt, and concrete.

Flotsam: floated material which includes tree limbs, lumber, automobile tires, and locally-derived twigs incorporated into deposits of sand and gravel.

Anthropogenic debris: human-generated debris, trash.

Shore processes.

Wind drift: wind driven movement of water and materials across the water surface.

Along shore transport: movement of entrained materials along the shorezone.

Along shore currents: movement of water near shore and along shorezone parallel to shore.

Lake set-up: elevated lake surface caused by any process, whether or not storm-related. Nonstorm-related processes include wind drift, currents, and lake seiche. Storm processes include barometric pressure differences and wind set-up.

Table 1.2. (continued)

Wind set-up: the component of lake set-up and lake storm surge caused by wind. Lake set-up is accompanied by a lowered lake level called lake set-down or negative lake set-up (Figure 1.7).

Lake seiche: (noun and verb) oscillation of a lake's surface as a standing wave. Lake set-up initiates a lake seiche. Storm winds set up the lake surface, elevating portions and lowering others. When wind strength diminishes or wind direction changes, oscillation begins. Lake seiche of Great Salt Lake results in alternating lake set-up and lake set-down as the lake oscillates.

Wave runup: the rush of water and entrained sediment landward and upward from where waves break, across a shorezone, to a shoreline expression. Wave runup begins from a set-up or set-down lake surface.

Swash: synonymous with runup but generally refers to the runup of several waves or wave trains in contrast to wave runup that implies the runup of individual wind waves as well as swell.

Waves.

Wind waves: waves that result from wind blowing across the water surface.

Individual wind waves: waves of diverse energies of a disorganized, confused, sea.

Wave trains: series of waves of similar energy, height, and speed, that travel as a group.

Swell: wave trains that have traveled beyond their storm of origin.

Significant wave height: the average height of the upper one-third of waves of a group of individual wind waves, swell, or waves over a period of time.

Disorganized sea: the state of the surface of a water body when it consists of individual wind waves that have not organized into wave trains.

Fully arisen sea: the state of the surface of a water body when waves have organized into wave trains that are the maximum height for a given wind speed, fetch, and storm duration.

Fetch.

Fetch: a vector used to estimate the wave-generating area of a waterbody. Maximum fetch length for Great Salt Lake is the longest distance from a shorezone, across open water, to land. Direction of maximum fetch is measured from the shorezone clockwise in degrees from north.

Fetch-dominated waterbody: a waterbody with a surface area sufficiently large so that the transfer of storm-wind energy into the lake surface results in a fully arisen sea with wave height limited by wave instability.

Fetch-limited waterbody: a waterbody with a surface area sufficiently small so that storm-wave height is not limited by physical stability of waves but by energy transfer into the lake surface.

Sources: Komar (1998); Masselink and Hughes (2003); and USACE (1984; 2002).

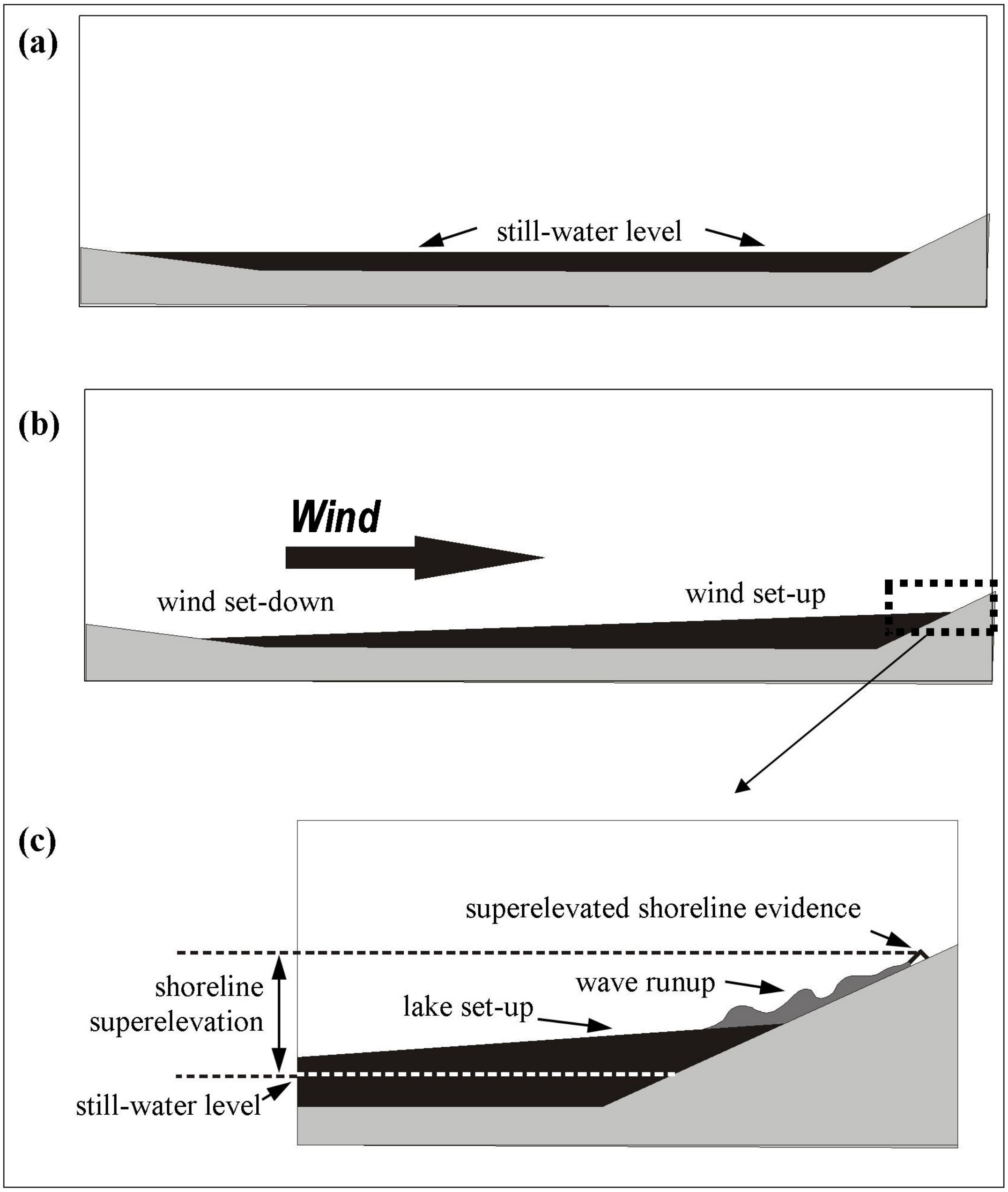


Figure 1.7. Storm-related lacustrine coastal processes.
Storm waves construct shoreline expressions of Great Salt Lake. Diagram (a) shows an undisturbed horizontal lake surface, the still-water lake level. Diagram (b) shows effects on lake surface of wind blowing across the lake. Wind set-up along the downwind, windward shore is compensated by wind set-down along the leeward shore. Dotted line indicates detail shown in (c). Diagram (c) is a detailed view of the downwind shorezone. Wind set-up is the major component of lake set-up. Waves rush up the beach face from that set-up surface and form expressions of the shoreline.

uncertainties in datum ties, instability of gages, and reoccupation of level lines (Loving, 2002). This dissertation uses the official highstand elevation as still-water lake elevation. This definition is a conservative estimate of superelevation because it is a conservative choice of still-water lake elevation. The lake's official peak is for a single day, June 3, 1986, a day of relatively calm water (USGS, 2004a). Therefore, the storms that created 1986/87 highstand shoreline expressions of Great Salt Lake occurred when the lake was below the lake's highstand still-water elevation.

Generalized Wave Environments of Great Salt Lake

Generalized wind-wave environments of Great Salt Lake are depicted in the nomograph of Figure 1.8. Significant wave height nomographs of the USACE *Shore Protection Manual* (1984) show relationships among fetch, storm duration, wind strength, and height of significant waves for open-water conditions of marine and large-lake water bodies. Great Salt Lake is not an open-water wave environment and, as with any wind-wave nomograph, "these simple methods of forecasting sea state … are imprecise and substantial errors must be tolerated and accounted for" (Australian Bureau of Meteorology, 2005, section 4.3.3).

The nomograph (Figure 1.8) shows relationships for storm-wave conditions of Gilbert Bay and the west side of Antelope Island. Conditions are estimated for the strongest, longest, most dangerous wave conditions discussed in Chapter 3. Significant wave height, the average height of the upper one-third of waves, is estimated as 3.5-5.5 ft (1-1.7 m). Maximum fetch across Gilbert Bay is 60 km (< 37 mi). Duration of strong, steady, storm winds is estimated as < 8 hours. Wind stress, a function of wind speed (Komar, 1998), is based on near gale-force winds. Sustained winds across Great Salt Lake during 1986/87 may have attained near-gale conditions (Beaufort scale 7, with white foam of breaking waves blown in streaks across the water surface). Sustained

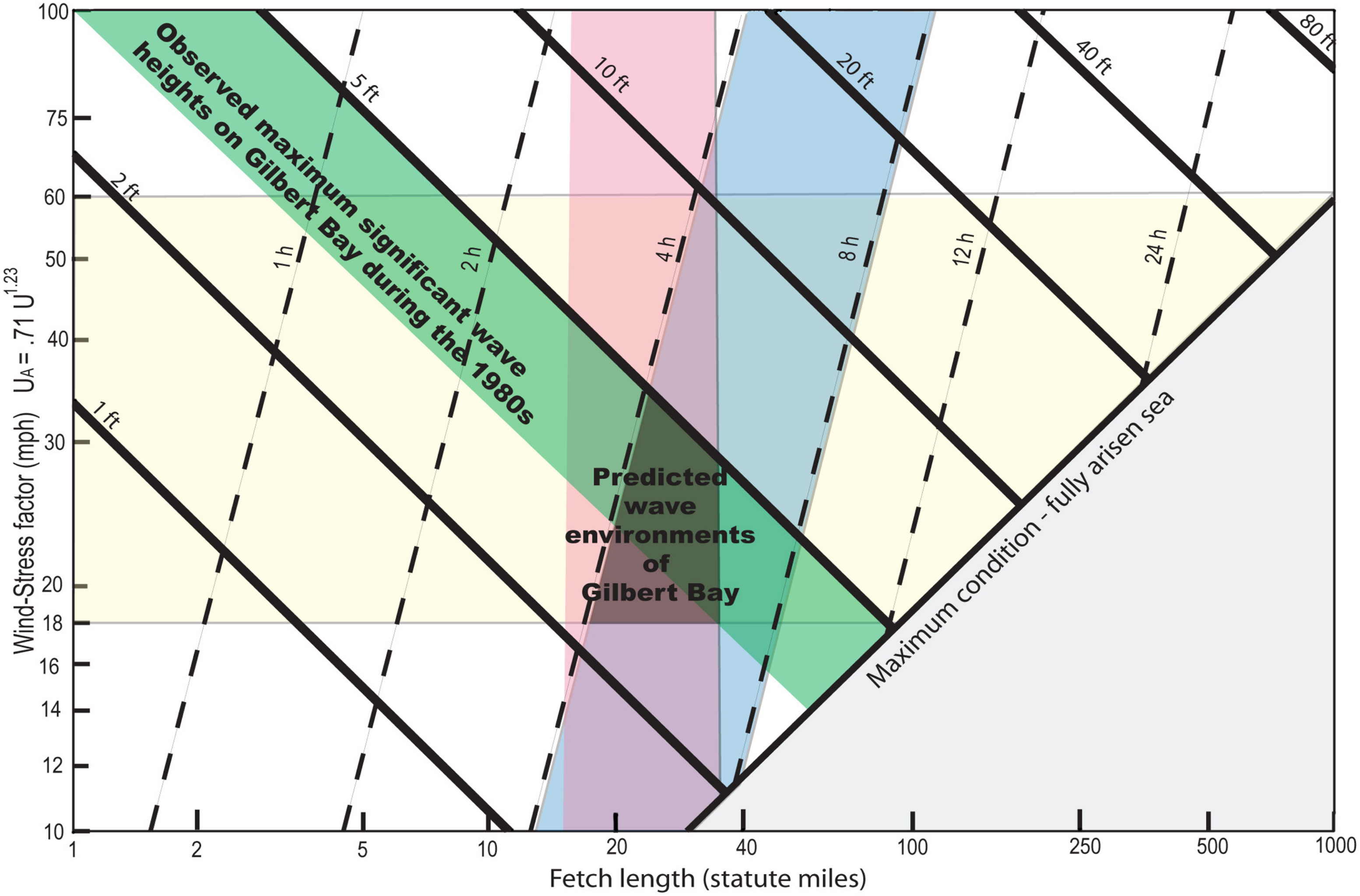


Figure 1.8. Nomograph illustrating wave environments of Great Salt Lake.
The nomograph shows wave environments, fetch, storm duration and wind strength. Source of base nomograph: USACE, 1984.

winds associated with near-gale conditions of 32-38 mph (14-17 m/sec) translate to wind stress values of 50-62 mph (23-28 m/sec). Duration of intense winds associated with synoptic low-pressure systems typical of major storms of 1986/87 rarely exceeds 6-8 hours before changing course or intensity (Alder, 1986, 1987, oral commun., 1998).

Although estimates of conditions of 1986/87 are highly generalized and are, in part, based on recollections of storm conditions by search and rescue personnel, they appear reasonable and are internally consistent. The intersection of the longest fetch and maximum expected wind stress falls within the range of observed significant wave height. The nomograph indicates that conditions associated with major storms across Great Salt Lake do not result in a fully arisen sea. Great Salt Lake is a fetch-limited lake. To achieve a fully arisen sea of 5.5 ft (1.7 m), storms of near-gale force persist for about 12 hours and generate waves across fetch of 100 mi (160 km). Such conditions are classified as a fetch-dominated (USACE, 2003).

Units

Data are presented in the metric units except elevation data that were collected or reported in feet. Unit conversions are in parentheses. USGS monitors still-water elevation of Great Salt Lake in units of ft a.s.l. with precision of 0.1 ft. Metric conversions of elevation are rounded to 0.1 m (0.33 ft). This understates precision of elevation data reported in metric units. However, rounding to 0.01 m (.03 ft) would overstate survey precision.

Field investigations on Antelope Island used 4200 ft (1280.2 m) a.s.l. as the reference datum for surveyed elevations. Comparisons of data sets and relative shoreline superelevation reference this datum. However, absolute shoreline superelevation is calculated using USGS-adjusted gaged elevation of 4211.6 ft (1283.7 m), the official highstand elevation of Great Salt Lake for the 1980s wet cycle

(Tibbetts and others, 2004). Unless otherwise indicated, geographic coordinates refer to Universal Transverse Mercator (UTM) projection, zone 12, North American Datum (NAD27). Elevation data are referenced to North American Vertical Datum 1929 (NGVD29).

CHAPTER 2

SHORELINE SUPERELEVATION ON ANTELOPE ISLAND

Elevations of 1986/87 inundation expressions of Great Salt Lake on Antelope Island were used to examine assumptions that undisturbed shoreline evidence is originally horizontal and represents still-water lake elevation with negligible, random deviations. In order to examine these assumptions it was necessary to obtain two sets of evidence: (1) magnitude of superelevation and (2) spatial distribution of superelevation.

Methods

Shoreline expressions of 1986/87 were identified and mapped, and their elevations were surveyed at 1228 point locations along the 64-km shoreline of Antelope Island. Two criteria, position and materials, define the 1986/87 inundation shoreline uniquely. The inundation expression of the 1986/87 shoreline of Great Salt Lake is the highest, inland shoreline expression that contains 20th-century anthropogenic debris. Higher, prehistoric, Holocene shorelines do not contain 20th-century anthropogenic debris, such as plastics, and modern lumber. Lower, younger shorelines that incorporate lumber, tires, and plastic can be distinguished from 1986/87 expressions by their lakeward position, but they generally are not easily distinguished from pre-1986 shoreline expressions.

Shoreline expressions of 1986/87 on Antelope Island include three types of debris: terrigenous, anthropogenic, and organic. Terrigenous debris is dominantly sand

and gravel derived from bedrock and surficial materials and cannot be unequivocally dated as 1986/87 debris. Anthropogenic debris and organic debris are diagnostic of 20th-century inundation. Anthropogenic debris incorporated in shoreline expressions is either material that floated and was carried onshore at the lake surface or entrained materials that sank as waves came onshore. Floated anthropogenic debris incorporated as shoreline evidence includes automobile tires, railroad ties, telephone poles, lumber, and plastics. Anthropogenic debris that did not float includes bowling balls, marbles, asphalt, concrete, and pottery. Organic debris ranges in size from brine fly pupae cases to tree trunks. Two types of organic debris were classified as part of field surveys: (1) locally derived organic debris, such as windrows of sagebrush twigs and disintegrated organic matter and (2) driftwood of tree limbs and tree trunks carried across the lake from mainland sources. In the year following the lake's highstand, floated organic material of abundant brine fly pupae cases formed almost continuous debris lines around the island demarcating the most inland extent of inundation. However, at the time of the elevation survey a decade after the lake's highstand, fire, erosion, and burial had destroyed much of the smaller organic evidence.

Surveyed locations were classified based on material type as (1) primarily flotsam, that is, materials that floated, (2) primarily bedload, which consists of materials that sank, or (3) a mixture of both. Floated anthropogenic debris was more easily identified and more abundant than bedload anthropogenic debris.

The possibility that expressions of 1860s-70s shorelines could be mistaken for 1986/87 shoreline evidence on Antelope Island was of concern. A reconnaissance survey in 1986 to identify evidence of the two shorelines concluded that elevations of 1860s-70s shoreline expressions along the east shore of Antelope Island were approximately equal to 1986 shoreline expressions (Mabey, 1986). If debris of the 1860s-70s had survived, wave action of 1986/87 would have incorporated it into

1986/87 shoreline expressions. Field procedures on Antelope Island also included searching for 1860s-70s evidence. At several places, for example, at Unicorn Point and along southwestern shorezones, reddish oxide coloration on coarse gravels distinguishes shoreline expressions interpreted to be from the 1860s-70s from those of 1986/87 shoreline expressions (Figure 2.1). No anthropogenic debris of the 1860s-70s, such as lumber with square nails, was positively identified along shorelines of Antelope Island. Managers of pre-1986 livestock operations on the island report that anthropogenic evidence of the 1860s-70s had virtually no chance of surviving fires that have burned off most of the island's vegetation and shore debris (T. Smith, oral commun., 1998; W. Olwell, oral commun., 1998; M. Harward, oral commun., 2000).

Elevation Field Survey

The elevation survey was initially designed to compare elevations of shoreline evidence at eight geomorphically significant areas around Antelope Island. Field techniques were tested on the north part of the island in 1996, and, based on this field experience, the spot-checking approach was abandoned in favor of surveying elevations of the inundation shoreline expression around the entire island. Even after a decade of exposure, most of the 1986/87 inundation shoreline expression could be identified. Shoreline expressions of approximately 59 of the 64 kilometers of shoreline were surveyed (Figure 2.2).

Surveyed elevations were recorded in a digital data logger in the field with northing, easting, and elevation measured from the survey instrument station. Geographic coordinates of instrument stations were determined using GPS data loggers. Surveyed elevation data were downloaded into spreadsheets and geographic coordinates calculated from GPS-gathered geographic coordinates in spreadsheets. Elevations were measured in tenths of a foot. Distance and location were measured in

(a)

(b)

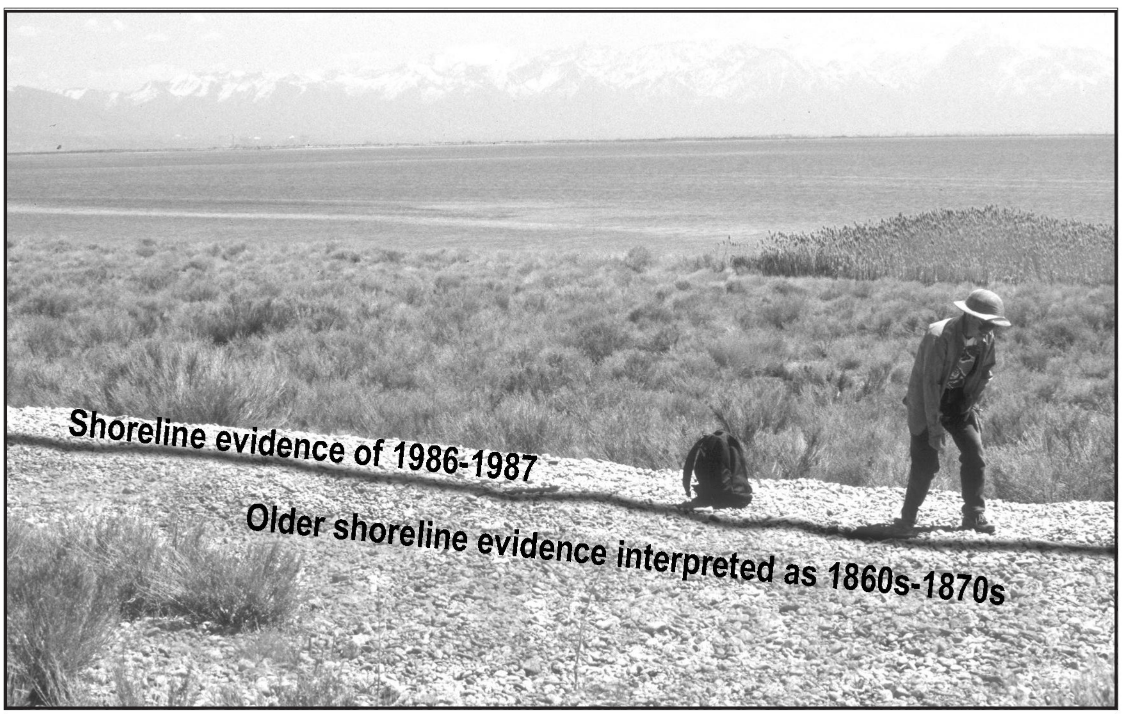


Figure 2.1. Evidence of 1860s-70s highstand.
Marjorie Chan stands on light-colored gravel deposits of 1986/87 and examines evidence of older beach deposits at virtually the same elevation. However the older deposits are stained faintly rust-colored (foreground). Note piece of 1986/87 floated debris at center of photo to left of pack. Contrast of image (b) has been enhanced.

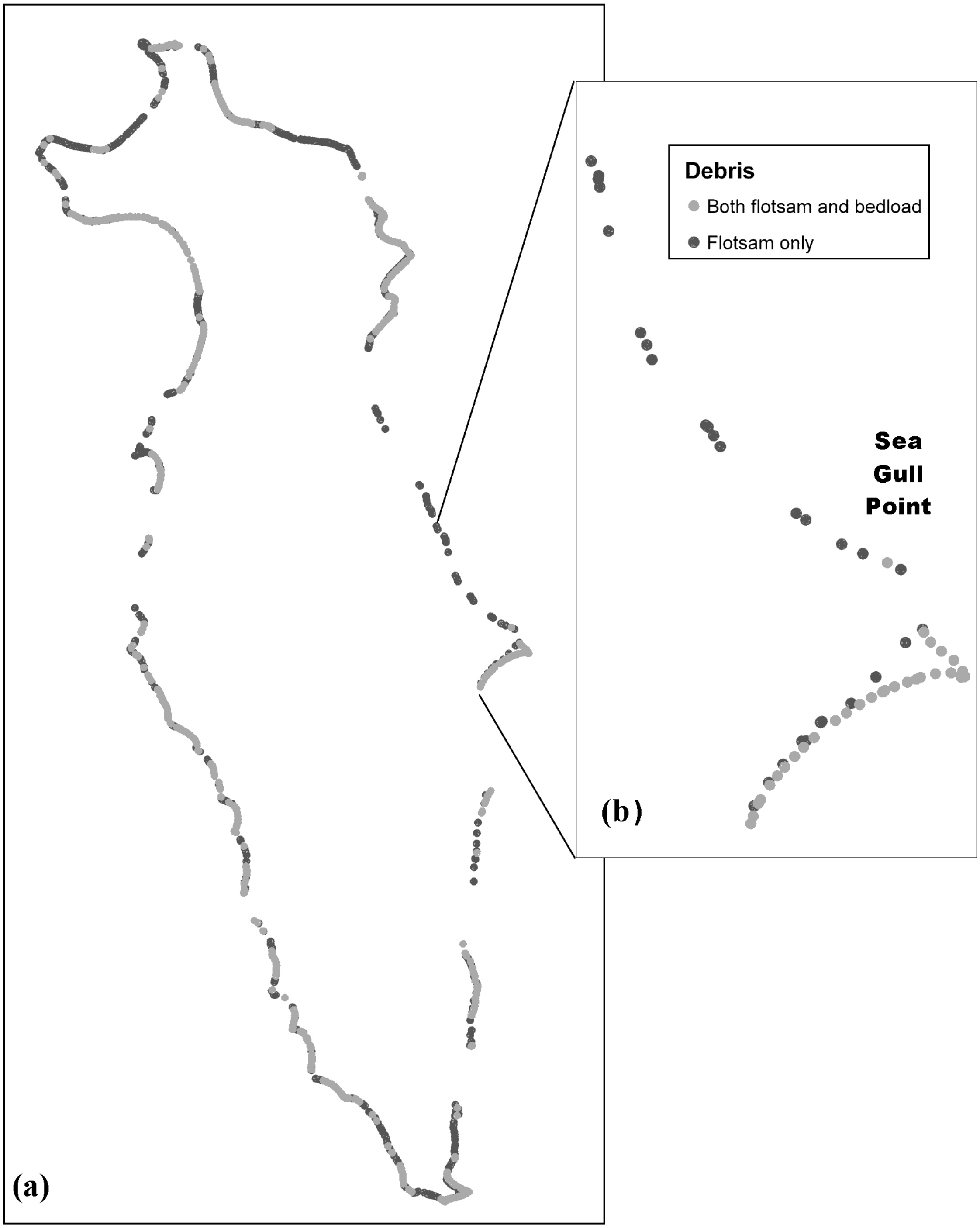


Figure 2.2. Surveyed locations of 1986/87 shoreline expressions.
Map (a) shows locations of 1228 surveyed locations. Map (b) shows a detail of the east side of the island including Sea Gull Point. Locations are displayed in geographic coordinates and colored to indicate the dominant type of debris at each surveyed location.

meters from the survey instrument and later located in geographic space based on the geographic location of the survey instrument station.

Each of the 1228 surveyed locations is on the highest or most inland shoreline expressions with evidence of 1986/87 floated anthropogenic debris. Approximately 200 of the 1228 survey points are locations where more than one shoreline expression was surveyed. For example, more than one expression was surveyed for lagoons with floated debris along their backshore and gravel ridges as their barrier beach (Figure 2.3).

Accuracy of Elevation Data

The accuracy of the elevation data depends upon (1) the precision of surveying equipment, (2) the skill of the rodperson in selecting and occupying representative shoreline locations, and (3) the accuracy and consistency of vertical control. High-precision total station surveying equipment was used to survey the shoreline (Sokkia Technology Inc, 1994). Locations used for survey control were reoccupied to test internal consistency, and elevations at reoccupied locations were dependable within 0.1 ft (0.03 m).

Efforts were taken to increase skill and consistency in selecting representative locations to survey. Field techniques were tested over two field seasons, 1996 and 1997, before the 1998 elevation survey. Because some shoreline expressions are more variable than others, more locations were surveyed along highly variable shorelines than along smooth, uninterrupted expressions. Where evidence was intermittent, fewer locations could be surveyed. Where shorezone stretches consisted of more than one active shoreline expression, more than one location was surveyed. Some overlapping shorezone stretches were resurveyed for redundancy.

Distance between surveyed point locations averages about 50 m. However,

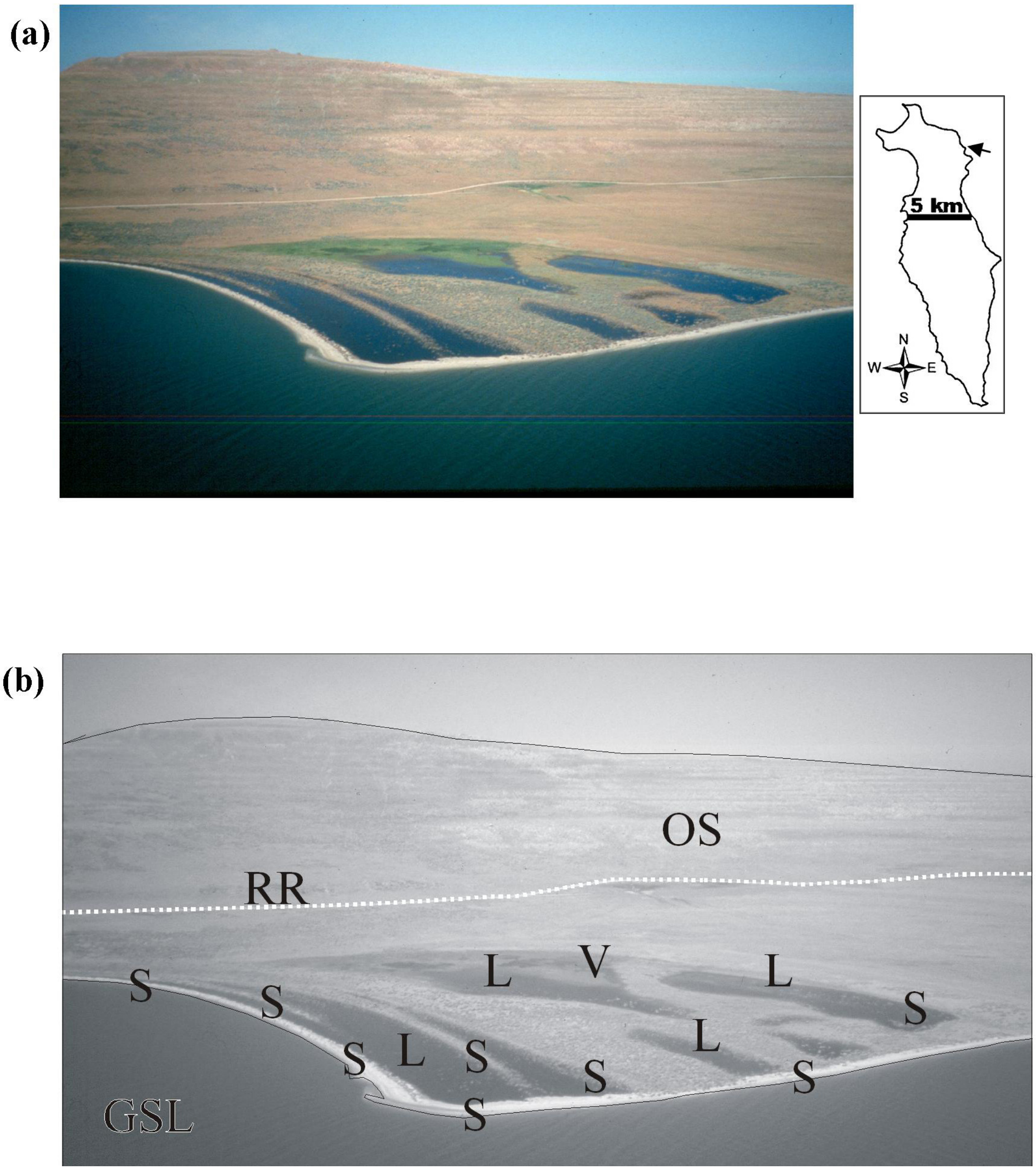


Figure 2.3. Multiple shoreline expressions of a complex shorezone.
Photograph (a) taken June 1986 shows multiple expressions of the shoreline at Tin Lambing Shed on the east side of Antelope Island. The photograph was taken within a week of the June 3, 1986, official lake historic highstand. Annotated photograph (b) indicates the highstand still-water lake elevation with a thin black line. Shoreline expressions (S) of 1986 are above the highstand still-water lake elevation. The shorezone includes the beach face (underwater in this photograph), lagoons (L), and vegetation changes (V). In the background, are older shorelines (OS) of Lake Bonneville, and the road to the ranch house (RR).

distance between surveyed locations exceeds 0.5 km for 13 shorezone stretches. These data gaps are not random. They represent shorezones where evidence was not left in 1986/87, where it is no longer identifiable by anthropogenic debris, or where it has been altered by ground failure, buried by wind-blown sand, obscured by vegetation, destroyed by fire, or disturbed by human projects. Data gaps along bedrock shores include shoreline stretches where evidence was swept clean during 1986/87. These inundation expressions probably had high shoreline superelevation based on observations in 1986-1989 of debris stranded on bedrock headlands. Other data gaps represent shores where fire has destroyed evidence. Such shores have sufficient soil to support grasses that burn. Locations along these shores probably would have intermediate or low shoreline superelevation and would have had sufficient debris, including windrows of brine fly pupae cases to have been surveyed in 1988. These missing elevations are a loss to the Antelope Island data set for purposes of examining associations of inundation elevations and shore processes.

The relative skill and the field procedures used by the rodperson are sources of potential error. Some shoreline expressions are clearly demarcated by a line of debris. Others are complex, such as at Tin Lambing Shed (Figure 2.3). The rodperson exercises judgment when choosing locations representative of the farthest inland and highest shoreline evidence. If the survey were repeated or if another survey team were to choose different locations to survey, elevations and results would differ due to the variable character of deposited debris. However, the 1998 survey was sufficiently detailed that general island-scale patterns would not be changed by additional surveyed locations. Vertical accuracy, including human and instrument error, of elevation data of the Antelope Island data set is estimated as ± 0.3 ft (0.1 m).

Surveyed locations along shoreline expressions of Antelope Island are internally consistent. Vertical control on Antelope Island was established using three redundant datums: surveyed control along the east side of the island established by Davis County, lake elevation monitoring by USGS, and photographic documentation of 1986 shorelines. Most surveyed stretches were tied at surveyed turning points common to two surveyed stretches.

Although surveyed elevations of the Antelope Island data set are internally consistent, their tie to vertical control of the USGS Gilbert Bay boat harbor gage is not straightforward. Vertical control is a major challenge to accurate surveying in the basins of the Basin and Range and a challenge to monitoring levels of Great Salt Lake (Loving, 2002). Inconsistencies result from several causes. First-order survey lines are less dense in Utah than in coastal states. Basin materials have inherent problems with instability. Road crews have destroyed many benchmarks. Natural conditions destroy others, such as burial by sediments during lake flooding and corrosion by highly saline sediments. Advances in GPS technology will make survey control less of a challenge for future researchers, but GPS equipment with vertical accuracy to 0.1 ft was not an option for the 1998 Antelope Island elevation survey.

The Antelope Island data set used 1998 USGS-monitored, unadjusted, real-time lake-level data of the boat harbor gage as vertical control for field work. The boat harbor gage was relocated in 1985 due to flooding, in 1989 due to subsidence, and in 2003 to its present location as part of an equipment upgrade. The USGS has adjusted the boat harbor lake-level data sets four times between 1983 and 2001 to compensate for unstable ground, changes of benchmark control, equipment relocation, to account for discrepancies in lake level between Gilbert and Gunnison Bays, and to recalculate previous adjustments (Loving, 2002). The Antelope Island data set vertical datum based on 1998 USGS monitoring is consistent with Davis County survey control to the island. Photographs of places along Antelope Island's east shore were taken as part of a helicopter survey of lake flooding in June 1986, within a week of the official highstand of the lake. These photographs document still-water lake level along the east side of the island that is consistent with Davis County survey control.

Relative shoreline superelevation of Antelope Island shoreline expressions is the difference in elevation among locations surveyed on the 1986/87 inundation shoreline expressions, in contrast to absolute shoreline superelevation referenced to a still-water lake-level datum tied to sea level. This dissertation uses 4211.6 ft (1283.7 m) a.s.l., the USGS official, adjusted, highstand elevation for Gilbert Bay (Tibbetts and others, 2004; U.S.G.S., 2004a, 2004b) as still-water lake elevation for calculations of absolute shoreline superelevation. Relative shoreline superelevation is internally consistent and unaffected by adjustments of still-water lake elevation ties to sea level, such as those that have adjusted survey control of USGS lake gages.

Antelope Island Data Set

Data gathered in the elevation survey were exported into a GIS database with their geographic coordinates (Figure 2.4). Then a generalized shore-route was digitized and linearly referenced much like the measured route of a highway (Figure 2.5). Surveyed locations were projected onto the shore-route. Thus, every surveyed location has UTM coordinates of geographic space and location along the shore-route calculated as distance in meters, clockwise from Ladyfinger Point (Atwood and Cova, 2000). The shorezone was divided into its contrasting west and east sides and into 12 shorezone regions in order to examine spatial patterns (Figure 2.6). Two prominent features are the breaks between the west and east portions of the shoreline: Ladyfinger Point and Unicorn Point. Boundaries of the 12 shorezone regions are based on headlands or breaks in shoreline curvature that divide the shore-route into 12 segments of approximately equal length that share similar coastal exposures.

Patterns of shoreline superelevation were examined using GIS displays.

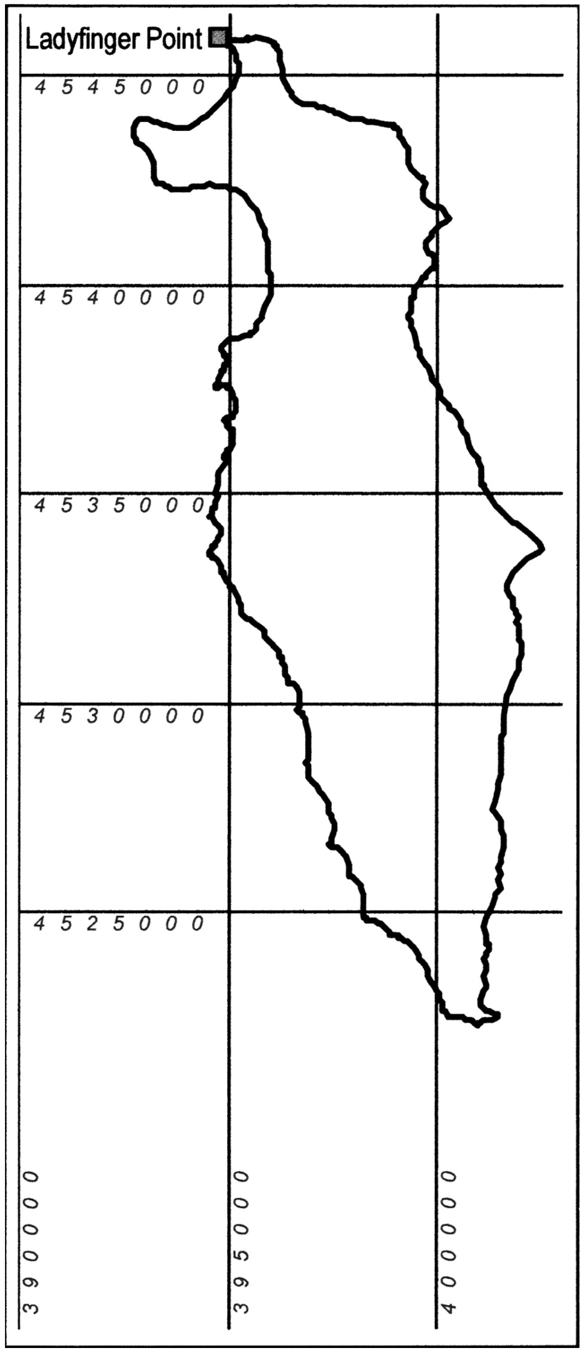


Figure 2.4. Location in geographic space.
Shorezone data are referenced to geographic coordinates using the Universal Transverse Mercator longitude and latitude grid. For example, the location at Ladyfinger Point is UTM zone 12 North: easting = 394,775, and northing = 4,545,913.

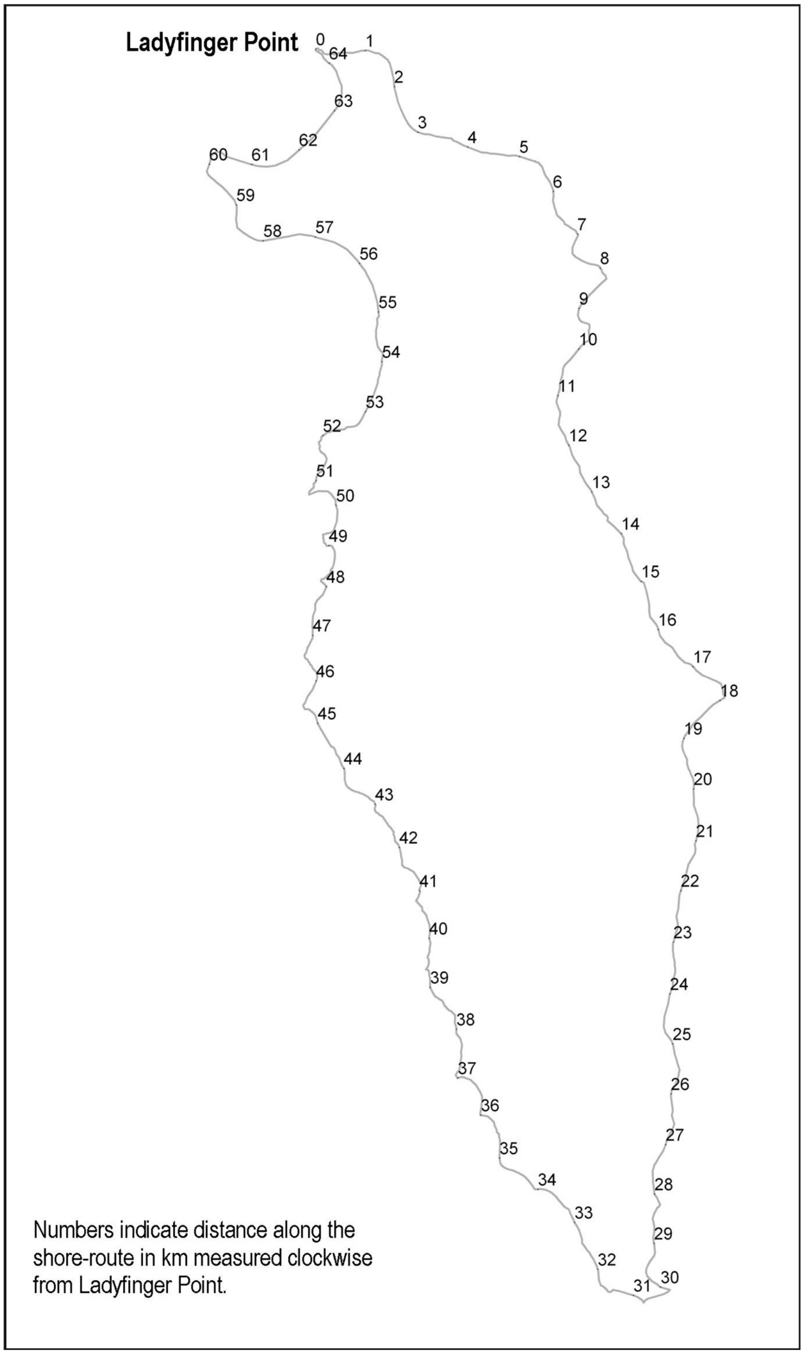


Figure 2.5. Location along the linearly referenced shore-route.
Shorezone data are referenced to a hypothetical, digitized shore-route around the island. Ladyfinger Point is the beginning and end of the route with location referenced to the shore-route of 0 m and 64,385 m.

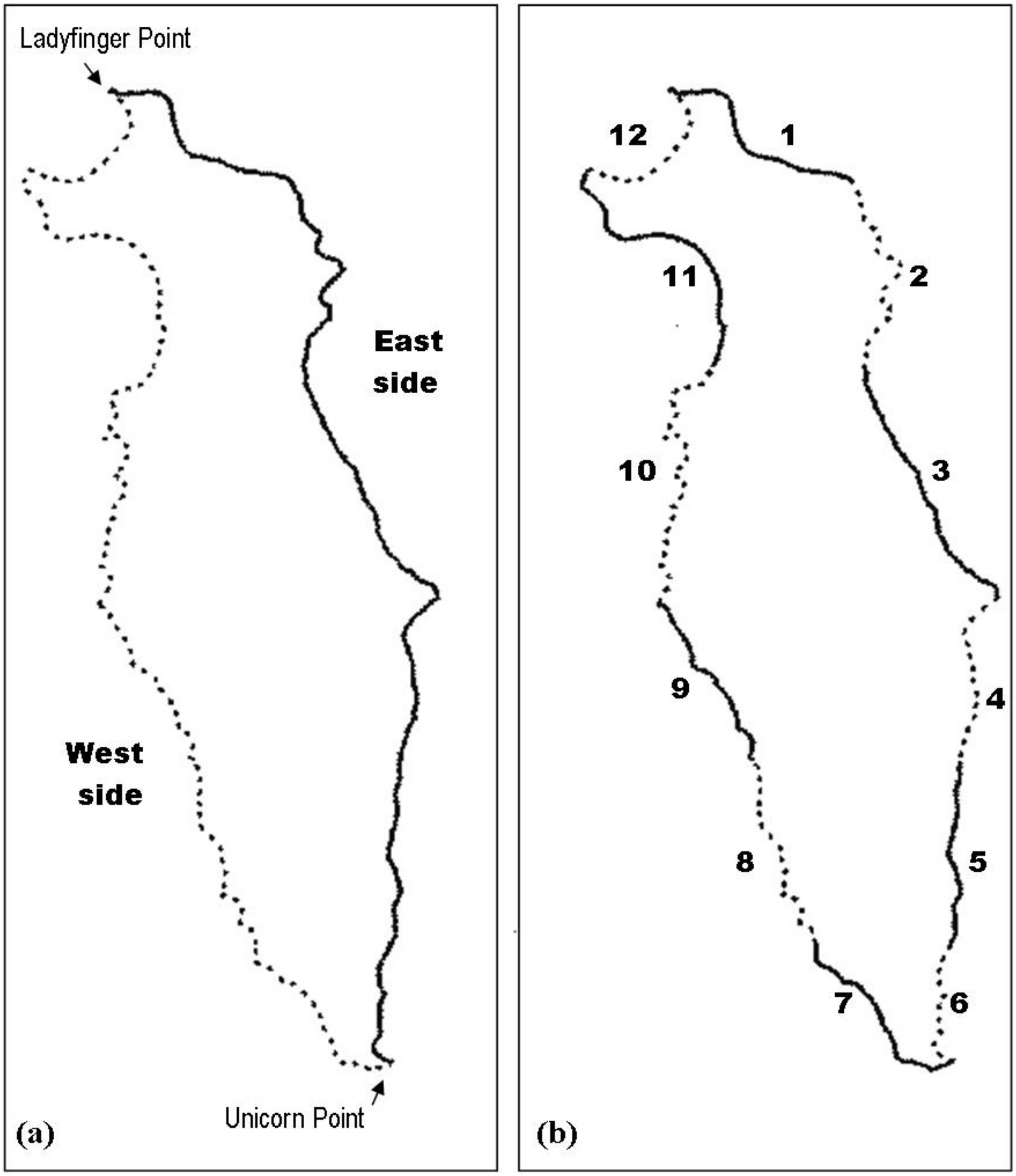


Figure 2.6. Shoreline regions.
Map (a) shows west versus east sides of the island. The endpoints for the west-east segments are Ladyfinger Point at the north and Unicorn Point at the south. Map (b) shows 12 regions of the shoreline, numbered clockwise from Ladyfinger Point. The endpoints for the 12 regions were chosen to have comparable length and are bounded by prominent geomorphic features such a headland or spit.

Shoreline superelevation was examined against location using scatterplots and box plots. Data were displayed using equal intervals and quantiles. Superelevation data were divided into three classes: high, medium, and low (Figure 2.7). Shoreline superelevation greater than 3.4 ft (1 m) includes elevations ≥ 4215 ft (1284.7 m) a.s.l. was classified as high, and includes approximately one-third of the surveyed elevations (400 of 1228). Approximately one-third, 414 of 1228, of the surveyed elevations have less than 2.2 ft (0.7 m) superelevation, meaning < 4213.8 ft (1284.4 m) a.s.l., and are classified as low. The remaining intermediate values between 4213.8-4215 ft (1284.4-1284.7 m) a.s.l. include about one-third of the values (414 of 1228).

The linearity of the shoreline provided opportunities to use GIS techniques to examine the data visually as locations along a line and as locations in traditional geographic space (Atwood and Mabey, 2002; Atwood, 2003, 2004). Findings of Antelope Island research are not based on statistical analysis. Field work data collection did not attempt to capture a minimum or maximum number of samples for every elevation or for all shore stretches. Spacing between elevation locations is not random and results from choosing representative locations on well-exposed shoreline expressions chosen to map trends of elevation change.

The Antelope Island data set was examined for potential error, specifically for errors of position, errors of attribute values, errors of logic and consistency, and errors of completeness. Potential errors of position and location include errors of location in geographic space and errors of position in linearly referenced space. The approach to recognition and correction of errors of location in geographic space was redundancy of data collection and redundancy of data display. Location in geographic space was checked by displaying data sets across digitized aerial photographs and digitized USGS topographic maps, 1:24,000 scale, NAD27 as ground truth. Surveyed positions were measured as distance from survey instrument stations. The location of the instrument

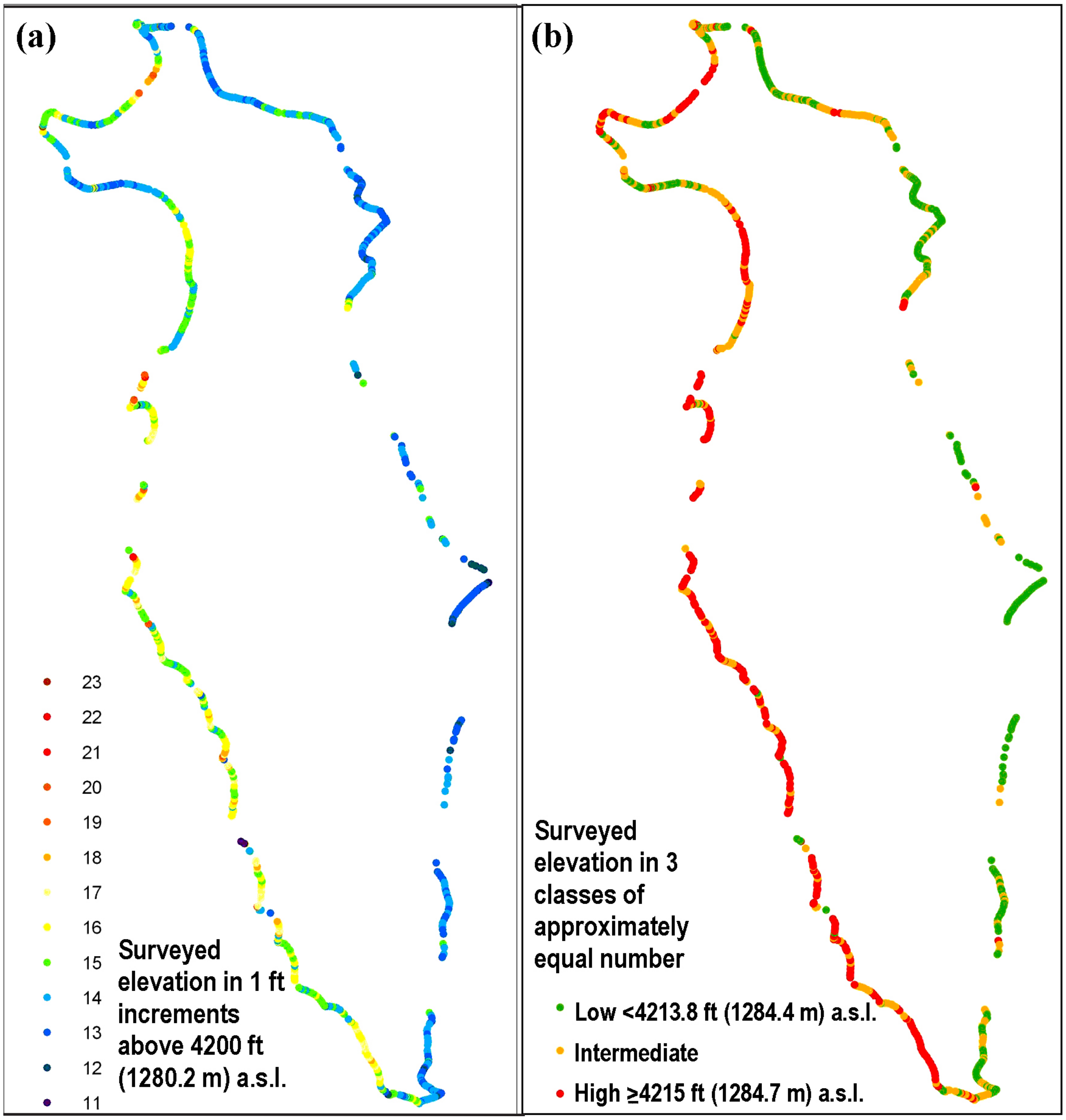


Figure 2.7. Superelevation of shoreline evidence of Antelope Island.
Map (a) displays surveyed elevations of expressions of the 1986/87 shoreline on Antelope Island in 1-ft (0.3-m) increments using the 4200 ft (1280.2 m) a.s.l. datum of the field survey. Map (b) displays the data in three classes: high, intermediate, and low. Values also are in feet above 4200 ft (1280.2 m) a.s.l. Shoreline superelevation is the difference in elevation between surveyed elevations and 4211.6 ft (1283.7 m), the lake's 1986/87 highstand still-water elevation. High superelevation is superelevation equal to or greater than 3.4 ft (1 m). Low superelevation is superelevation less than 2.2 ft (0.7 m). The classification breaks of (a) are equal increment, and of (b) are approximately equal populations. Each of the three classes of (b) that represent high, intermediate, and low shoreline superelevation consists of approximately 400 surveyed elevations.

station and trend of the route of the survey were checked against differentially corrected GPS-collected locations.

Potential errors of position and location also include potential error along the linearly referenced shore-route. The shore-route is the hypothetical shoreline digitized to represent the 1986/87 shoreline (Figure 2.8). Some shore-route locations may be as much as 50 m from their location in geographic space. This magnitude of horizontal survey uncertainty appears acceptable for purposes of this research, to document and analyze island-scale patterns. For analysis of an individual bay, data display in geographic coordinates provides more accurate spatial display of data points than location along the digitized shore-route.

Potential errors of assigned attribute values include possibilities of inaccurate field identification and inaccurate data entry. The Antelope Island data set was collected on the assumption that it would be used at a relatively coarse scale to examine contrasts at island-scale not at the scale of individual bays. Shorezones of individual bays incorporate considerable variability of materials and physical characteristics, such as roughness (Komar, 1998). The approach to inaccurate classification and inaccurate data entry was redundancy and abundant data collection.

Potential errors of consistency are of concern because, as field work progressed, skills evolved in distinguishing shorezone characteristics. The 2-year process of extensive testing of data collection techniques, criteria, and procedures reduced this potential source of error, but it was not eliminated. For example, shoreline expressions with highest superelevation values likely result from high-energy wave action and surveyed elevations accurately describe them. However the lowest values of superelevation are on shoreline expressions formed by low-energy waves that did not transport abundant debris and construct extensive features. For these reasons, surveyed values of very low shoreline expressions may be inaccurately low.

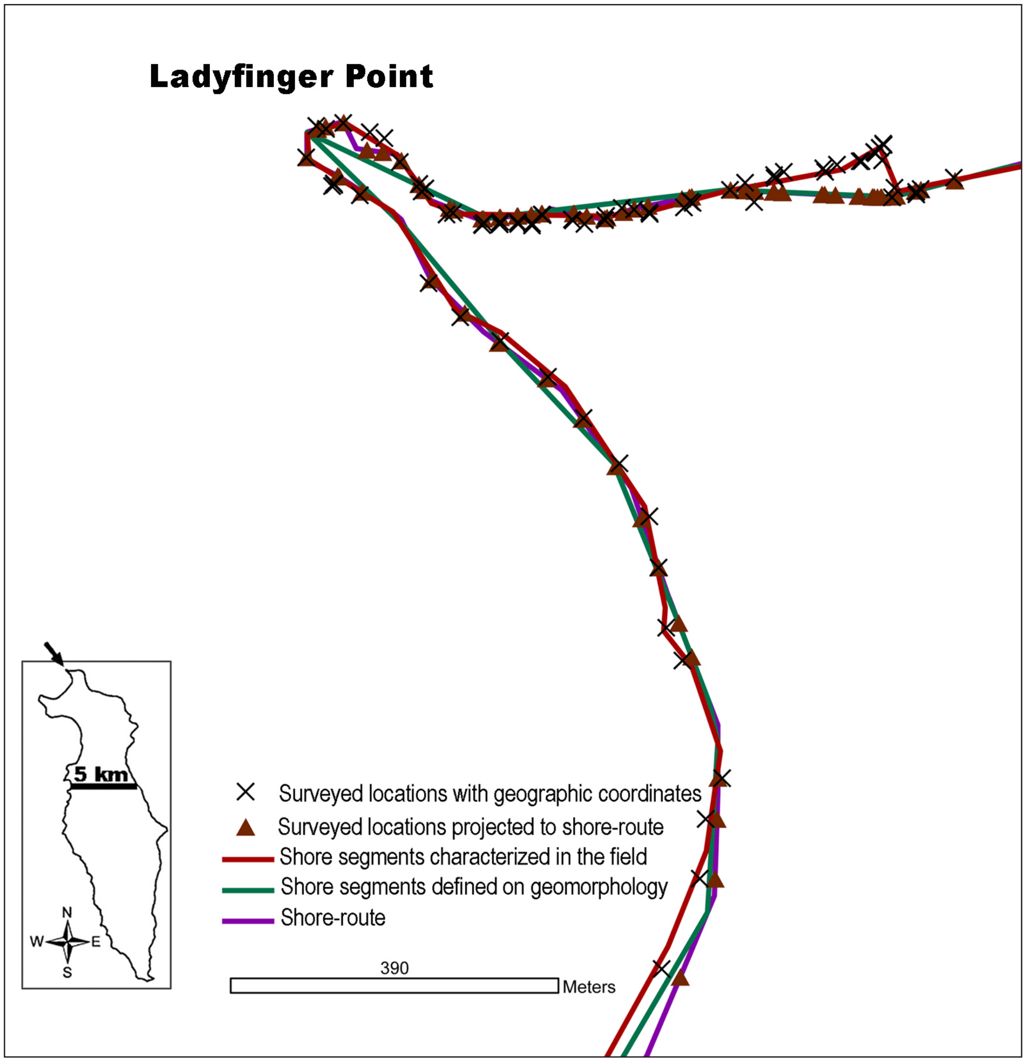


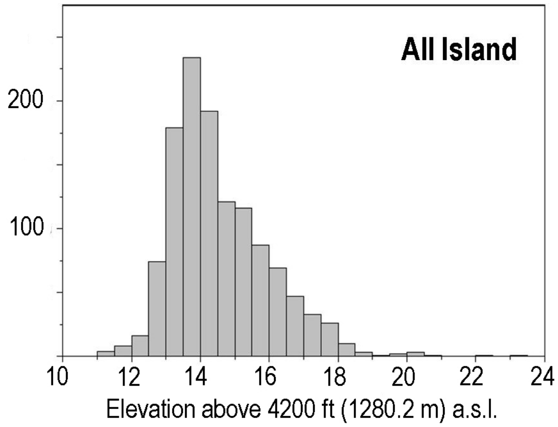
Figure 2.8. One shore-route represents several definitions of shore segments.
A shorezone is a corridor not a single, well-defined line. The shore-route is the digitized line to which spatial information collected for shores of Antelope Island was projected. For example, in this image, point locations of surveyed elevations are shown in geographic space as crosses. Their locations projected onto the shore-route are shown as triangles. Shore segments characterized in field investigations of 1998 were attributed as line features using GPS data loggers. Attribute values of these shore segments also were projected to the shore-route. Geomorphic characteristics, such as aspect and fetch, were defined for shore segments based on logical geomorphic breaks, such as headlands or bays. Attribute values of the geomorphically defined shore segments also were projected to the shore-route.

Potential errors of completeness include gaps in the survey because evidence had been destroyed in the decade between 1986/87 and field work of 1996-1998. Gaps introduce a bias against poorly demarcated shore stretches. For example, range fires burn high flotsam caught in dry-grass-vegetated areas of flammable brush. By necessity, surveyed debris was the remaining, furthest inland, highest wave-carried debris that still existed in 1998, that was identified, and that was considered representative. In burned areas, care was taken to find the remaining portions of railroad ties or nonflammable debris that demarcated farthest, inland inundation. Photographs and field notes provide redundant documentation of shorezone characteristics.

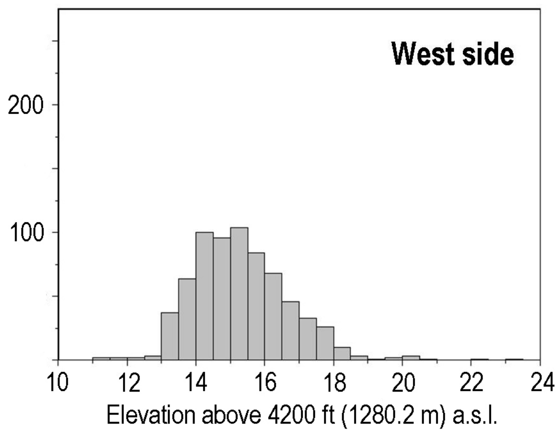
In spite of these identified concerns, the Antelope Island surveyed-elevation data set is large, near-complete, and quantifies shoreline superelevation and its variability around the island. The data set presents a representative picture of the magnitude and distribution of superelevation but is not intended to be statistically robust.

Results and Discussion

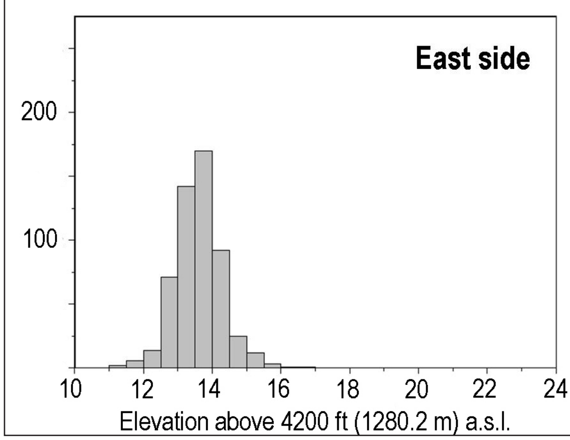
Shoreline superelevation could be determined in 1998 for more than 90 percent of the 1986/87 shoreline, although evidence was not as abundant and uninterrupted as in 1987, immediately after the highstand. For the island as a whole, elevations on the inundation shoreline range from 4211.1 ft (1283.5 m) a.s.l. to 4223.4 ft (1287.3 m) a.s.l. (Figure 2.9). The median value of elevations is 4214.2 ft (1284.6 m) a.s.l. and the mean value is 4214.5 ft (1284.6 m) a.s.l. Using a still-water lake level of 4211.6 ft (1283.7 m) a.s.l., absolute shoreline superelevation ranges from elevations slightly below still-water lake elevation to wave-tossed debris almost 12 ft (3.6 m) above still-water lake elevation. Absolute shoreline superelevation averages 2.9 ft (0.9 m) above



Summary	All Island
Minimum	11.1
1st Quartile	13.5
Mean	14.5
Median	14.2
3rd Quartile	15.3
Maximum	23.4
Surveyed locations	1228



Summary	West Side
Minimum	11.2
1st Quartile	14.3
Mean	15.3
Median	15.1
3rd Quartile	16.1
Maximum	23.4
Surveyed locations	689



Summary	East
Minimum	11.1
1st Quartile	13.2
Mean	13.6
Median	13.5
3rd Quartile	13.9
Maximum	16.7
Surveyed locations	539

Figure 2.9. Magnitude and frequency distribution of 1228 surveyed elevations. Units are in feet above 4200 ft (1280.2 m) a.s.l. Bar intervals are 1 ft (0.3 m). Elevations of 1986/87 inundation shoreline expressions on the west side of the island are generally higher and more variable than those on the east. The range of relative shoreline superelevation is 12.3 ft (3.7 m), from a low of 4211.1 ft (1283.5 m) a.s.l. to 4223.4 ft (1287.3 m) a.s.l. Quartile breaks are used in box and whisker plots, such as Figure 2.10.

still-water lake elevation for the island as a whole. One-third of the surveyed shoreline expressions have elevations greater than 3.4 ft (1 m) above still-water lake elevation (Appendix A).

Shoreline Superelevation Patterns

Shoreline superelevation of 1986/87 shoreline expressions on Antelope Island is not spatially random. It has geographic patterns when studied as west-versus-east contrasts and as progressive changes along 12 contiguous shore regions (Figure 2.10). Although the data plots are not smooth, general patterns are evident even when all data are plotted in a single scatterplot or three-dimensional (3-D) display (Figure 2.11).

The west-east contrasts of superelevation are striking (Figures 2.7, 2.9, 2.10, and 2.11). In general, the 1986/87 shoreline of Great Salt Lake on Antelope Island is higher on the west side of the island than on the east side. The mean value of surveyed elevations on the west side of the island is 1.7 ft (0.5 m) higher than those of the east side. Surveyed elevations of shoreline expressions of the west side of the island are, on average, 3.7 ft (1.1 m) above still-water lake elevation, whereas those of the east side are, on average, 2 ft (0.6 m) above still-water lake elevation. Variability of shoreline superelevation also has west-east geographic contrast (Figures 2.9 and 2.11). Greater variability is associated with west-side superelevation. Although both sides of the island have extreme low values below still-water lake level, the east side does not have extreme high values of superelevation (Figure 2.10). The spread of values is greater on the west side (Figure 2.9) and the middle 50 percent of values, the interquartile range, has greater spread for the west side (Figure 2.10). The east side values have a high peak at their center in contrast to the broad peak of the values for the west side (Figure 2.9). West-side superelevation data are skewed toward higher values, and east side superelevation data are skewed toward lower values (Figure 2.9).

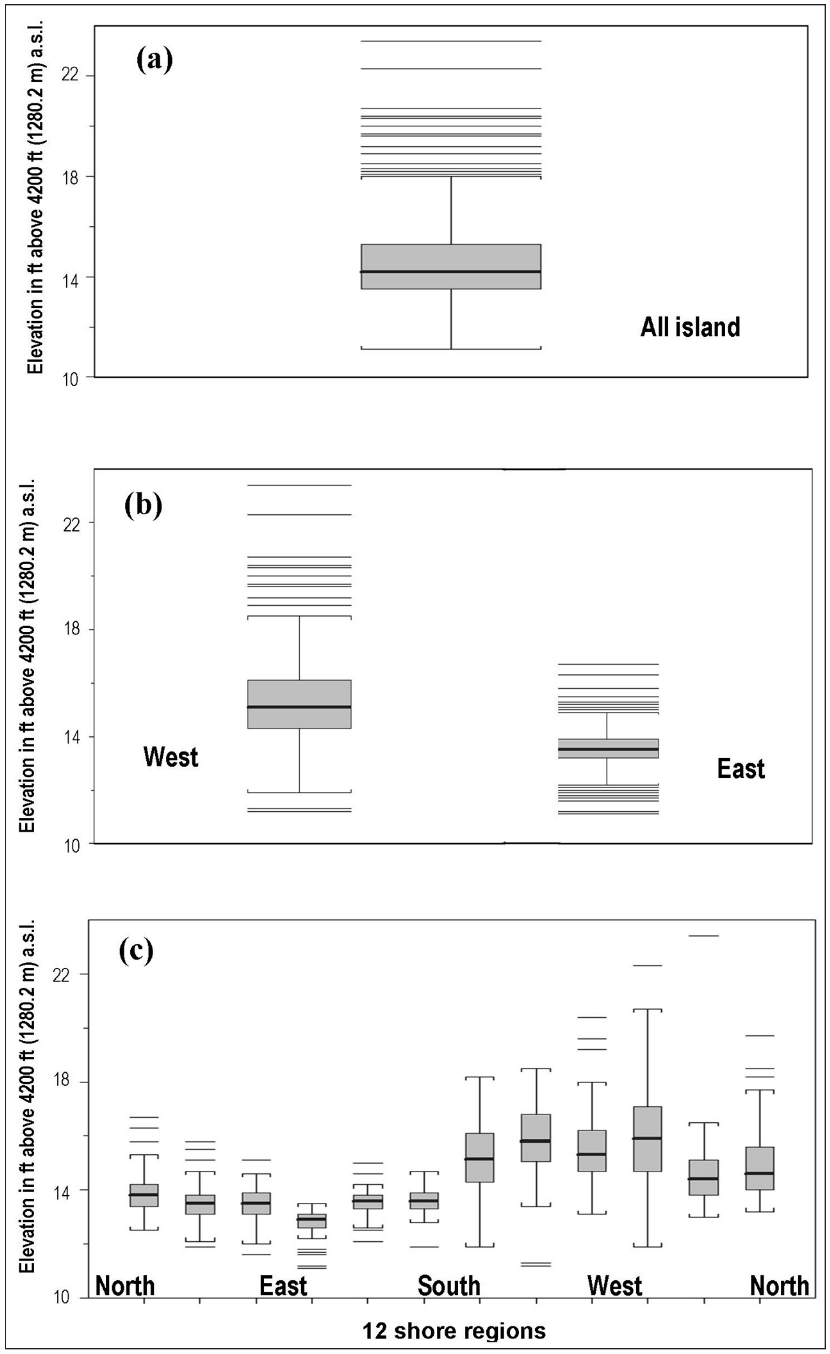


Figure 2.10. Box and whisker plots of shoreline superelevation.
Plot (a) shows data for entire island, (b) shows data split into west and east subsets, and (c) shows data split into the 12 regions of Figure 2.6. Box and whisker plots of this dissertation use a solid line to represent the median value, a shaded box to identify the interquartile range of upper and lower quartiles, whiskers that extend to values within 1.5 times the interquartile range, and lines to represent values outside the whiskers.

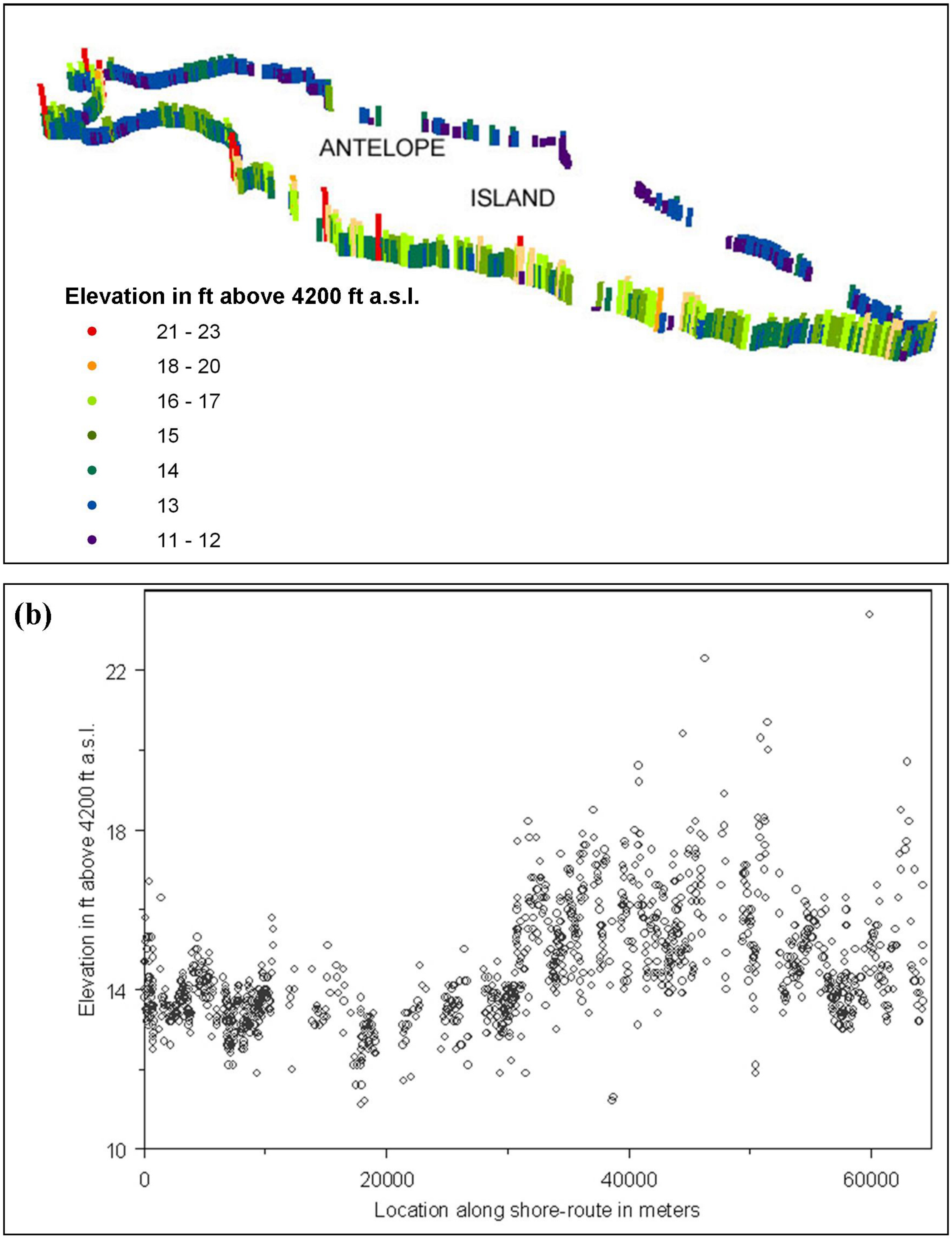


Figure 2.11. Island-scale patterns of shoreline superelevation.
In the upper diagram (a) superelevation data are displayed in 3-D. View is across the island toward the northeast. Surveyed elevations are represented by contrasting hues and as relative height of columns. In diagram (b) data are displayed as a scatterplot. Shoreline superelevation has less scatter along the east side of the island (locations from 0 to 30,183 along the shore-route) than along the west side (from 30,184 to 64,385).

The island's shoreline was divided into 12 regions as a way to analyze the Antelope Island data set at a finer scale than west-side versus east-side contrasts and at a coarser scale than by individual bays (Figures 2.6 and 2.10). Clockwise from Ladyfinger Point, the median value of shoreline superelevation decreases for four regions toward the Ranch House (region 4). Then, continuing clockwise around the shore, superelevation increases unevenly to its highest values along region 10, the rocky headland and pocket beaches north of Cambria Point to Elephant Head. Regions 11 and 12, White Rock Bay, Buffalo Point, and Bridger Bay, have intermediate values and complete the path. Box and whisker plots indicate that the spread of values, the interquartile range, is consistently wider for western regions of the shore than for regions on the east side (Figure 2.10)

Patterns are also evident when the data are shown as values along some bays and headlands (Figure 2.11). For example, Bridger Bay at the north part of the island has elevation differences of > 7 ft (> 2 m) increasing toward the back part of the bay (Figure 2.12). Along the southwest side of the island, such as Curlew Bay, shoreline superelevation increases by over 4 ft (1.2 m) from north to south (Figure 2.12). However, some bays show little variation. For example, long shore stretches of much of the east side of the island have consistently low shoreline superelevation (Figure 2.7). Contrasts of shoreline superelevation patterns were evident across some headlands. Perhaps the most dramatic contrast is at Unicorn Point where a higher, southwest-facing gravel ridge of 1986/87 is juxtaposed against a lower, southeast-facing gravel ridge (Figure 2.13).

Implications of Superelevation

The contrast of high shoreline superelevation on the west side of the island versus low superelevation on the east contradicts the first three statements of Table

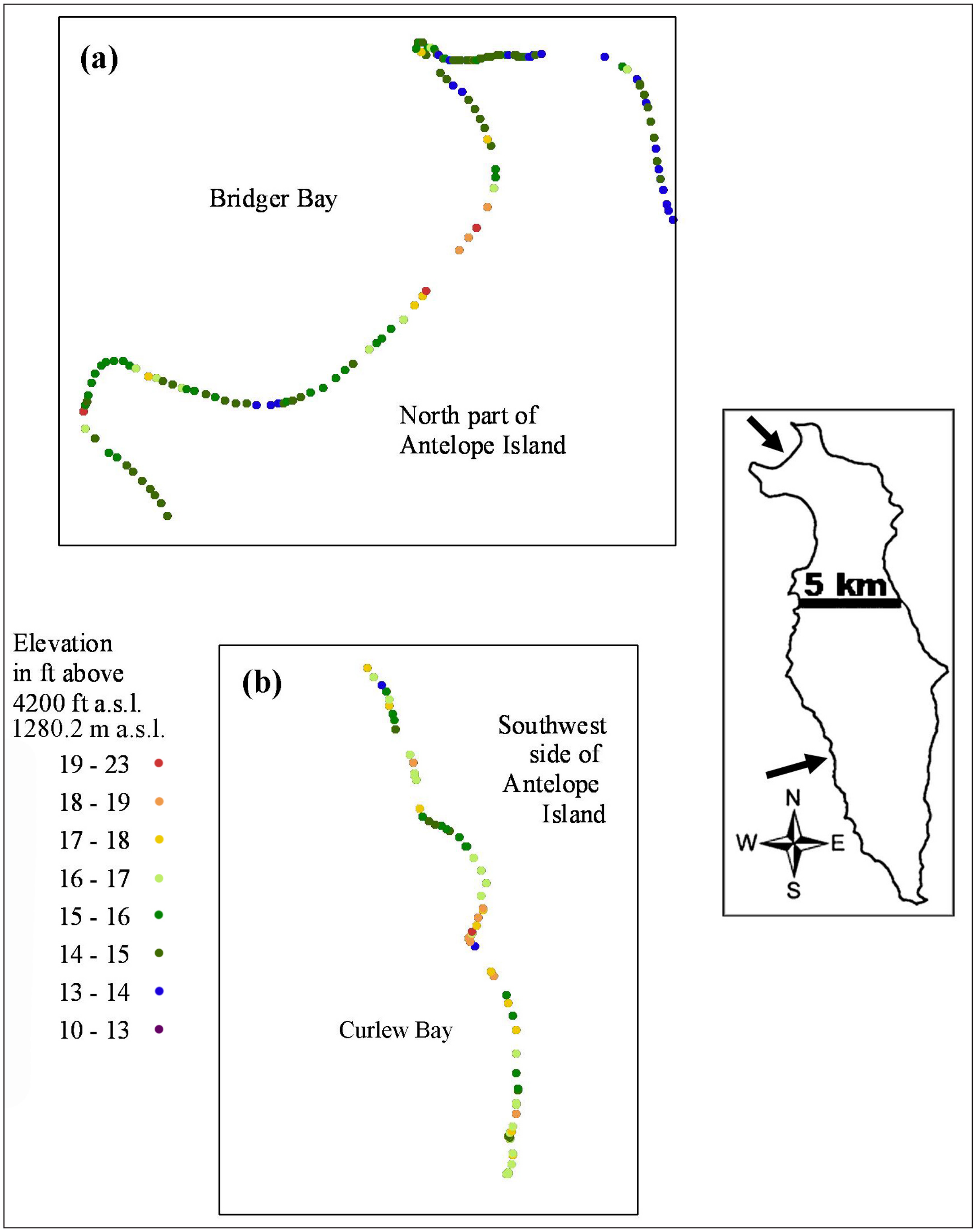


Figure 2.12. Bay-scale patterns of shoreline superelevation.
Map (a) shows shoreline superelevation along Bridger Bay at the north of the island. For Bridger Bay, shoreline superelevation increases inland from the headlands toward the back of the bay. Elevations range from 4213.3 ft (1284.2 m) a.s.l. to 4219.7 ft (1286.2 m) a.s.l. Map (b) shows superelevation of shoreline expressions along Curlew Bay, on the west side of the island. Shoreline superelevation increases toward the southern headland. Elevations range from 4214.3 ft (1284.5 m) a.s.l. to 4219.6 ft (1286.1 m) a.s.l.

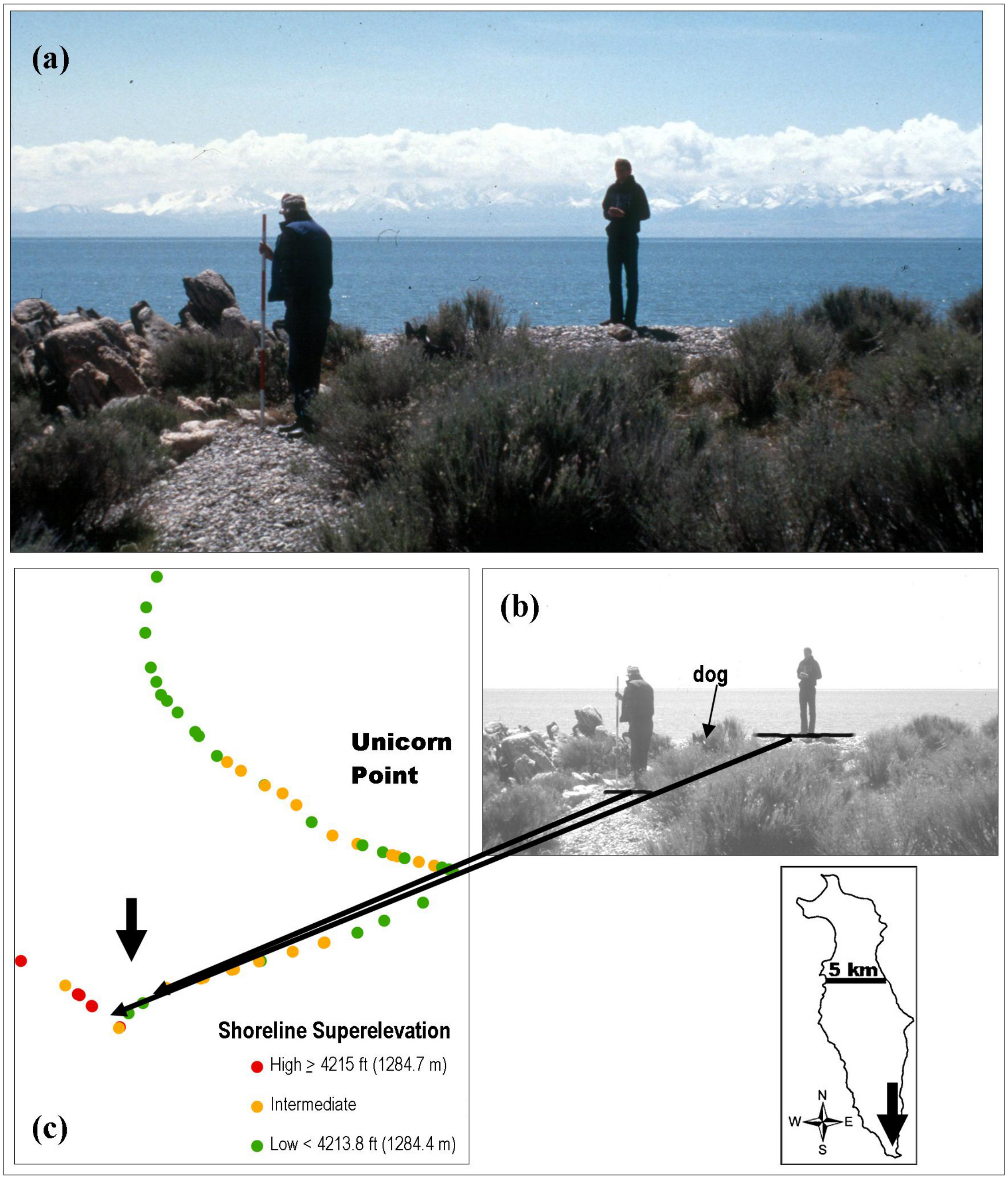


Figure 2.13. Contrasts of exposure and contrasts of shoreline superelevation. Photograph (a) taken in 1998 looks south across Unicorn Point. Annotated photograph (b) shows relative elevations of two depositional expressions of the 1986/87 shoreline. Persons on the lower southeast-facing gravel ridge, and on the higher west-southwest-facing ridge, are both approximately 6.2 ft (1.9 m) tall. Dog in rabbitbrush is approximately 2 ft (0.6 m) tall, the approximate difference in elevation between the two 1986/87 shoreline expressions. Map (c) shows surveyed superelevation projected to the shore-route. Elevations on expressions facing west-southwest are high in contrast to those facing southeast that are intermediate to low.

1.1 that summarize working assumptions concerning the magnitude, prevalence, and patterns of shoreline superelevation. The Antelope Island data set shows that assumptions of original horizontality of shoreline expressions of shallow closed-basin lakes are not valid. The data set indicates that making use of a paleoshoreline as an originally horizontal datum should be done with caution.

If shoreline expressions of 1986/87 were not recognized as contemporaneous, they could be interpreted as evidence of more than one highstand fluctuation. Such misidentification would lead to inaccurate assessments of evaporative losses and misinterpretation of climate conditions. For example, 1986/87 shoreline expressions on the west side of Antelope Island, such as those at 4215 ft (1284.7 m) a.s.l. along Buffalo Scaffold Bay, are contemporaneous with those at 4218 ft (1285.6 m) a.s.l. for the bay north of Picture Rock. Both bays are on the southwest shore of the island. If, however, these two expressions of the same shoreline were interpreted as expressions of two paleolake highstands, the misidentification would lead to an interpretation that two paleolakes with surface areas that differ by almost twofold had occupied the basin. If their contemporaneous age were not recognized, not only would estimates of still-water lake elevation be inaccurate by 3 ft (1 m) and 6 ft (2 m), respectively, but frequency of highstand fluctuations also would be overestimated. At elevations above 4212 ft (1283.8 m) a.s.l. small elevation increments are projected to result in major public losses and expenditures (Steffen, 1983). Misidentification of the magnitude and frequency of late-Holocene lake fluctuations could lead to inaccurate assessment of recurrence flooding hazards and extent of property at risk.

The Antelope Island data set shows that, for paleoshoreline research where relatively small deflections are important evidence of regional processes, shoreline superelevation should not be considered a randomly dispersed phenomenon that contributes only minimal uncertainty to identification of still-water lake elevations.

Elevations or shoreline superelevation are generally 1-4 feet (0.5-1 m) greater on the west side than the east side of the island. Although this difference in elevation is small in comparison to > 200 ft (> 60 m) signals of isostatic deformation of Lake Bonneville shorelines at the Bonneville level (Bills and others, 2002), it is on the order of magnitude of other paleoshoreline differences, including: highstand fluctuations of Holocene levels of Great Salt Lake (Murchison, 1989; Oviatt and Miller, 1997); stretches of Bonneville-level shorelines, such as across the Black Rock Desert (Currey, 1982); paleoshorelines within subbasins of Lake Bonneville, such as Tule Valley (Sack, 1990); paleoshorelines of closed basins of Nevada, such as in Dixie Valley (Caskey and Ramelli, 2004), Diamond Valley (Tackman, 1993), and Ruby Valley (Lillquist, 1994); and differences of Lake Lahontan paleoshorelines (Adams and Wesnousky, 1998). It also is on the order of magnitude of surface displacements of faults, such as the West Valley Fault (Keaton and others, 1993), the East Great Salt Lake fault (Dinter and Pechmann, 1999), and differences along the Bonneville shoreline attributed in part to local isostatic loading (Link and others, 1987).

Antelope Island field surveys demonstrated that documenting patterns of shoreline superelevation, even for decade-old evidence, is a challenge. Quantifying island-scale or lake-scale patterns of shoreline superelevation requires exceptional evidence including narrowly constrained age of shoreline expressions, abundant shoreline expressions, and precise surveying. Field identification was complicated where shoreline expressions were complex, such as multiple, active beach ridges (Figure 2.3), or where a decade of exposure to terrestrial erosion or deposition had destroyed or buried evidence. Superelevation of shoreline expressions is variable at the scale of individual bays, at the scale of the entire island, and at scales in between bay-scale and island-scale. Trends of superelevation could have been misidentified had the elevation survey relied on spot surveying rather than near-complete surveying of the island’s shore. The striking west-east contrast of shoreline superelevation will be explored in the following chapters.

CHAPTER 3

SUPERELEVATION: EVIDENCE OF LAKE PROCESSES

Patterns of superelevation of the 1986/87 shoreline expressions on Antelope Island were examined for evidence of two lake processes, wave runup and lake set-up. Specifically, patterns of elevation were analyzed for evidence of variability of runup, for evidence of relative contribution of wave runup and lake set-up to shoreline superelevation, and for evidence of a tilted lake-surface due to wind set-up.

Gilbert observed that waves are the dominant agents of geomorphic change that create shoreline evidence of Great Salt Lake (Gilbert, 1885, 1890). Without wind, the surface of Great Salt Lake is calm. On a calm day, wavelets less than an inch high lap the shores of Antelope Island and do not entrain and deposit shorezone materials that become superelevated shoreline expressions. Storm waves create the shoreline evidence of Great Salt Lake. Possibly fewer than a dozen storms created the 1986/87 evidence of shoreline superelevation of Great Salt Lake on Antelope Island (Atwood, 2002). After a storm, or in response to light-to-moderate winds, swell on Great Salt Lake consists of wave trains with waves less-energetic those of individual wind waves during storms. These wave trains arrive on shore, entrain materials of the shorezone, transport material along shore as well as orthogonal to shore, and create shorezone expressions below expressions of the inundation shoreline.

Wave runup and lake set-up are the two lake processes that are largely responsible for storm-related lakeshore flooding of Great Salt Lake (USACE, 1996), and waves of storm flooding cause superelevated shoreline expressions. Although wave runup and lake set-up are different processes, they both result from the transfer of wind energy into the lake surface (Pugh, 1987; Komar, 1998). Both processes have marine counterparts that are components of marine storm surge, a subject of extensive empirical and theoretical research (USACE, 1984, 2002). Factors that cause wave runup and those that cause sea surface set-up are complex and nonlinear and include interactive, feedback relationships (Komar, 1998). No simple equation relates magnitude of wave runup, a shorezone process, to magnitude of wind set-up, an open-water process that is only one component of lake set-up in the shorezone.

Wave Runup

Wave energy comes from the transfer of wind energy into the lake surface. The energy of a wave is proportional to the square of its height (Jackson, 1997). Waves reach the shore, break, and rush up the beach face. The magnitude of wave runup is the difference in elevation between still-water lake elevation and the elevation waves attain onshore. Shorezone slope affects wave runup as do friction factors and shorezone materials (Komar, 1998). Highest runup of waves on a smooth impermeable beach face is on the order of 0.7 of deep-water significant wave height (Komar, 1998). USACE (1984) graphs provide estimates of wave runup onto constructed shore features, such as sea walls.

The opportunity of wind energy to transfer into the lake surface is related to the size of the wave-generating surface, wind strength, wind duration, and friction factors (Komar, 1998). The capacity of waves to absorb energy is limited by their physical instability. As waves grow, they become tall and steep. They oversteepen, break apart, and lose some of their energy to the surrounding wave field (USACE, 2002; Komar, 1998; Pugh, 1987). Shallow water depth also can limit the size of waves. Generalized conditions of Great Salt Lake depicted on the wave-height nomograph indicate that waves of Great Salt Lake do not reach their energy saturation, and that the lake surface during storms is not a fully arisen sea (Figure 1.8).

Antelope Island State Park rangers know Great Salt Lake from the perspective of search and rescue. Mitch Larsson, manager of Antelope Island State Park 1978-1993 and participant in search and rescue missions on the lake, recalls reports of maximum wave heights of 10 ft (3 m) at the south end of Gilbert Bay outside the boat harbor associated with a storm of the early 1980s. He personally witnessed disorganized seas of open-water conditions with maximum height of 8 ft (2.4 m) during 1986/87 on Gilbert Bay and partially organized swell with individual wind waves of maximum 5 ft (1.5 m) on Farmington Bay. Larsson estimates significant wave heights, the average of the one-third most-energetic waves, associated with major storms on Gilbert Bay as approximately 3.5-5 ft (1-2 m) for winds from the west and northwest, and as 3 ft (1 m) for Farmington Bay associated with winds from the north. Based on these assumptions, average wave runup for the upper one-third of waves associated with storms of 1986/87 is inferred to be on the order of 3.5 ft (1 m) for Gilbert Bay and 1.5 ft (0.5 m) for Farmington Bay based on USACE (1984).

Individual waves of a disorganized sea vary in height, energy, and direction. Irregular wave energies cause irregular distribution of wave runup. During storms, the lake surface becomes a disorganized sea of individual wind waves with a broad spectrum of wave heights and travel directions. Distances across Great Salt Lake are sufficiently short that high-energy waves of disorganized seas arrive onshore before they organize into wave trains of similar energy. Individual wind waves associated with storms of Great Salt Lake arrive onshore with differing heights and energies. Individual wind waves, as their name implies, differ from waves of organized swell. Swell consists of series of waves of similar height, wave length, and energy traveling across expanses of water beyond the storm winds that initially imparted their energy

(Komar, 1998). Swell develops in response to wind across the surface of Great Salt Lake. However, wave height of swell is not as great as wave height of significant individual wind waves. Shoreline superelevation records the highest-energy individual wind waves, not the less-energetic swell.

Lake Set-Up

Lake set-up is the superelevated lake surface from which waves rush up the shore. Lake set-up is the net result of several processes, including wind set-up, the component of lake set-up caused by wind moving across the water surface. Negative lake set-up, or set-down, lowers water surface elevation along the upwind shore as lake set-up elevates it along the downwind shore (Figure 1.7).

Wind set-up is the lake analogue of superelevation of the sea surface due to marine storm winds (USACE, 2002). More than one approach has been used to predict the magnitude of marine sea-surface superelevation due to wind. Gill (1982) presents theoretical explanations of sea surface set-up developed from Navier-Stokes equations that assume an infinite sea of infinite depth. With those assumptions, sea-surface set-up is a tilted surface with magnitude that is a function of wind speed, wind duration, and a friction drag coefficient. The approach of Pugh (1987) uses empirically derived relationships of wind stress across the wave-generating area. With this approach, water depth, water density, and friction at the sea surface and at the sea bottom affect set-up magnitude. USACE (2002) approach to wind set-up on lakes and reservoirs is based on empirical evidence of associations among set-up, wind speed, fetch, and friction factors. USACE (1997) engineering requirements for reservoirs include requirements for freeboard and methods for calculating wind set-up for inland waterbodies.

$$S = (U^2 \times F) / 1400\ D$$

where

S = set-up in ft,

U = wind velocity in mph,

F = fetch in mi,

and

D = depth of water in ft.

(USACE, 1997, p. 15-3)

Applied to Great Salt Lake, this equation yields set-up on the order of 2-2.5 ft (0.6-0.8 m) for Gilbert Bay, using the following estimates for conditions of Great Salt Lake, but not taking into account water density or other factors specific to the lake:

U = 40 mph (18 m/sec),

F = 60 mi (100 km),

D = 30 ft (10 m),

and

S = 2.3 ft (0.7 m).

This calculated wind set-up of approximately 2 ft (0.6 m) agrees with observations of storm-related fluctuations recorded by USGS lake gages in Gilbert and Gunnison Bays. USGS gages record changes in lake-surface elevation, including lake set-up and seiches. Lake seiche is a standing wave that causes lake-surface oscillations after lake set-up conditions relax or winds change direction. USGS monitoring of lake-surface elevation indicates that maximum lake set-up is on the order of 2 ft (0.6 m). A review of USGS-monitoring records for October 1985 to September 1986 identified 17 storms of interest for lake set-up research including two storms with lake set-up between 2 - 2.3 ft (0.6 - 0.7 m). As depicted for Great Salt Lake by Lin and Wang (1978), lake seiche is a northwest-southeast tilt of lake-surface elevation with maximum magnitude of about 2 ft (0.6 m) that progressively increases along the long axis of Gilbert Bay (Figure 3.1). The node of no vertical surface displacement is opposite the north end of Antelope Island. Highest offsets are at the south end of Gilbert Bay, south of Antelope Island.

Seiche records of November 1998 show the maximum seiche recorded during Antelope Island field work of 1998 (Figure 3.2). Real-time monitoring by the USGS of this event recorded initial lake set-up of about 0.5 ft (0.2 m) at Promontory at the northeast part of Gilbert Bay followed by about 1-ft (0.3-m) rise at the boat harbor gage along the southeastern shore of Gilbert Bay. This pattern reflects basin morphometry: seiche magnitude is greater at the more constricted, southern margin of Gilbert Bay than along its broader northern margin. The concurrent set-down at the south shore boat harbor and set-up at Promontory are evidence of a tilted lake-surface; however, as will be discussed, the set-up pattern may be considerably more complex.

Wave Runup, Lake Set-Up, and Shoreline Superelevation

Processes of wave runup and marine set-up are known to contribute to the extent of coastal inundation associated with marine storm surge (Komar, 1998). The degree to which lacustrine processes of lake set-up and wave runup contribute to inundation of lacustrine shores was examined using 1986/87 shoreline superelevation along shores of Antelope Island. Specifically, three questions were addressed: (1) what is the nature of evidence of lake set-up on shores of shallow, closed-basin lakes; (2) what is the nature of evidence of wave runup on those shores; and (3) what is the relative magnitude of lake set-up and wave runup on those shores.

If wind set-up causes a tilted lake-surface, then lake set-up would include a broad, set-up signal due to wind. If the wind set-up surface were a tilted surface similar to a seiche set-up surface, then the component of lake set-up in the shoreline superelevation signal in response to northwesterly storm winds would increase from north to south along the west side of the island. If the wind set-up surface were a west-

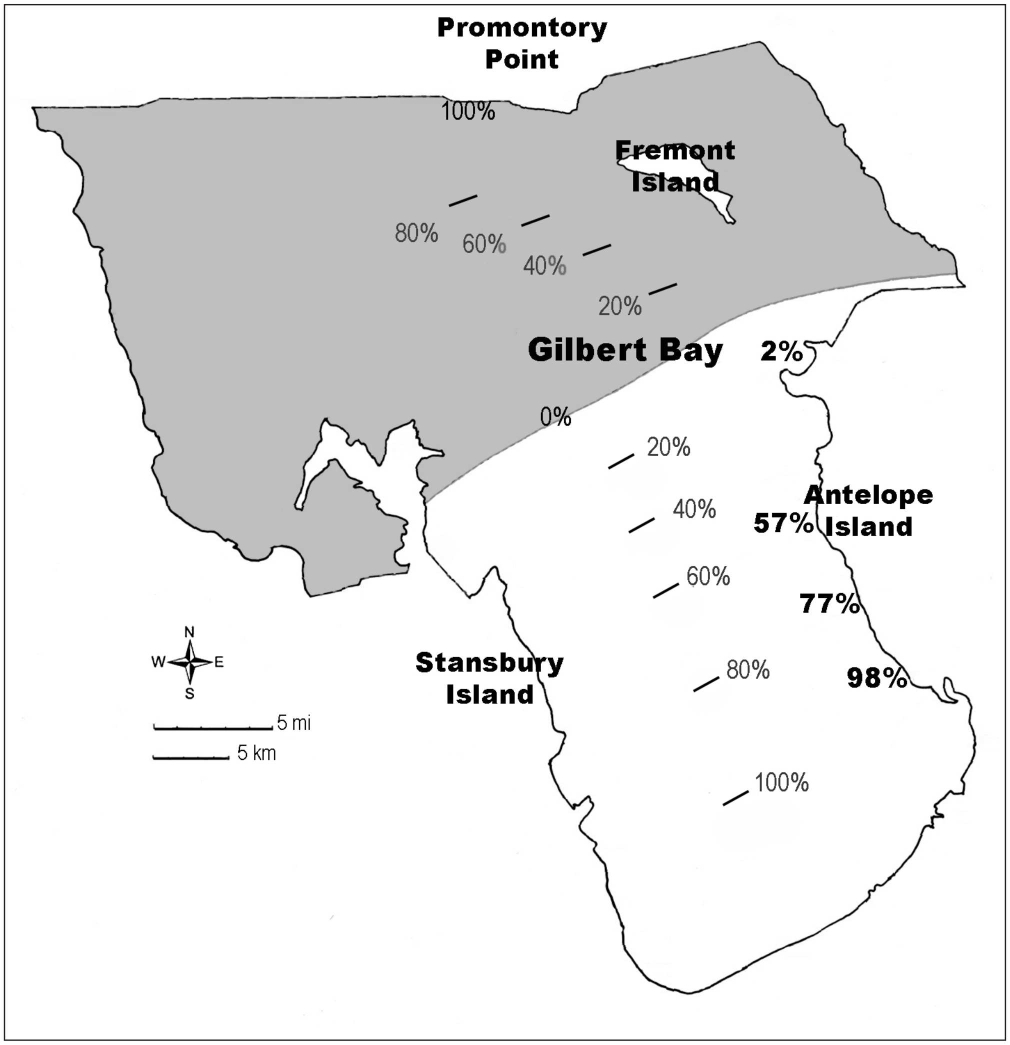


Figure 3.1. Tilted lake-surface of seiche of Gilbert Bay.
This diagram shows the tilted surface of a lake seiche adapted from Lin and Wang (1978). The northern tip of Antelope Island, Ladyfinger Point, is opposite the node of seiching and shown as experiencing only 2 percent of the full range of lake set-up. The most southern shores of Antelope Island are shown as experiencing 98 percent of the full range of lake seiching, as much as 2 ft (0.6 m) of lake set-up. Lake set-up due to wind set-up initiates lake seiches. This simple tilted-surface model indicates progressive increases in lake set-up along the western shore of Antelope Island.

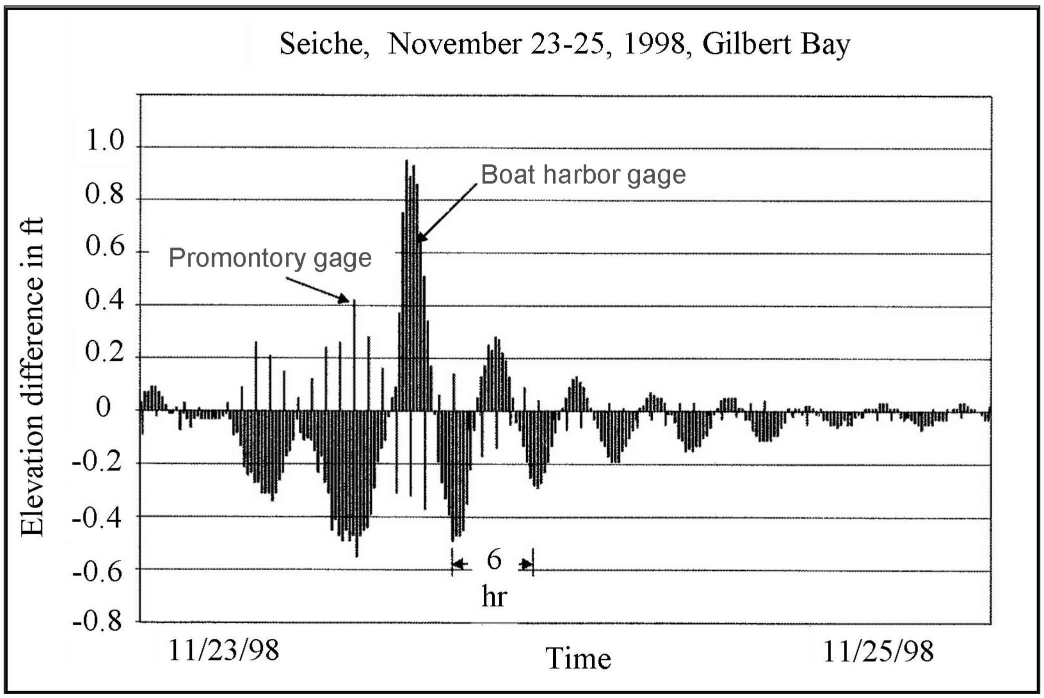


Figure 3.2. Seiche of Great Salt Lake.
Data from USGS lake-level gages on Gilbert Bay at Promontory Point and at the boat harbor of the south shore are shown as elevations relative to a common, still-water lake level that has been adjusted for discrepancies in lake datums. See Figure 1.1 for gage locations. Storm winds from the south caused lake set-down along the south shore of Gilbert Bay during 11/23/1998 and lake set-up at Promontory. Set-up and set-down initiated seiching with alternately rising and falling lake levels. Initial set-up at the south shore boat harbor gage was approximately 1 ft (0.3 m). Seiche magnitude was approximately 1.5 ft (0.6 m), almost two times higher at the boat harbor than at Promontory. The magnitude difference appears to be due to basin configuration. This seiche event was the largest recorded during the 1998 field surveys.

east tilted surface, then lake set-up along the downwind, west side of the island would be greater than that along the east, leeward side of the island. The east side of the island would experience lake set-down associated with strong storm winds from the west and lake set-up associated with less vigorous storm winds from the east. Assuming storm winds from the west, if lake set-up alone accounted for general patterns of shoreline superelevation for the entire island, then shoreline evidence along the west side of the island would be superelevated, and evidence of the east side of the island would be set-down.

The signal of wave runup from a wave-energy environment of individual wind waves coming onshore during storm events from a disorganized sea would be local and variable compared to the comparatively broad signal of lake set-up. Shores exposed to long fetch, strong wind, and long storm duration would experience higher-energy wave environments than those with short fetch, in the lee of land, or in places with highly variable winds. Based on these assumptions, shores of Antelope Island facing west and northwest into strong winds and long fetch across Gilbert Bay would have higher wave runup caused by higher-energy wave environments than those of Farmington Bay. Not only would significant wave energy be greater on the west side, but variability of wave energies also would be broader. Not every wave surges to the same elevation along a shorezone stretch. Holding other shore factors constant, shores facing into disorganized seas with low-, intermediate-, and high-energy waves, such as along the west side of Antelope Island, would have greater variability of wave runup than those facing into disorganized seas with low- and intermediate-energy waves, such as along the island's east side.

It was anticipated that the contribution of wave runup to shoreline superelevation would be large, on the order of 10 ft (3 m) maximum, so it was not known whether the contribution of lake set-up, approximately 2 ft (0.6 m) maximum, would be recognizable given the greater magnitude of wave runup.

Methods

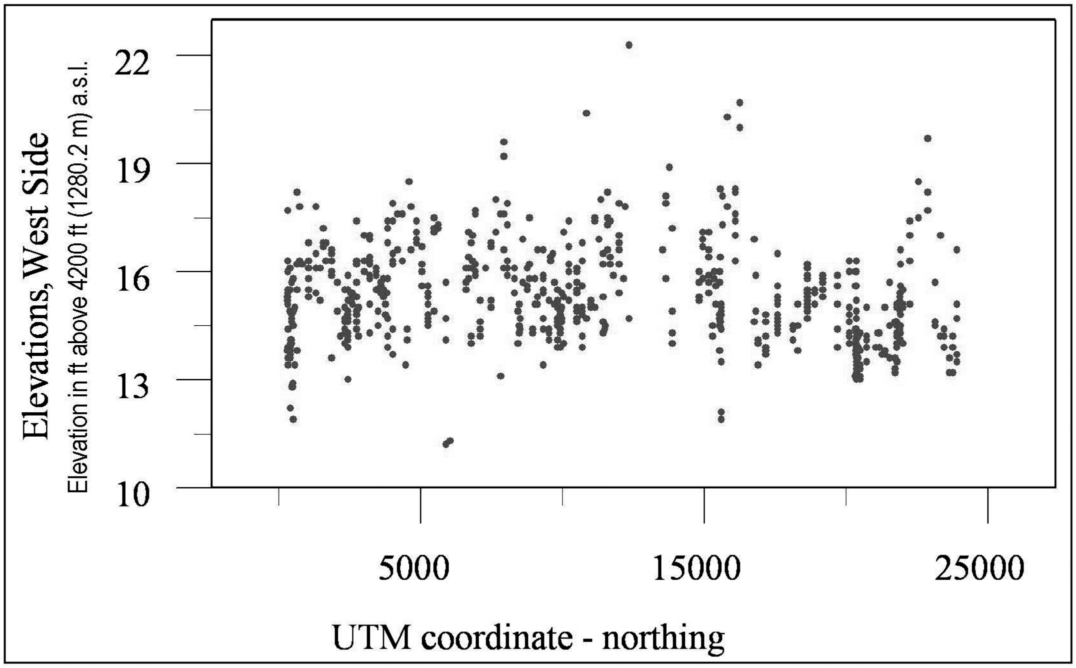
Questions of lake set-up and wave runup were addressed by examining spatial patterns of magnitude and variability of shoreline superelevation. Patterns of shoreline superelevation were examined visually for anticipated relationships, including (1) north-to-south patterns of lake set-up, (2) west-east evidence of lake set-up and wave runup, and (3) variability of elevations indicative of diverse energies of individual wind waves. Values of northing and easting were displayed for the 1228 surveyed locations of the inundation shoreline against shoreline superelevation as graphs and scatterplots. Northing and easting were known for each surveyed location of the Antelope Island data set from their UTM coordinates.

Results and Discussion

This chapter addresses the second set of statements of Table 1.1, concepts that concern shore processes. Shoreline evidence of Antelope Island does not support the first statement that the surface set-up by wind during storms resembles the set-up surface of lake seiche. The data set gives credence to the second and third statements that wave runup explains the magnitude and variability of shoreline superelevation around Antelope Island and that shoreline superelevation represents wave energy.

West versus east patterns of magnitude and variability of shoreline superelevation are striking. North-to-south patterns are not evident in graphs plotting superelevation against northing (Figure 3.3) or against easting. Specifically, a north-to-south increase in the lake set-up component of shoreline superelevation along the west side of Antelope Island is not evident from elevation-survey data. West-to-east trends of superelevation also are not evident along just the west side or just the east side of the

(a)



(b)

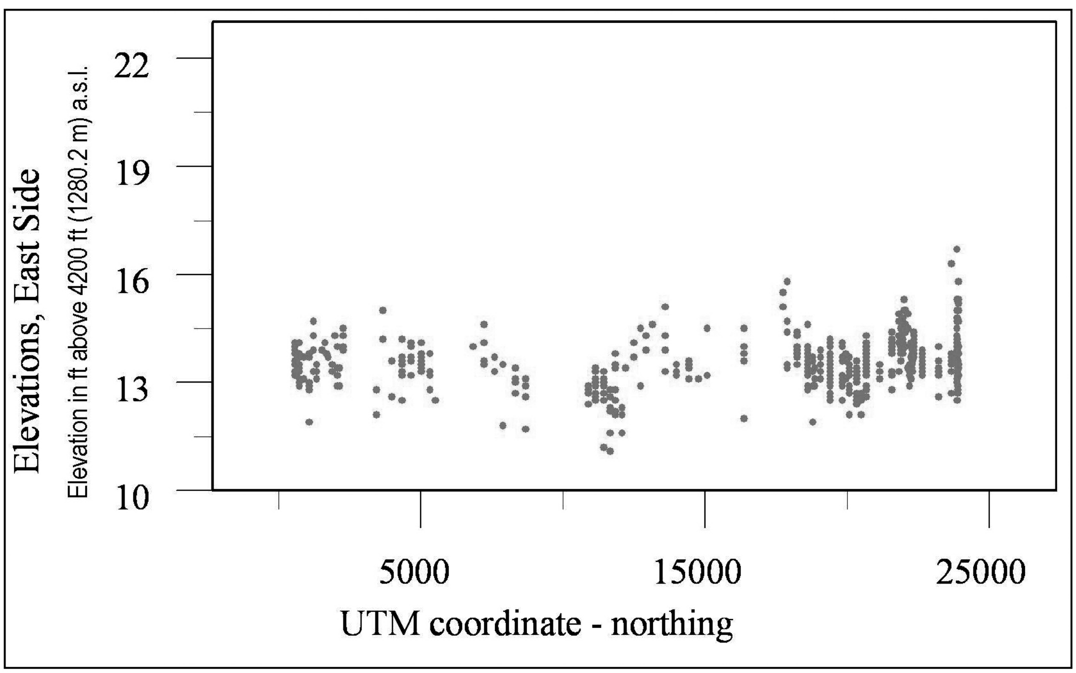


Figure 3.3. North-south location and shoreline superelevation.
Neither scatterplot (a) of the west side of the island, nor scatterplot (b) of the east side shows a strong pattern of shoreline superelevation associated with north-south location. If shoreline superelevation were dominantly due to a simple, tilted, set-up, lake surface, elevations of shoreline expressions along the west side of the island would increase toward the south. A progressive pattern is not evident.

island, although, as has been discussed, west-side superelevation is, in general, higher than east-side superelevation. For the east side of the island, easternmost locations appear to have slightly lower than average shorelines. For the west side of the island, easternmost and westernmost locations appear to have slightly lower than average values.

It cannot, however, be concluded that wind set-up does not contribute to patterns of shoreline superelevation on Antelope Island. Alternative explanations for the lack of association of northing with shoreline superelevation include (1) wind set-up is not a simple, northwest-southeast tilted lake-surface, (2) other components of lake set-up mask the tilted lake-surface component of wind set-up, and (3) the wave runup component of shoreline superelevation masks the lake set-up component of shoreline superelevation.

With respect to the first explanation of patterns of wind set-up, wind set-up may be a complex phenomenon that does not leave a simple signal along Antelope Island's west shore. Set-up may be progressive and advance along the island's shore. Set-up may include a significant west-east component. West-east set-up would be consistent with west-east contrasts in relative shoreline superelevation. However, absolute superelevation on the east side of the island does not provide evidence of lake set-down along the east side of Antelope Island. East-side shoreline expressions are not consistently below still-water lake elevation. Instead, of the six surveyed locations below still-water lake elevation, four are on the island's east shore and two along the west shore. All six low elevations can be explained by wetland vegetation that dissipated wave energy and entangled debris as it came on shore and do not appear to be low due to lake set-down.

The second explanation, that other components of lake set-up mask the contribution of wind set-up, recognizes that wind set-up is only one component of lake set-up. Other components of lake set-up include inverse barometric pressure effects and wind drift. For example, wind physically blows and stacks water at downwind extremities of bays. Lake set-up, instead of consisting of a progressive increase in lake-surface elevation along the west shore of Antelope Island, may be an abrupt stacking of water south of Antelope Island at the margin of Gilbert Bay.

The third explanation, that effects of wave runup mask effects of lake set-up, is supported by calculations of expected wind set-up versus expected wave runup and by observations of lake-surface fluctuations at USGS gages. Scatterplots of northing for the west and east sides of the island show patterns that are consistent with expected magnitude and variability of shoreline superelevation due to wave runup alone. Expected wind set-up caused by major storms across Gilbert Bay ranges up to 2 ft (0.6 m). Average wave runup of significant waves along the west shore of Gilbert Bay is estimated to be on the order of 3.5 ft (1 m) with wave runup of observed-tallest waves on the order of 8 ft (2.5 m). The average superelevation of the upper one-third of surveyed values along the west side of the island is 5.2 ft (1.6 m), within the range of expected values for wave runup. Highest-energy waves can explain highest superelevation values of approximately 12 ft (3.7 m). Wave runup also explains the highly variable distribution and higher superelevation of the west side of the island versus the lower energy, less variable patterns of the east side of the island.

Wave runup and lake set-up caused by storm winds from the north and from the east probably destroy evidence of lake set-down on the west side of Farmington Bay. Waves caused by strong storm winds from the north associated with winter, low-pressure systems come onshore with significant wave height less than 2 ft (0.6 m) and associated wave runup heights of 1.5 ft (0.5 m). Lake set-up due to easterly winds is < 1 ft (< 0.3 m). These rough estimates are based on personal observations of storms and discussions with park rangers (M. Larsson, oral commun., 2005). The extent to which the west side of Farmington Bay sets up along the east shore of Antelope Island in response to strong winds is unknown because the bay's surface is not monitored in real-time, nor are the direction and strength of easterly winds well-documented.

Discussions of later chapters of this dissertation are based on evidence presented in this chapter, specifically, that differences in shoreline superelevation are due to differences in wave-energy environments. Three lines of evidence underpin this premise: (1) patterns of magnitude and variability of shoreline superelevation data can be explained by differences in wave runup due to differences in energies of individual wind waves; (2) superelevation data do not show evidence of broad patterns of lake set-up; and (3) calculations by consulting engineers, based on USACE guidelines, for wave runup and lake set-up on Great Salt Lake predict wave runup approximately three to five times that of lake set-up (Rollins Brown and Gunnell Inc and Creamer & Noble Engineers, 1987).

The question concerning relative contributions of lake set-up and wave runup to shoreline superelevation is important because lake set-up not only instigates lake seiches but also affects lake currents (Lin and Wang, 1978). In turn, lake currents affect lake bottom sedimentation, lake water chemistry, and biotic systems (Baxter and others, 2005). The results presented here do not resolve the question of relative contributions of these factors, although there is strong evidence that wave runup is the dominant factor associated with shoreline superelevation. A research program that includes an array of lake elevation gages in combination with high resolution remote sensing could monitor and document surface elevation changes across Great Salt Lake as they evolve in real time through storms. Such a research effort combined with buoys and current meters could investigate effects of lake set-up on lake circulation including effects on nutrient and contaminant transport.

CHAPTER 4

ASSOCIATIONS WITH COASTAL CONDITIONS

This chapter discusses associations of island-scale patterns of shoreline superelevation with five physical conditions of coastal environments: fetch, wind strength, shorezone slope, coastal landforms and shorezone materials. Each of these coastal conditions influences wave energy (Komar, 1998) and, therefore, each was expected to be associated with shoreline superelevation. Two of the conditions, fetch and wind strength, influence the transfer of wind energy into the lake and, therefore, wave energy. Based on Gilbert (1890), it was expected that fetch would largely explain patterns of shoreline superelevation. Three of the conditions (shorezone slope, coastal landforms, and shorezone materials) influence dissipation of wave energy. These three conditions not only affect wave-energy environments, but they also are changed by them (Komar, 1998).

Shoreline superelevation, an indicator of relative wave energy around Antelope Island, was used to explore whether longer fetch causes higher superelevation; whether relative superelevation indicates direction of strong winds; and the extent to which shorezone slope, coastal landforms, and shore materials are reliable evidence of relative wave-energy environments.

Understanding the relationship of fetch to superelevation on Great Salt Lake is important because, if quantifiable, the relationship could be used to predict the extent of storm-related inundation hazards along the lake's shores. Establishing a relationship between direction of strongest winds and superelevation is important as a potential paleoclimate indicator. If superelevation of shoreline expressions of 1986/87 is a reliable signal of direction of storm winds of 1986/87, then that same signal or set of signals might be used to determine direction of strong winds for paleolakes of similar size and configuration. Paleowind direction and strength are subjects of research for Pleistocene Lake Bonneville and Lake Lahontan (Schofield, 2002; Adams, 2003; Felton, 2003). The strength of relationships between shoreline superelevation and slope, landforms, and shorezone materials not only is of interest to coastal geomorphologists examining coastal processes of shallow, closed-basin lakes, but also is of practical importance to risk managers and engineers considering alternative approaches to shore protection from storm-wave damage.

Methods

Coastal characteristics of interest were characterized in the field, derived from maps, and were combined with data from the elevation survey into the Antelope Island data set (Table 4.1). The data set was examined for relationships among shoreline attributes using displays, plots, and graphs. Relationships were examined in the context of marine and lacustrine coastal processes and geomorphology.

Ten shorezone characteristics were mapped in the field:

- abundance of locally derived vegetative debris,
- abundance of lumber,
- abundance of large, natural driftwood,
- abundance of nonwood, anthropogenic materials, such as plastic or rubber,
- abundance of sand,
- abundance of gravel,
- size of largest particle moved by shore processes of 1986/87,
- substrate, i.e., terrigenous materials underlying shore materials,

Table 4.1. Data sets used for Antelope Island shoreline superelevation research.

Data Set	Superelevation	Shorezone character	Fetch	Aspect and profile	Geologic materials	Planform shape
Method used to collect data	Field work. Surveyed using total station equipment.	Field work. Detailed-scale mapping. Values recorded in GPS data loggers.	Derived. Base map, USGS (1998) 1:500,000 scale.	Derived. Base maps, USGS 7.5' topographic quadrangle maps 1:24,000 scale.	Derived. Base map, UGS geologic map, (Doelling, and others, 1990) 1:24,000 scale.	Derived. Base map, Antelope Island State Park map, (1991) 1:42:000 scale.
Mapped feature given attribute values	1228 points represent locations surveyed on 1986-1987 inundation shoreline expressions.	667 line segments represent the shoreline stretches of the field survey.	24 vectors radiate from midpoints of 305 geomorphically-defined shore segments.	305 line segments represent 305 geomorphically-defined shore segments.	208 line segments represent segments of the shore-route with breaks at boundaries of mapped geologic units.	94 line segments represent changes of planform shape along the mapped outline of the island.
Attributes discussed in this dissertation	Superelevation; Elevation of 1986-1987 inundation shoreline expressions.	Abundance and type of materials; Largest particle moved; Beach type.	Maximum fetch length; Direction of maximum fetch.	Aspect; Slope of upper shorezone; Slope of lower shorezone.	Bedrock versus surficial materials; Bedrock units.	Concave versus convex planform shape of the shoreline; Linearity.

- beach materials exposed along the 1986/87 shorezone, and
- shorezone type (erosional, depositional, or both erosional and depositional).

Classifications of abundance of materials (above) were based on visual assessment of the amount of materials present, not percentages of materials of the shore.

Investigations included two field seasons of testing techniques and criteria for shorezone characterization before the shorezone characterization survey of 1998. Stretches of the shorezone were attributed with values for each of the 10 characteristics plus location using Trimble GPS GeoExplorer data loggers with horizontal accuracy of 3-5 m after differential correction. Beginning and ending points of 667 shorezone segments were determined in the field based on changed character of the shorezone Figure 4.1. Changed character included change in relative abundance of materials, types of material, or shorezone type, such as from erosional to depositional. All of the island's approximately 64-km shorezone was characterized for the 10 attributes with no data gaps, although some shorezone segments had values of "not visible" or "none." The average segment length is 94 m. The longest segment is 459 m along a straight stretch of shore on the east side of the island south of the Ranch House.

Potential error associated with positional accuracy of the line segments of the field survey is relatively well understood (Trimble Navigation Limited, 2000). Errors of projection or location were evident when data were displayed across USGS topographic maps. Potential errors of completeness of the shore characterization data set are of at least two types: (1) failing to characterize an important shorezone characteristic, and (2) failure to include evidence because evidence had been destroyed in the decade between 1986/87 and field work of 1996-1998. Data collection using data loggers with data dictionaries encouraged consistency of data collection but also focused attention on attributes in the data dictionary at the expense of what was not anticipated. Photographs and field notes provide additional documentation of shorezone

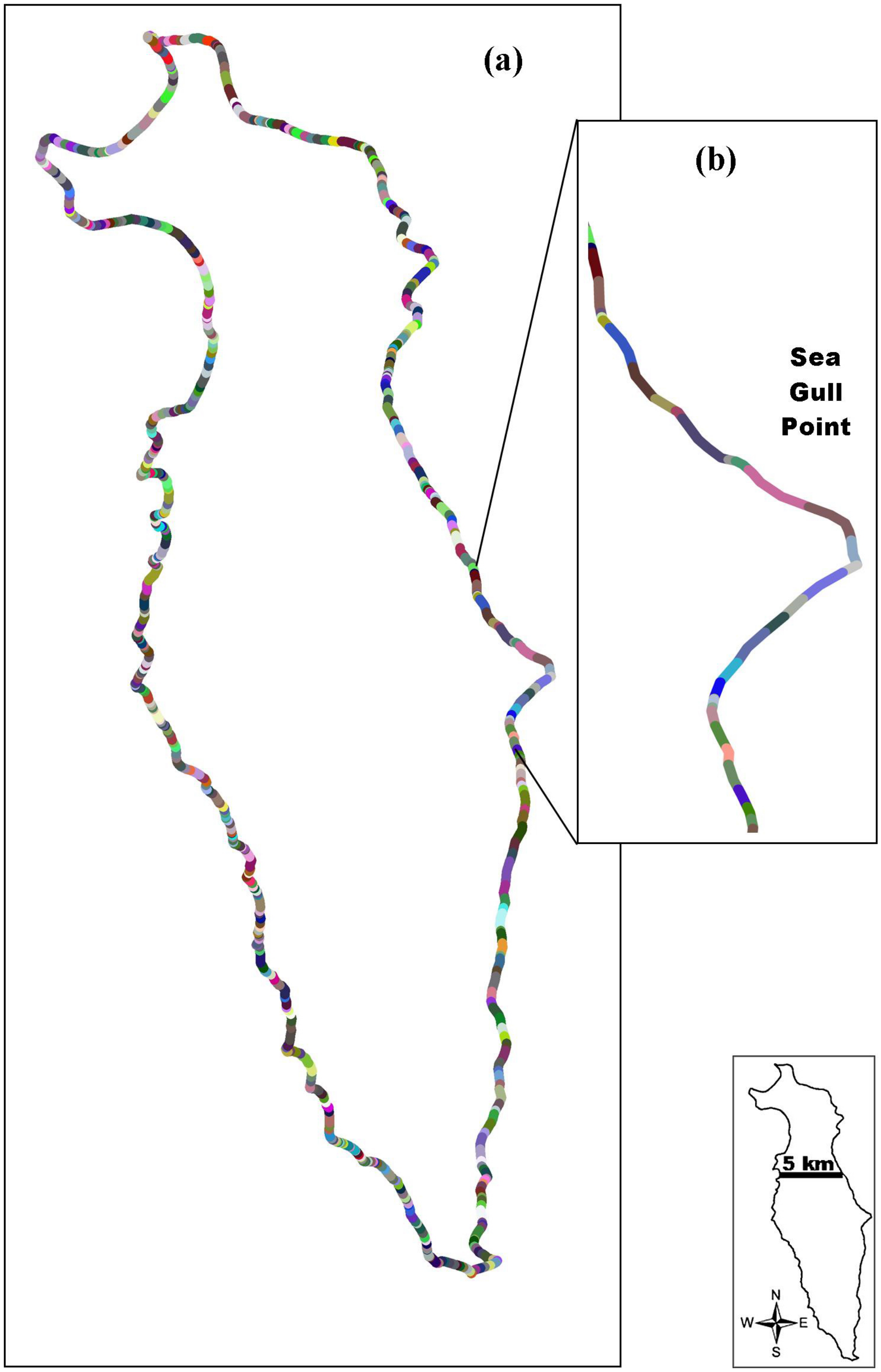


Figure 4.1. Shore segments characterized.
Shorezone attributes of the 1986/87 shorezone, such as type and abundance of debris, were mapped as part of the 1998 field surveys. Line segments of map (a) show the 667 mapped segments. Beginning and end points of each segment were based on field interpretation of a notable change in general shorezone character. For discussion, see text. Inset map (b) shows greater detail for part of the island's east shore.

characteristics. For example, a shorezone characteristic that was not included in the data set was wetland vegetation of 1986/87 in the shorezone. Attribute error is of concern because shore stretches were characterized as they changed general character. Determination of changed character was not based on a single attribute. For example, a change from erosional to depositional character was sufficient basis to begin a new line segment for characterization, but a change from a sheet of sand to patches of sand on the inundation shoreline expression was not. With experience, recognition of changed character of the shorezone evolved. This potential source of error was anticipated and addressed by not mapping the shore as a continuous set of line segments but by mapping different parts of the island's shore nonsequentially.

Additionally, several shorezone characteristics were derived from maps. Fetch was measured digitally from the USGS (1988) State of Utah relief map originally at 1:500,000 scale. Attributes of shorezone morphometry, such as slope and aspect, were derived from digital USGS topographic 7.5-minute quadrangle maps originally at 1:24,000 scale. Geologic attributes of the shorezone were derived from Utah Geological Survey (UGS) mapping of Antelope Island at 1:24,000 scale (Doelling and others, 1988; Doelling and others, 1990). Attributes that describe shoreline segment's planform shape, such as linearity, were derived from the Antelope Island State Park simplified contour map of Antelope Island, Public Information Series #16 map at 1:48,000 scale (Utah State Parks and Recreation, 2001).

GIS techniques were used to reference attribute data to a common, linearly referenced shore-route (Atwood, 2003). This was necessary because line segments used to describe shoreline stretches for field surveys had beginning points, ending points, and paths that are not coincident with those derived from maps (Figure 2.8). The beginning and ending points for the 667 shorezone stretches of the field survey of shorezone characteristics were defined based on field observations of changed conditions. The beginning and ending points of the 305 shore segments attributed with geomorphic characteristics, including aspect and shorezone slope, were based on general geomorphology, such as logical breaks at headlands and spits evident on published topographic maps. The 208 segments attributed with geologic characteristics were derived by intersecting the digitized shore-route with polygons representing the geologic units of UGS Map 117 (Doelling and others, 1990). The 94 segments used to define planform shape were based on visual smoothing into alternating convex and concave segments of the outline of island shown on the public information contour map (Utah State Parks and Recreation, 2001).

Operational Definitions for Antelope Island Research

Fetch

Fetch is the unobstructed open sea surface across which wind generates waves (USACE, 2002). However, for most purposes, including Antelope Island research, fetch is calculated as a vector: the distance and direction from a point on shore, across open water to a point on land.

Fetch was measured for each of the 305 continuous shore segments attributed with geomorphic characteristics using commercial GIS software (Idrisi, Cartalinx, ArcInfo, and ArcView). First, the fetch perimeter described by mainland, island, and causeway landmasses was digitized from the USGS State of Utah relief map (USGS, 1988). Causeways not flooded during 1986-1987 were considered landmasses, as were Fremont, Stansbury, and Carrington Islands. Second, the 305 shore segments that had been defined based on general geomorphology were assigned a midpoint. Third, that digitized midpoint was moved lakeward to be slightly off the digital shore-route. Fourth, a compass rose of 24 lines was centered at each midpoint. Fifth, the line segments of the compass rose were clipped where they intersected the fetch-perimeter or the island's shoreline. Sixth, the length of each of the clipped line segments radiating from the midpoint was measured and entered into a spreadsheet. Figure 4.2 displays fetch vectors for 10 shore segments along the northern shore of the island. Each shore segment midpoint has 24 fetch vectors radiating from it although landward fetch vectors are digitally clipped short by the island's shoreline. The longest fetch of a set of 24 vectors is the maximum fetch length for a shore segment. The direction of that line is the direction of maximum fetch. Patterns of shoreline superelevation were compared to patterns of maximum fetch length and direction of maximum fetch.

Direction of Storm Winds

Direction and strength of storm winds across Great Salt Lake were not monitored during the 1980s, and specific conditions for storms of highstand conditions of 1986/87, including wind strength, wind direction, storm duration, are not known for Gilbert and Farmington Bays. Publicly available, real-time, detailed weather records for locations on Great Salt Lake date from 1997-2000 when real-time monitoring stations were established on islands and near the shores of Great Salt Lake to better predict Wasatch Front weather and also in preparation for the 2002 Olympics (Utah State Parks and Recreation, 2001; Horel and others, 2002a; Schultz and others, 2002). Records from weather stations in the vicinity of Gilbert Bay indicate that wind records of the Salt Lake International Airport do not capture the range and variability of winds across Gilbert Bay (Steenburgh and Onton, 2001). For these reasons, multiple lines of evidence were used to infer the direction and strength of winds of 1986/87 for storms when the lake was high, including (1) regional wind patterns, (2) weather observations and observations of search-and-rescue personnel, (3) distribution of flotsam along shores of bays and headlands, and (4) island-scale sedimentation patterns. Together, these approaches indicate that strongest winds of 1986/87 were generally from the west

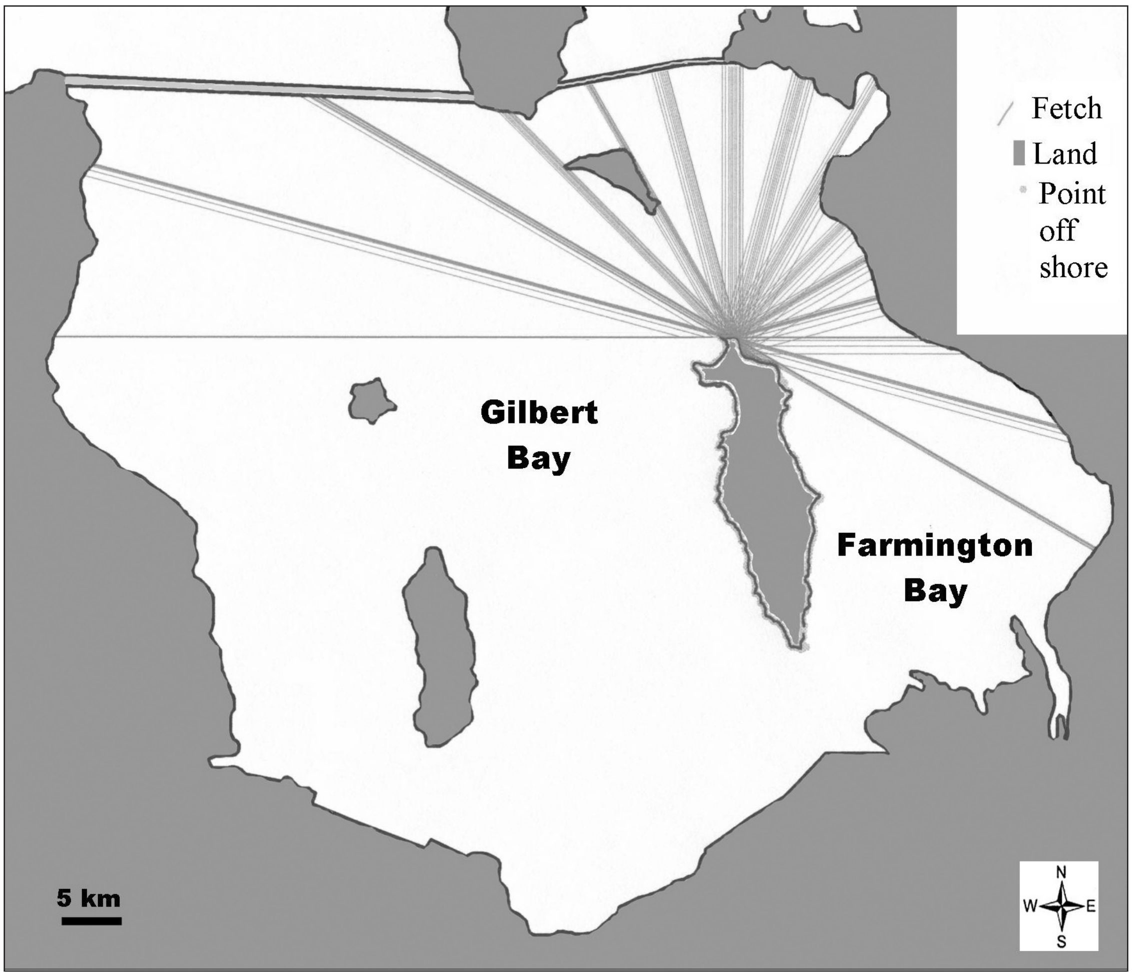


Figure 4.2. Fetch.
The map shows fetch vectors for a series of 10 shore segments along Antelope Island's northern shoreline. The center point of a digital compass rose was placed digitally approximately 15 m offshore from the midpoint of each of 305 segments of the shoreline. The digital compass rose consisted of 24 vectors radiating from a center point, each representing a 15° increment. Distance from the compass rose center point to land was measured digitally for each of the 24 vectors. Each shore segment was assigned a maximum fetch, the longest of the 24 vectors. Direction of maximum fetch is the direction of that vector. Causeways not flooded during 1986-1987 were considered landmasses, as were Fremont, Stansbury, and Carrington Islands.

and northwest associated with low pressure storms systems.

Regional wind patterns associated with weather systems of the western United States are generally understood although weather of the Intermountain West is challenging to predict (Horel and others, 2002b). Pacific, winter, low-pressure systems typically begin with initial strong winds from the south and southwest, followed by stronger winds and gusts from the northwest (Anderson, 1975).

Weather observations and reports of conditions and effects of specific storms can be inferred from newspaper records of 1986/87, personal journals of William Alder of the National Weather Service Forecast Office (1986, 1987), and post-1990s MesoWest wind records (Horel and others, 2002a). During March-June of 1986/87, when Great Salt Lake was at its historic high levels, Pacific low-pressure systems entered the region from the west and northwest and traversed the lake (Alder, 2002). According to Alder (1986, 1987), a major low-pressure system of June 7-9, 1986, when the lake was within a week of its historic highstand, caused storm waves to breach the dikes that bounded the north margin of Stansbury Bay. The ensuing flooding of evaporation ponds of Stansbury Bay lowered Gilbert Bay by 0.5 ft (0.15 m). A cursory review of USGS seiche records suggests that this storm and a storm system of May 21-22, 1986, likely produced some of the strongest winds across the lake during 1986/87 when the lake was near its highstand elevation. According to search-and-rescue personnel on the lake, winter and spring storms with strongest winds from the northwest result in wave conditions far more energetic, chaotic, and dangerous than strong, steady summer-monsoon winds from the south associated with swell on the lake (M. Larsson, oral commun., 2005).

In contrast, easterly winds across Farmington Bay are not as strong or persistent as winds from the west across Gilbert Bay (Horel and others, 2002a). Strong easterly winds occasionally flow over the crest of the Wasatch Range, funnel through Weber

Canyon and other Wasatch Front canyons, but they lose much of their strength before reaching Antelope Island (Holland, 2002; Stewart and others, 2002; Stewart, 2004). During Antelope Island research of 1996-2000, the maximum height of observed wind waves due to easterly winds was 2 ft (0.6 m). During this event, along-shore drift from south to north was observed at Seagull and Unicorn Points.

Distribution of wind-blown debris provides another line of evidence of direction of strong storm winds during 1986/87. Wind blows flotsam and surface water generally downwind across the lake surface. Wind-drift, wind, and individual wind waves transport flotsam onshore where it is stranded on the beach zone. Abundance and type of floated debris on Antelope Island were examined for indications of onshore, along-shore, and offshore lake currents; for direction of strong onshore wind; and for associations with shoreline superelevation at island-scale and along individual bays. Along-shore transport is an important component of coastal evolution and was observed during field surveys associated with swell. The relative importance of orthogonal versus along-shore processes associated with individual wind waves associated with storm events was not evaluated as part of superelevation research. Bay-scale evidence of along-shore transport of terrigenous materials, such as transport southeast along Buffalo Bay of asphalt of the Syracuse Causeway destroyed in 1984, was noted as part of characterizing sediments of the 1986/87 shore.

Island-scale patterns of near- and offshore sediment types provided a third line of evidence for inferring direction and patterns of storm winds. As wind physically blows surface water generally downwind, it causes shoreward movement of the upper lake surface that contributes to lake set-up (Komar, 1998). Wind drift, lake set-up on the downwind shore, and lake set-down on the up-wind shore are expected to generate onshore and offshore currents depicted schematically in Figure 4.3. Onshore winds that blow water against the windward shore cause return currents that flow downward and

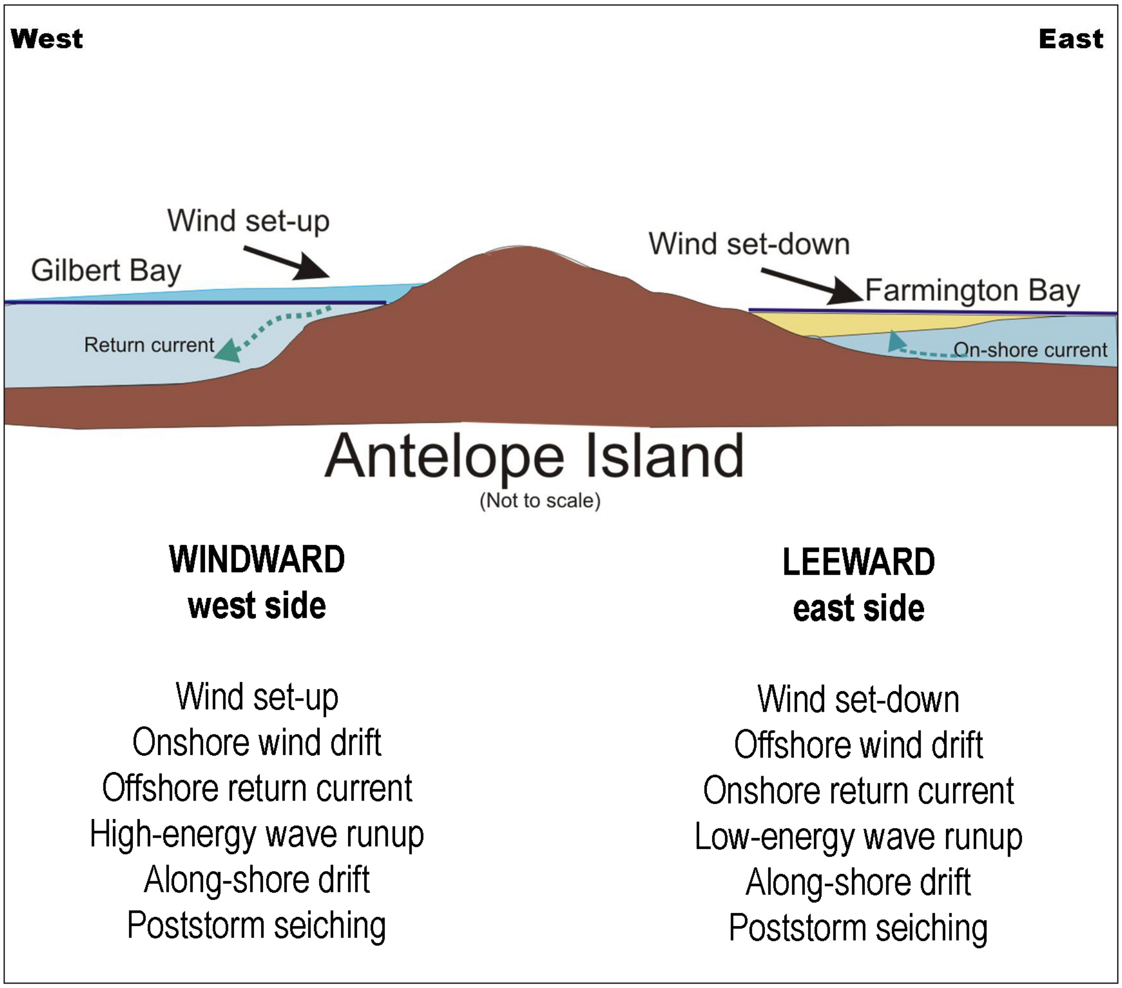


Figure 4.3. Wind and currents.
This not-to-scale diagram depicts the effects of strong winds that stack water onto the west side of the island and instigate descending return currents which carry sediment offshore. On the east shore, the same patterns of strong winds from the west blow water offshore and instigate up-welling, onshore currents. The diagram does not portray effects of along-shore currents that also are agents of geomorphic change in the shorezone.

offshore and tend to steepen the windward shore (Allen, 1984). Offshore winds that blow across and away from the island move water of the lake surface away from shore, setting up upwelling, onshore currents that tend to carry sediments toward shore and tend to decrease the slope of the leeward shore (Allen, 1984; Masselink and Hughes, 2003). As part of the Antelope Island research, sediment patterns were examined as evidence of onshore versus offshore wind-generated lake currents.

Additionally, shore aspect was used as a way to infer direction of strong, onshore, storm winds. Shore aspect is the direction a shorezone faces (Jackson, 1997), and storm winds orthogonal to the shore (parallel to shore aspect) generally have the greatest impact on storm-waves that create superelevated shorelines. Shore aspect is a definable, quantifiable, geomorphic coastal characteristic of shore segments and was determined for the 305 geomorphically defined shore segments of the 1986/87 shorezone. This was done by drawing a digital line from the beginning and ending points of each shore segment and measuring the direction normal to that line in degrees clockwise from north. The following assumptions underpin the use of aspect as evidence of direction of strong winds: (1) wind waves and wave momentum travel generally parallel to, and in the direction of, the storm winds that cause them, (2) wind waves of the chaotic, disorganized sea typical of storms on Great Salt Lake rush onshore as individual waves in their disorganized state of diverse energies traveling in the general direction they had in open water (USACE, 1997), (3) wind waves running orthogonal to shore and in the direction of onshore winds, rush farther up the shorezone than those that run oblique, parallel to, or opposite to the general direction of strong winds (Komar, 1998), and thus, (4) the direction a shore faces, shore aspect, at a bay-by-bay scale, can be used to represent the general direction of waves arriving onshore and general direction of storm winds responsible for the highest shoreline expressions of that shore segment. These assumptions are predicated on wave environments of

Great Salt Lake summarized in the nomograph of Figure 1.8 and disregard wave refraction, a phenomenon along marine shores exposed to wave trains and organized swell.

Shorezone Slope

Slope is the gradient of a landform surface measured in degrees, radians, or as percentage of vertical rise over horizontal distance (Jackson, 1997). Shorezone slope should affect shoreline superelevation if shorezone slope impacts wave energy. Waves break and dissipate energy in shallow water (Komar, 1998), so extensive, low-gradient slopes dissipate wave energy. Shorezone slope was calculated by measuring distance between contours of digitized 1:24,000 topographic maps (Figure 4.4). Upper-shorezone slope was calculated using distances measured between the 4200 and 4220 ft (1280.2 and 1286.3 m) a.s.l. contours. Lower-shorezone slope was calculated using distances measured between the 4195 and 4200 ft (1278.6 and 1280.2 m) a.s.l. contours. Upper- and lower-shorezone slopes were attributed to each of the 305 geomorphically defined shore segments.

The topographic contours of 4195, 4200, and 4220 ft (1278.6, 1280.2, and 1286.3 m) were chosen to define shorezone slope because published topographic contour maps of the island consistently have each of these intervals. These three contours are not ideal for capturing gradients of geomorphic interest across the shorezone. More detailed contour intervals would be preferable. However, the three contours provide a general sense of shore gradient around the entire island. The upper slope interval generally includes the 1986/87 still-water lake elevation and the wave runup zone to virtually all shoreline expressions. The lower slope interval generally defines gradients offshore from the 1986/87 shoreline.

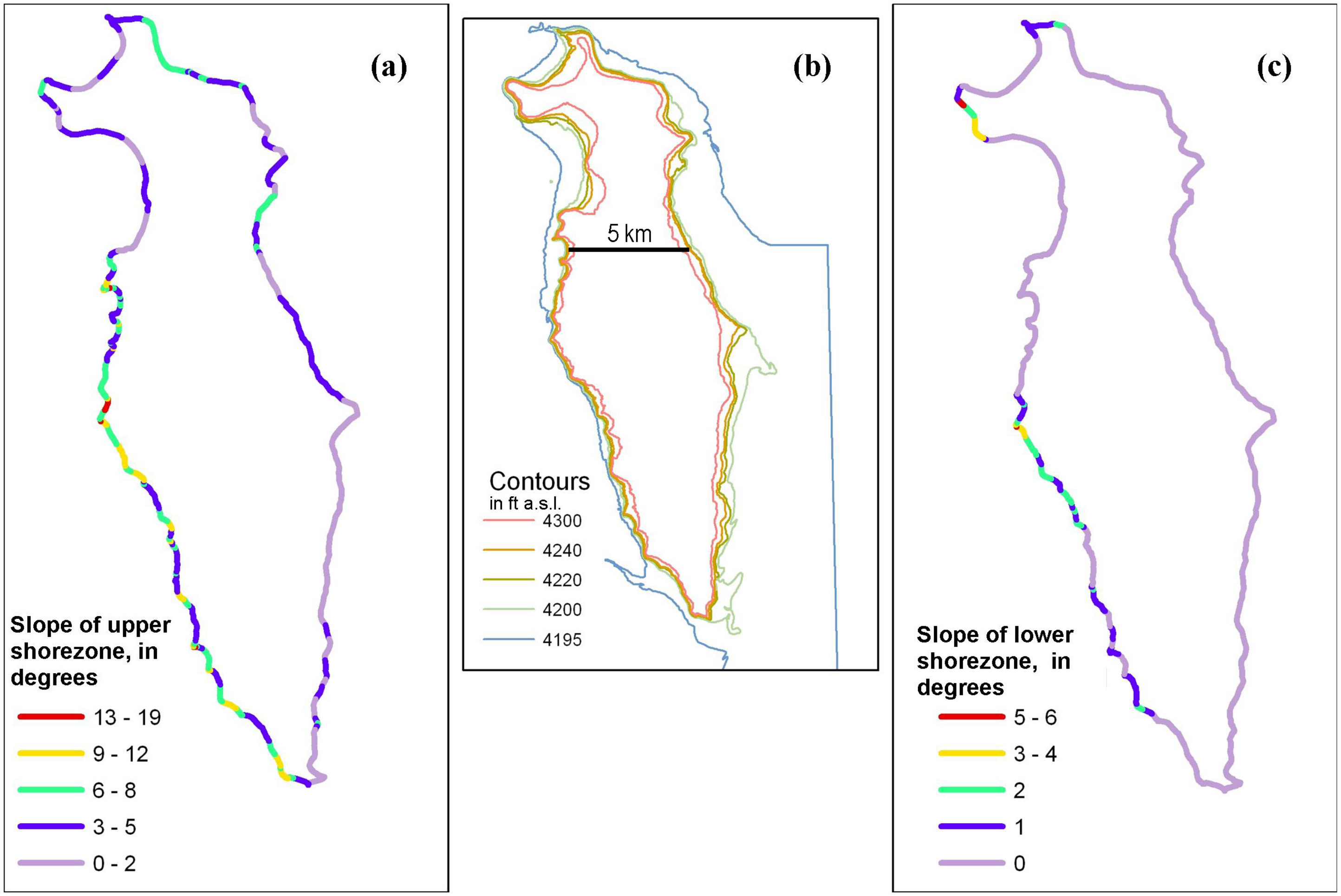


Figure 4.4. Shorezone slope.
Shore segments were attributed with upper-shorezone slope (a), and lower-shorezone slope (c), by measuring distance between contour lines (b) digitized from 1:24,000 USGS topographic maps. Upper shorezone was measured between the 4200 and 4220 ft (1280.16 and 1286.26 m) contours. Lower shorezone is between the 4195 and 4200 ft (1278.64 and 1280.16 m) contours.

Shorezone Materials

Shorezone materials can be categorized based on rock type, shape, size, chemistry, and physical properties, such as specific gravity (Jackson, 1997). Coastal geomorphic processes sort particles into characteristic suites of shorezone deposits (Clayton, 1979). Energetic waves can move larger particles than less energetic waves (Bagnold, 1977). Wave action and abrasion diminish the size of boulders and cobbles and round them (Folk, 1968). Fine materials are carried offshore or along shore leaving behind coarse lag deposits (Komar, 1998).

Abundance, type, and size of materials of the shorezone were among the characteristics mapped as part of 1998 field investigations. Mapped characteristics include relative abundance of sand and gravel along the inundation expression of the shoreline; materials of the beach face in the wave runup zone; abundance of debris, including locally derived vegetative material, driftwood, lumber, and trash; largest particles moved by waves in the runup zone near and at the inundation expression of the shoreline; erosional versus depositional beach type; and substrate type.

Classification was by visual inspection. For example, the attribute of largest particles moved by waves in the runup zone was classified as mud, sand, fine gravel, coarse gravel, cobbles, or small boulders by visual examination for the largest class of materials that obviously had been moved by waves during 1986/87 and for the smallest class of materials that had remained in place in the inundation zone. Substrate was defined as the terrigenous materials that waves cut into along an erosional shore or materials across which sediments of 1986/87 were deposited. Beach type was classified as erosional, depositional, or both erosional and depositional based on presence or absence of coastal sediments along the inundation expression and along the beach zone. The third class of beach type, both erosional and depositional, refers to shore stretches, particularly along the eastern side of the island, where sand and gravel were deposited at the inundation shoreline expression and where erosion dominated the beach zone.

Coastal Landforms

Coastal landforms are the shapes, forms, and features of coastal landscapes in contrast to the materials of the landscape. Coastal processes of erosion and deposition shape coastal landforms. When deposition exceeds erosion along a shorezone over an extensive period of time, the coast is accretional and dominated by sediments. When erosion dominates, the coast is erosional and includes landforms, such as sea cliffs and abrasion platforms (Komar, 1998). Coastal landforms not only are modified by wave runup, but they also modify wave runup (Komar, 1998). Headlands, coves, and shelves can concentrate wave energy, whereas extensive mudflats dissipate wave energy (Komar, 1998).

Coastal landforms were not mapped per se during the 1998 field investigations; however, mudflats and exposed bedrock were identified in the process of characterizing shorezone materials. Bedrock headlands are exposed bedrock on convex portions of the shoreline. Shores were classified as concave or convex as part of classifying shoreline planform shape.

Methods Used to Analyze Patterns

Individual shorezone attributes, such as longest fetch or upper-shorezone slope, were displayed as digital maps and examined for island-scale patterns. In this process, some detailed-scale patterns of individual bays were recognized, such as progressive changes in classes of shorezone materials. However, the purpose of the examination was to identify island-scale, not bay-by-bay scale, patterns of individual attributes. Patterns of individual shorezone attributes in the Antelope Island database were compared against island-scale patterns of shoreline superelevation using digital and hard-copy small-scale maps, side by side maps, scatterplots, histograms, traditional graphs, and 3-D displays (Atwood and Cova, 2000). Then columnar displays were used to compare shoreline superelevation with 18 attributes simultaneously, as pairs, and in other sets of combinations (Atwood, 2003, 2004; Atwood and Mabey, 2002). Figure 4.5 shows a small portion of a snapshot of columnar display downloaded from a computer screen. Values of 7 attributes are shown for approximately 12 km of Antelope Island's shoreline south and west of Ladyfinger Point. Contrasting combinations of colors can show relationships among nominal values of attributes, and combinations of hues, brightness, and saturation can show relationships among ordinal values of attributes (Brewer, 2005). For example, the attribute, substrate, has nominal values, and different colors indicate different kinds of materials that underlie beach sediments. The attributes sand, gravel, and organic debris, have ordinal values based on abundance of sand, gravel, and organic debris along the inundation expression of the 1986/1987 shoreline. Darker shades indicate increased abundance.

Color patterns of columnar displays representing high, intermediate, and low shoreline superelevation were compared with color patterns representing each of 18 shorezone attributes (Figure 4.6). First, the columns representing shoreline superelevation were color coded with red as high,; orange as intermediate, and green as low. Then a column representing a shorezone attribute was aligned digitally and interactively next to those of shoreline superelevation. Patterns were examined. Sometimes the pattern of one or two values of an attribute corresponded with high, intermediate, or low shoreline superelevation. In those cases, values of the shorezone attribute were colored red, orange, or green to correspond to the superelevation class which their pattern resembled. Cut-off values of the shorezone attribute were adjusted iteratively until the general pattern of a set of values of a shorezone attribute resembled the general pattern of a class of shoreline superelevation. The process was repeated

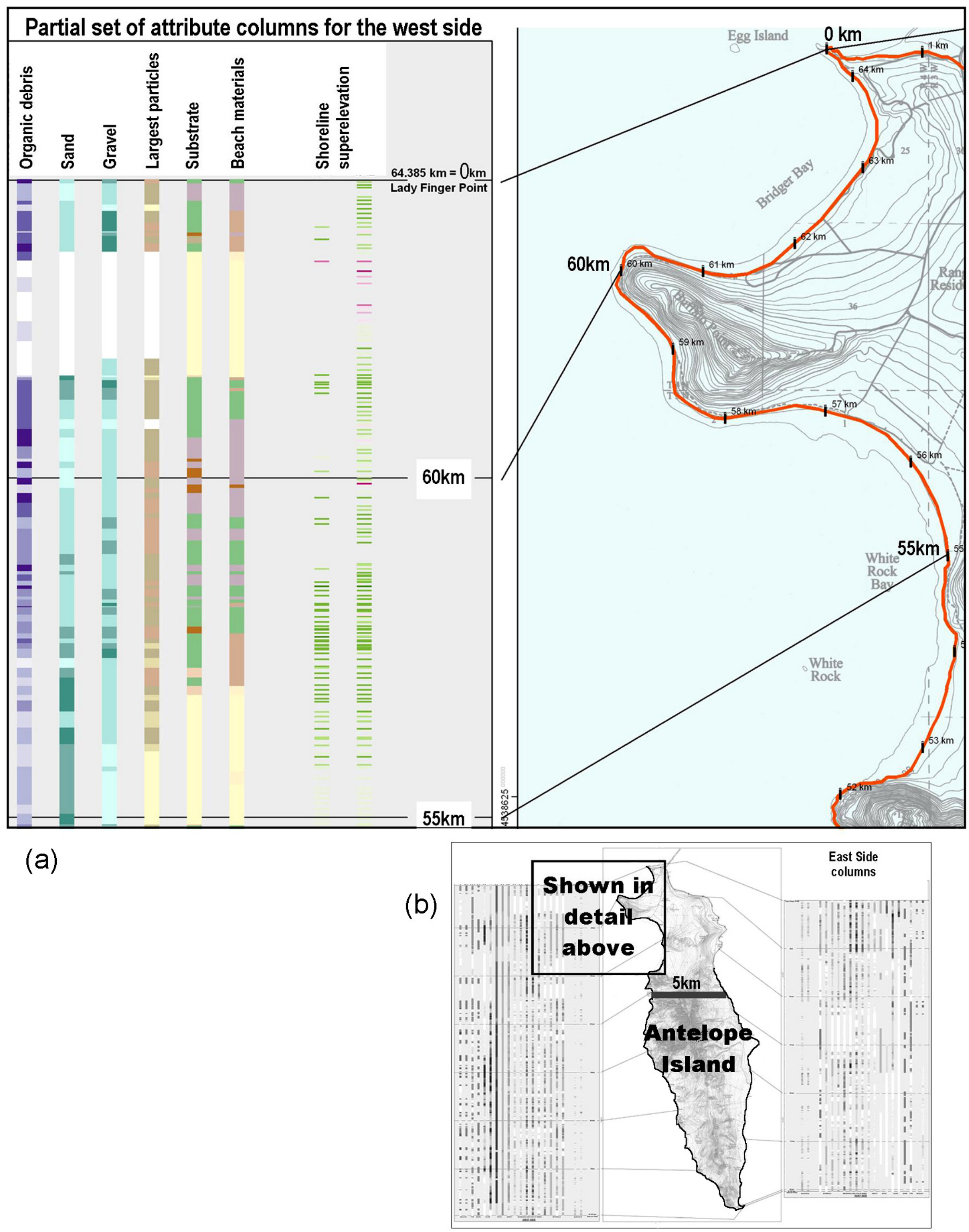


Figure 4.5. Columnar display of shorezone attributes.
The upper image (a) shows a portion of a GIS-generated display. The thumbnail (b) shows the full image in coarse scale intended only to show general layout. Each column of (a) represents a shorezone attribute. Hues represent values of attributes. Location along the shore-route is shown in geographic space on the map and along the columns as kilometer markers, such as 60 km. Columnar displays were used to analyze island-scale spatial patterns of shorezone attributes including shoreline superelevation.

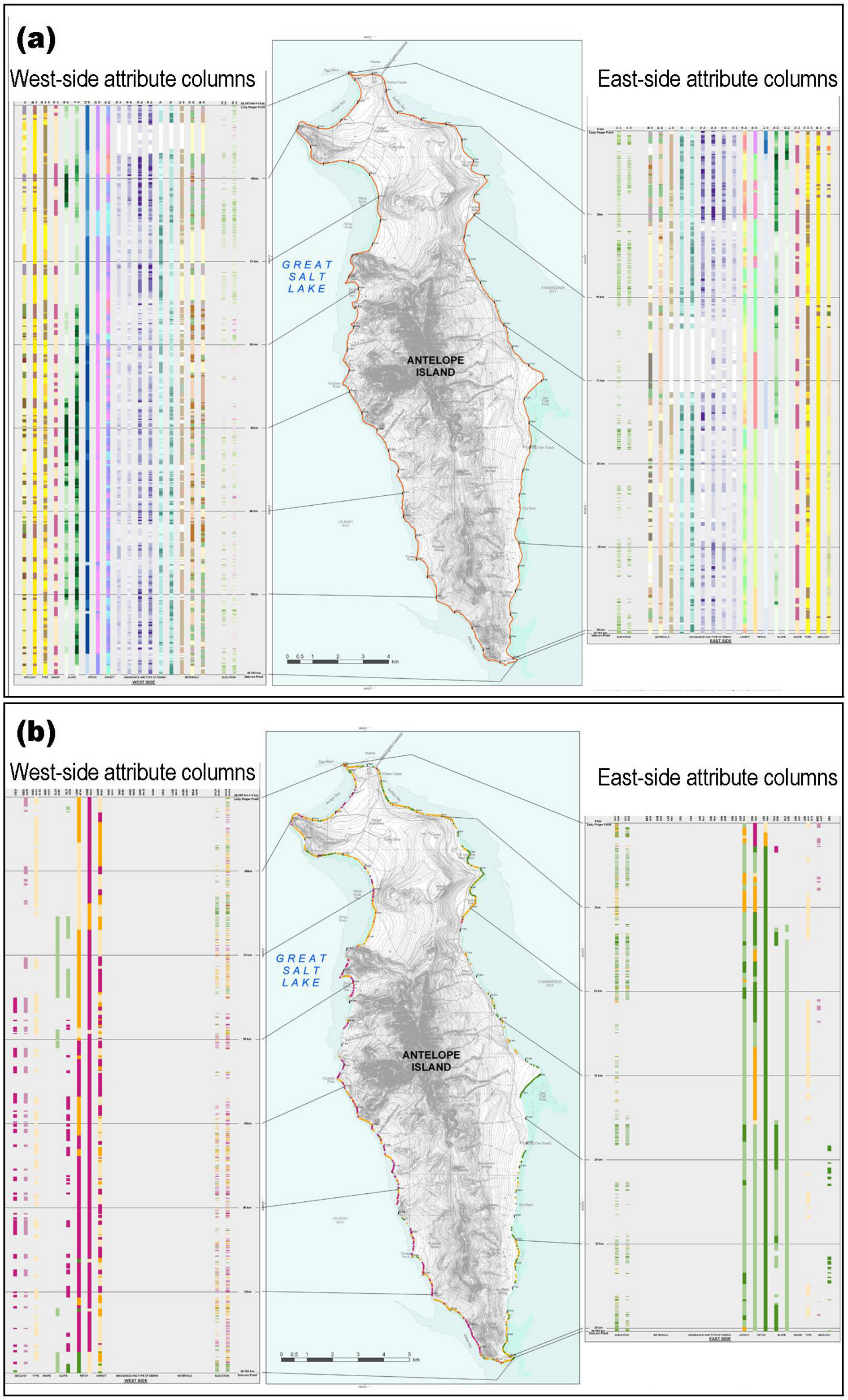


Figure 4.6. Columnar displays of data and of interpretation.
Columnar display (a) presents data of shorezone attributes (see detail, Figure 4.5). Patterns of the columnar displays were compared with patterns of shoreline superelevation. Associations are shown in columnar display (b). See text for discussion.

for each of the 18 shorezone attributes. Less bright hues represent less consistent associations than bright red, orange, and green. Blank portions of columns, shown in gray, indicate poor association of patterns between the shorezone attribute and shoreline superelevation. The technique of comparing patterns of columnar displays is somewhat analogous to the concept suggested by Dobson (1992) to match geographic patterns of fit, for example, the generally pattern of fit of continental margins.

Associations of patterns of shoreline superelevation and patterns of shoreline attributes were then examined in the context of marine and large-lake coastal geomorphic process research. For example, based on empirical research on storm surge height in marine conditions, it was expected that long fetch across Great Salt Lake would be associated with high shoreline superelevation on Antelope Island.

Results

As discussed in Chapter 3, superelevation values were classified into three near-equal population classes: high ≥ 4215 ft (1284.7 m) a.s.l., intermediate, and low < 4213.8 ft (1284.4 m) a.s.l. Island-scale patterns of shoreline superelevation, specifically, west-east contrasts of superelevation were compared with patterns of fetch, aspect as an indicator of direction of storm winds, shorezone slope, shorezone materials, and coastal landforms to explore coastal processes responsible for patterns of shoreline superelevation.

Fetch and Shoreline Superelevation

Fetch to the west, across Gilbert Bay, in general, is greater than to the east, across Farmington Bay (Figure 4.7). Maximum fetch is 60 km across Gilbert Bay. Minimum fetch is 22 km across Farmington Bay. Fetch values are bimodal with approximately 25 km of the island’s 64-km shoreline having maximum fetch between

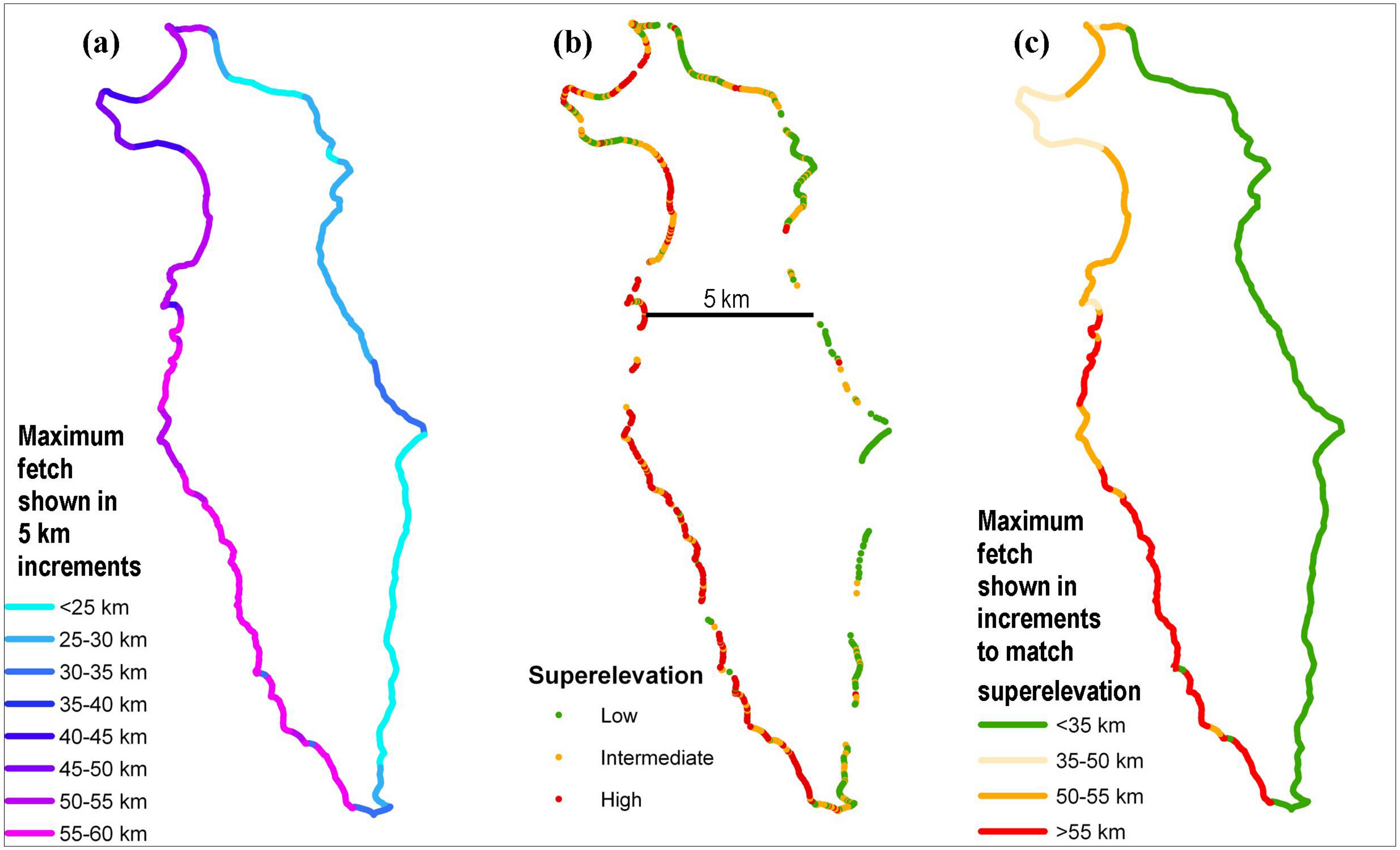


Figure 4.7. Maximum fetch and shoreline superelevation.
Map (a) shows values of maximum fetch classified arbitrarily in 5-km increments. Map (b) displays shoreline superelevation as the three classes used throughout the dissertation. Map (c) displays the data of (a) but the data are grouped to show their association with values of superelevation; e.g., patterns of maximum fetch < 35 km generally resemble those of low superelevation and are shown with the same color as low shoreline superelevation. Lighter saturation indicates less consistent association with superelevation.

20-30 km, and approximately 26 km having maximum fetch between 50-60 km.

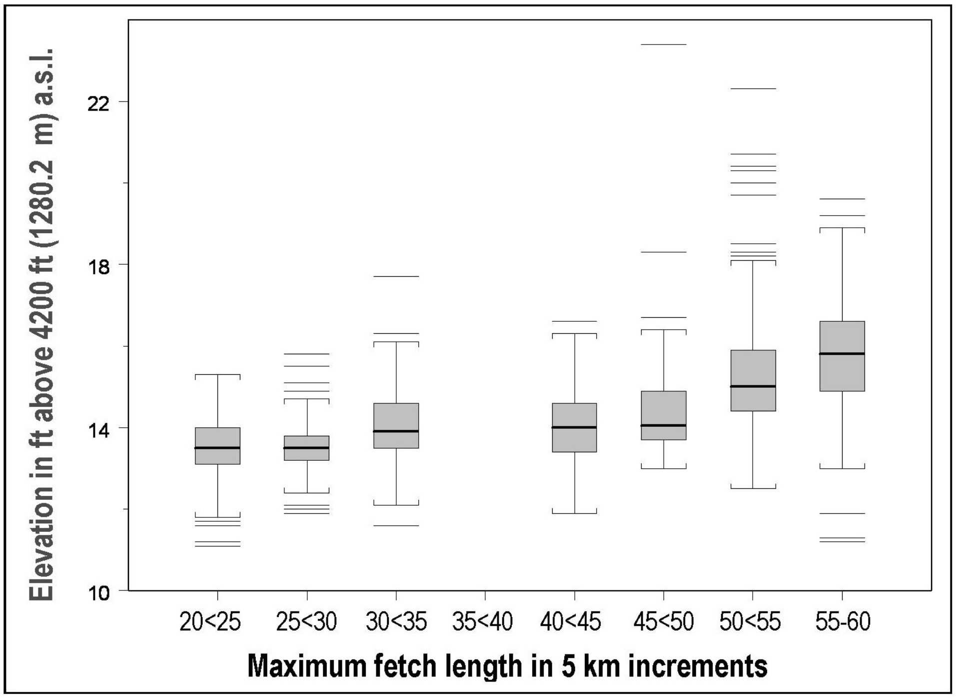
As expected, patterns of shoreline superelevation generally resemble those of fetch. Cut-offs of values of fetch were adjusted so patterns on the attribute column representing fetch visually resembled patterns on the attribute column representing shoreline superelevation. When maximum fetch is classified as (a) ≥ 55 km, (b) 50 to 55 km, (c) 35 to 50 km, and (d) ≤ 35 km, patterns of maximum fetch generally resemble patterns of shoreline superelevation classified as high, intermediate, and low (Figure 4.7). The association of high shoreline superelevation and longest fetch (≥ 55 km) is more consistent than associations of intermediate superelevation with intermediate fetch. Of the 294 surveyed locations with fetch ≥ 55 km, 220 (75 percent) have high superelevation, 64 have intermediate, and 10 have low superelevation. Of the 528 surveyed locations with fetch ≤ 35 km, 327 (62 percent) have low superelevation, 180 have intermediate, and 21 have high superelevation. The relationship of increasing shoreline superelevation with increased fetch is also evident in box and whisker diagrams (Figure 4.8).

As expected, direction of maximum fetch also is associated with shoreline superelevation. High shoreline superelevation is associated with maximum fetch to the west and west-northwest. Lowest shoreline superelevation is associated with maximum fetch to the east (Figure 4.8). For example, for the 45 surveyed locations with maximum fetch length toward due east, all have low superelevation. In contrast, for the 368 surveyed locations with maximum fetch toward the west-northwest, 72 percent have high superelevation.

Wind Strength and Shoreline Superelevation

As expected, the west side of the island generally has west-facing shores and the east side of the island generally has east-facing shores (Figure 4.9). Antelope

(a)



(b)

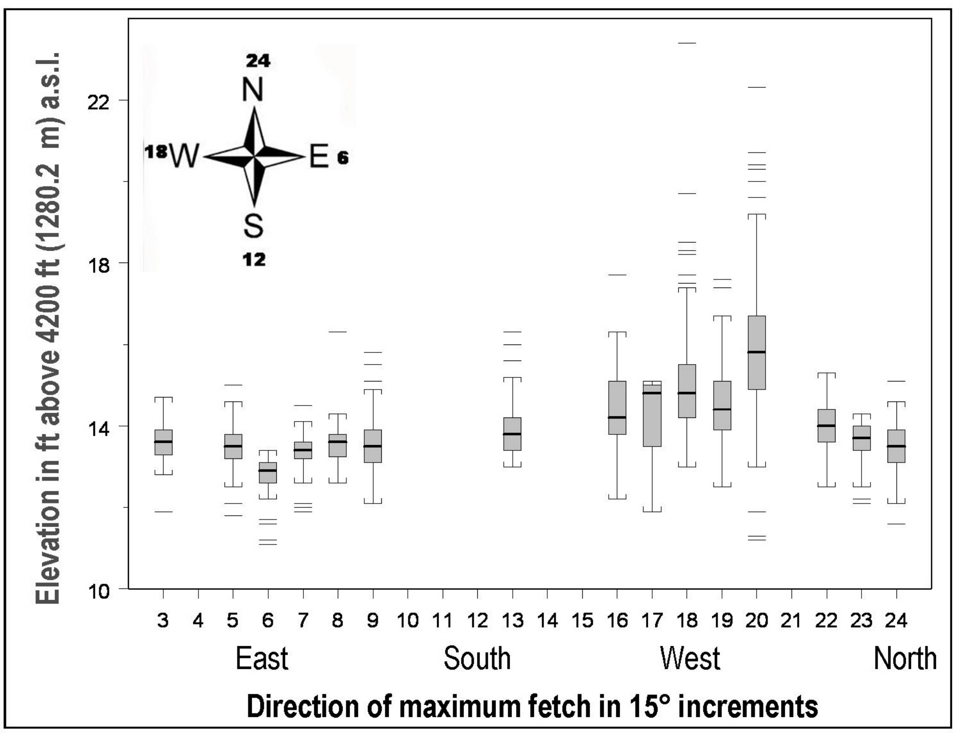


Figure 4.8. Plots of fetch and superelevation.
Box and whisker plot (a) shows that longer fetch is associated with higher shoreline superelevation. Diagram (b) shows that direction of maximum fetch to the west and northwest is associated with high shoreline superelevation. In contrast, maximum fetch to the east is associated with low shoreline superelevation.

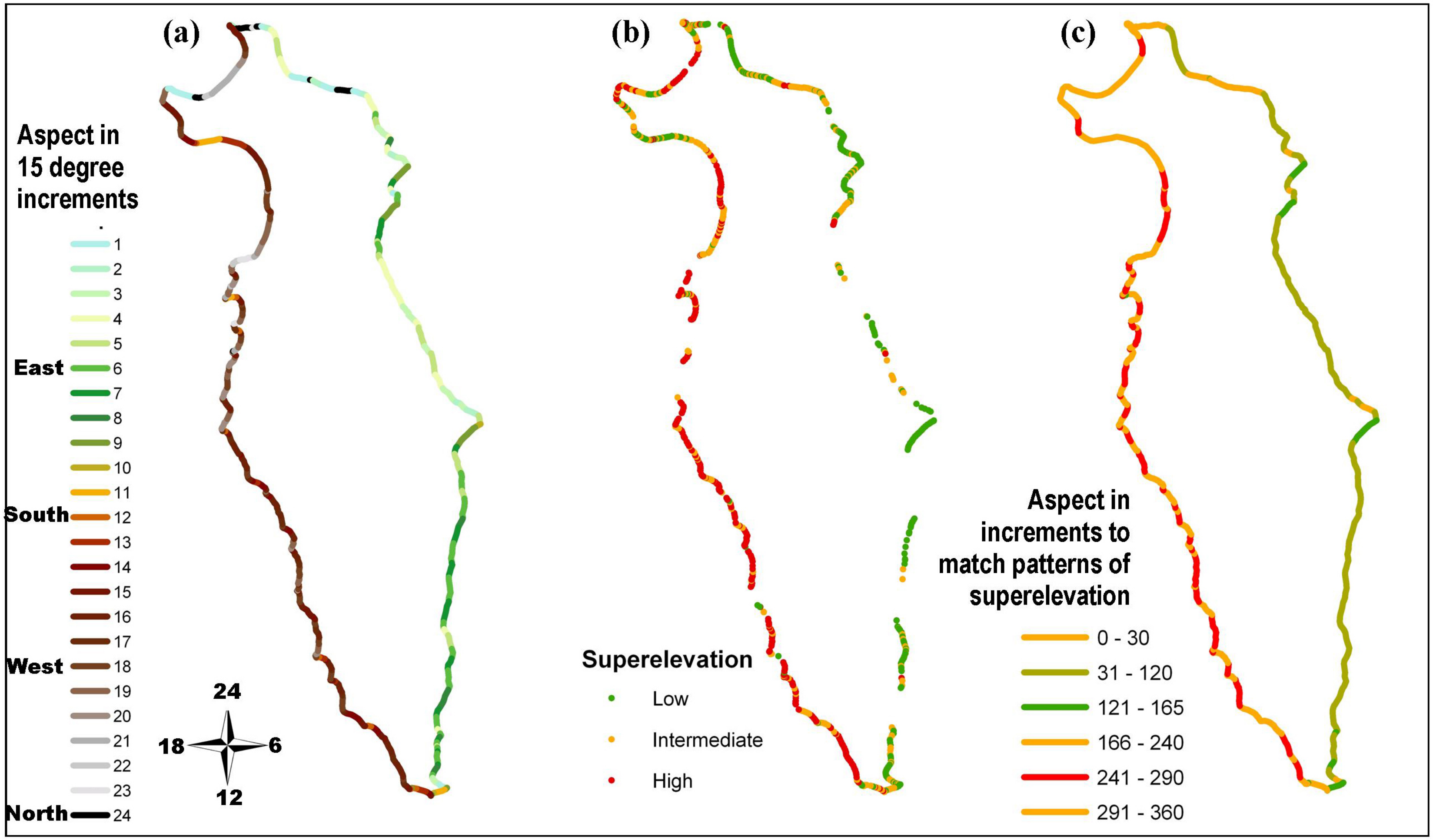


Figure 4.9. Aspect and shoreline superelevation.
Map (a) displays aspect in 24 compass directions. Map (b) displays shoreline superelevation as the three classes used throughout the dissertation. Map (c) displays the data of (a) with compass directions shown as their association with values of superelevation. Shores that face west have high shoreline superelevation. Those that face southeast have low shoreline superelevation.

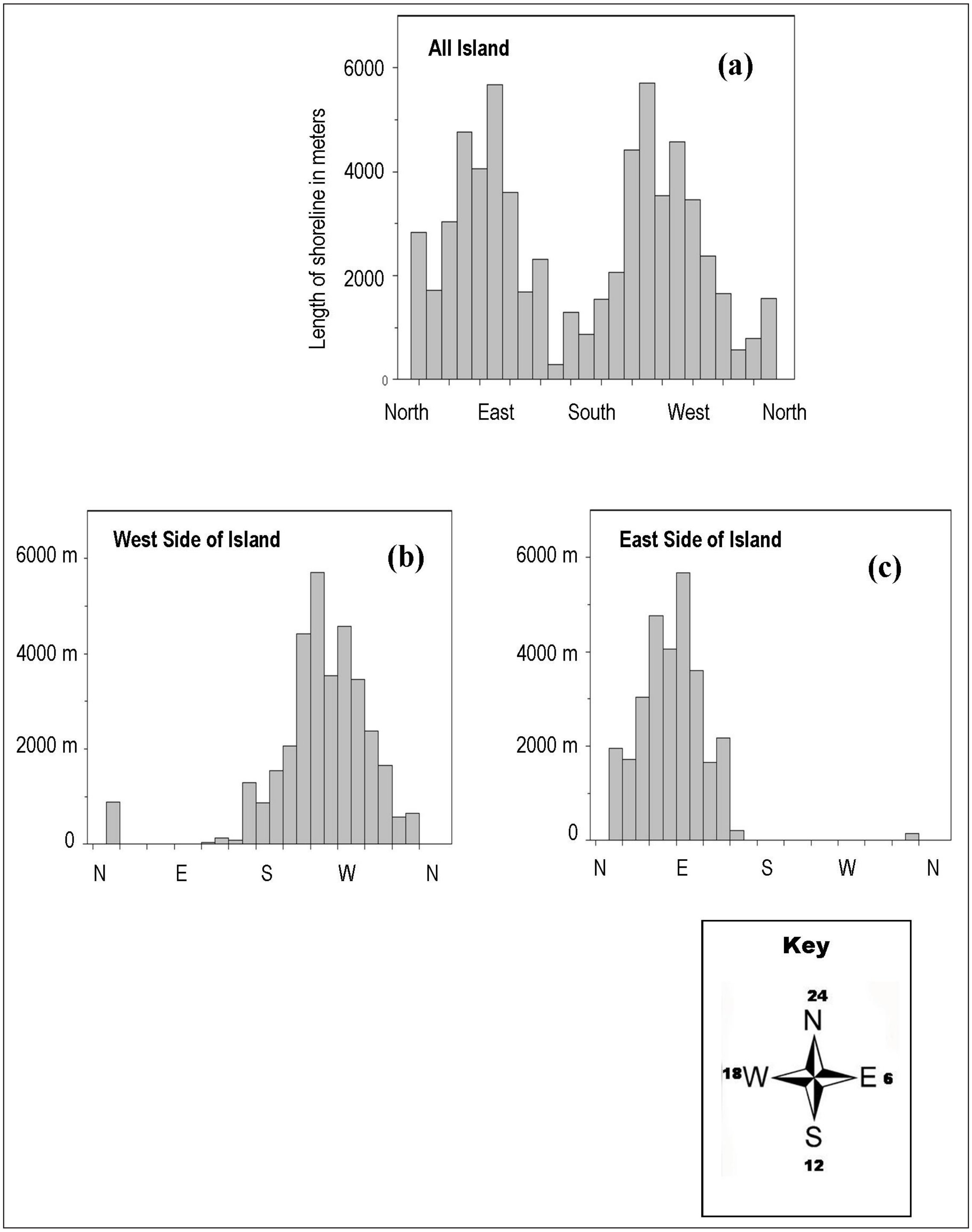


Figure 4.10. Histograms show frequency of aspect direction.
Histogram (a) shows all-island frequency of shorezone aspect in twentyfour 15° increments. Histogram (b) shows data for west side. Histogram (c) shows data for east side. Antelope Island has comparatively few shores that face toward the north-northwest or toward the south-southeast.

Island's elongate shape results in comparatively few north- or south-facing shores (Figure 4.10). The west side of the island has more shore stretches (410) than the east side (254) and a broader representation of aspect than the east side.

Patterns of shoreline superelevation generally resemble general patterns of aspect when classified as (a) 30-120°, (b) 120-165°, (c) 165-240°, (d) 240-290°, and (e) 290-30° (Figure 4.9). During 1986/87 shores of Antelope Island faced water in all 24 compass directions (Figure 4.10). Shores facing west and northwest, in general, have higher shoreline superelevation than those facing other directions. Specifically, west and west-northwesterly aspects between 240-290° correspond to high shoreline superelevation. Of 255 surveyed locations facing 240-290°, 76 percent have high shoreline superelevation, 23 percent have intermediate, and 1 percent has low superelevation. Intermediate shoreline superelevation is associated with north and south aspects. Southeast, east, and northeast facing shorelines generally have lower shoreline superelevation. Southeast facing shores (120-165°) have generally low shoreline superelevation with less variability than those on the west side. Of 111 surveyed locations on shores facing 120-165°, 63 percent have low shoreline superelevation, 33 percent have intermediate, and 4 percent have high superelevation. The relationship of lower superelevation and easterly facing shores is also evident in box and whisker diagrams and aspect compass rose (Figure 4.11).

Patterns of high superelevation resemble those of aspect facing west and northwest and those of long fetch (Figure 4.12). Of the 400 surveyed locations with high superelevation, 86 percent have fetch ≥ 50 km; 55 percent have fetch ≥ 55 km; and 50 percent have aspect 240-290°. Of the 200 surveyed locations with both high superelevation and aspect 240-290°, 199 have fetch ≥ 50 km and 140 have fetch ≥ 55 km. The overlap of fetch and aspect indicates that Antelope Island is located such that direction of long fetch and direction of strong storm winds coincide. Because of

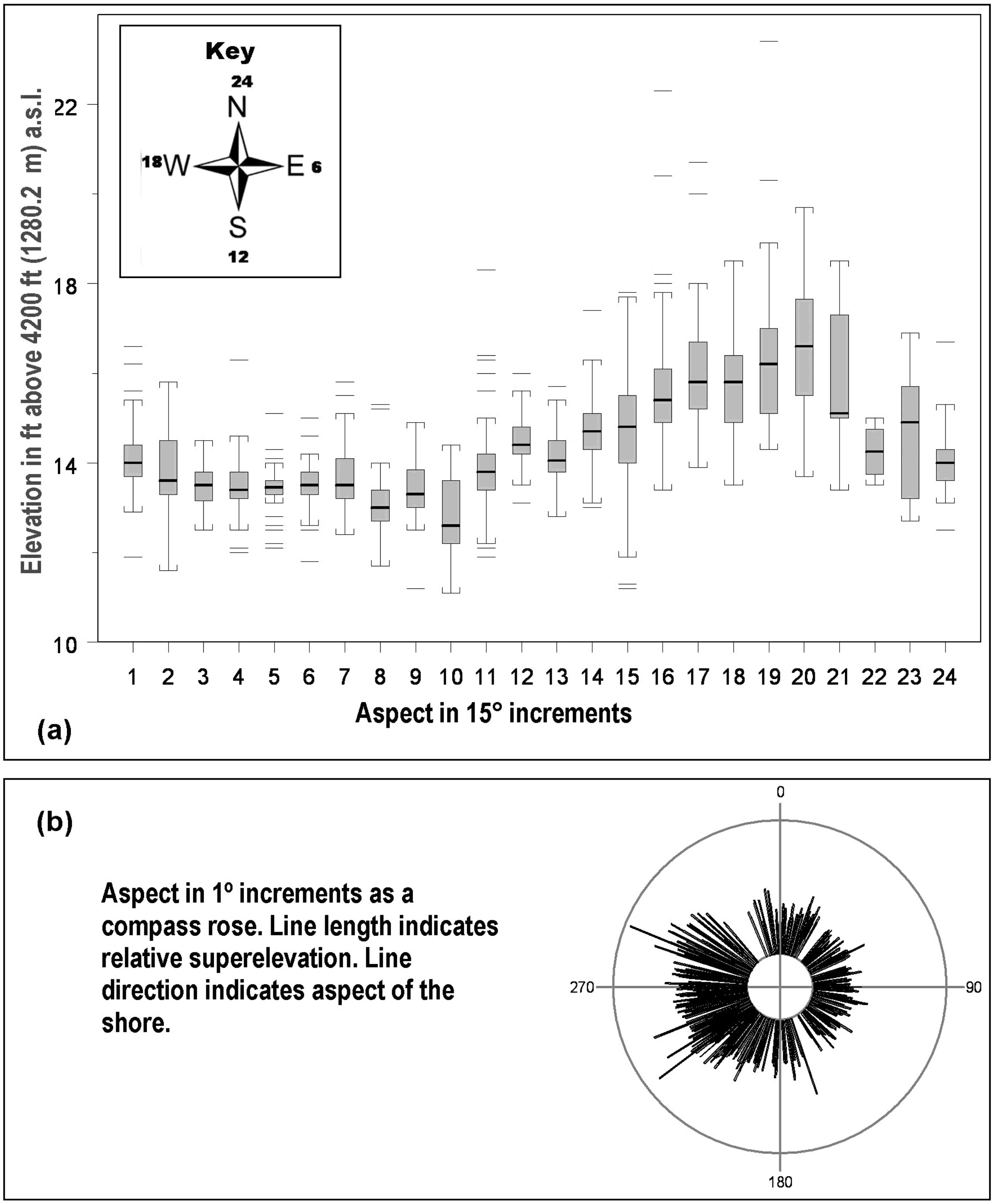


Figure 4.11. Plots of shore aspect and shoreline superelevation.
Box and whisker plots (a) and compass rose (b) show associations of shoreline superelevation and the direction a shore segment faces. Shores facing west and northwest have generally high shorelines. Those facing southeast have less variability and are generally lower.

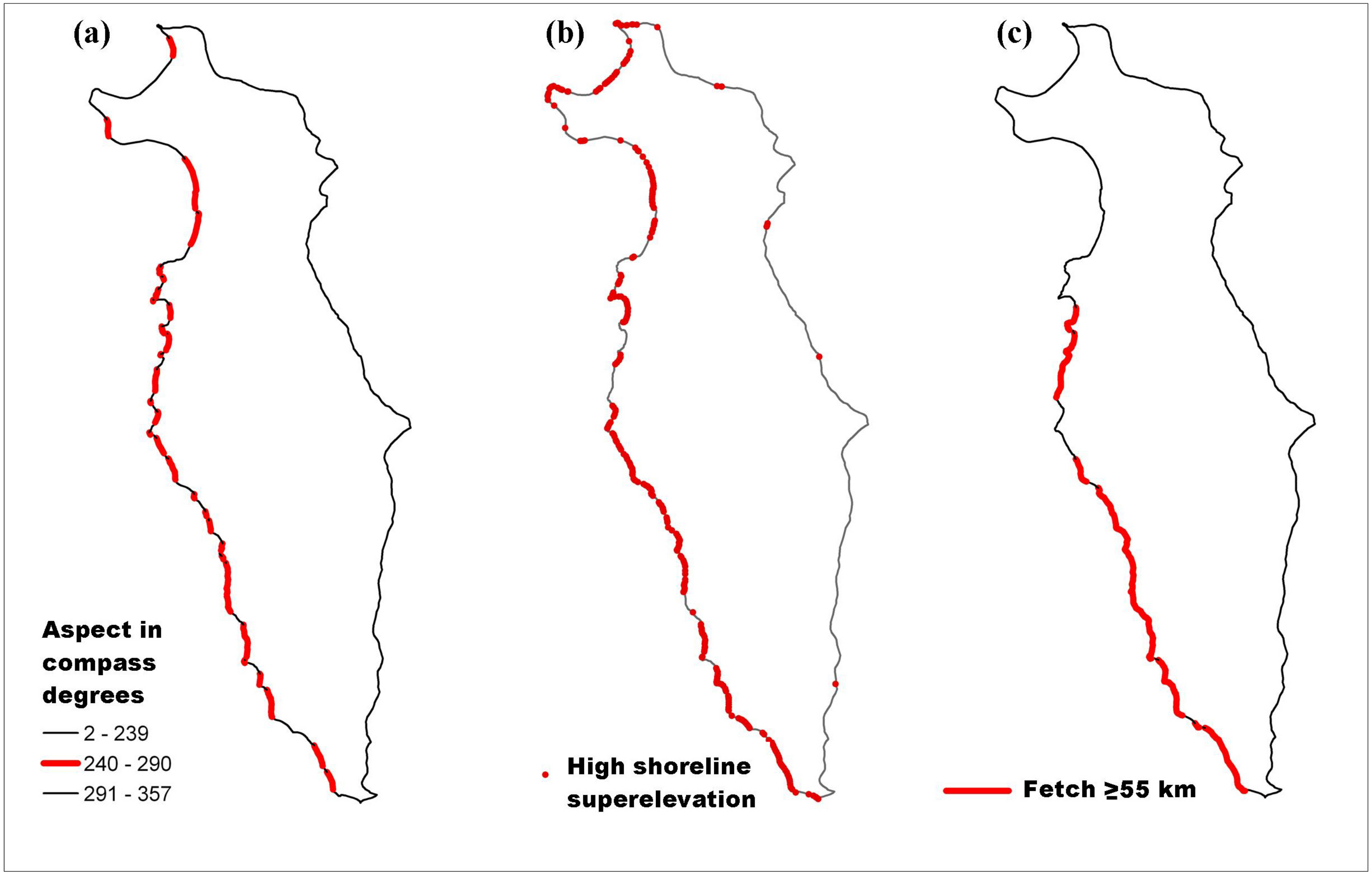


Figure 4.12. Shoreline superelevation, aspect, and fetch.
Patterns of (a) west-facing shores, (b) high shoreline superelevation, and (c) longest fetch generally resemble each other.

the overlap, the Antelope Island data set alone cannot be used to determine whether fetch totally explains shoreline superelevation. The data indicate that aspect and, by inference, strong winds are associated with shoreline superelevation; however, the association could be circumstantial due to the direction of fetch being a direction of storm winds.

Bay-scale patterns of wind-blown debris stranded on shores provide an independent line of evidence of associations of strong storm winds and shoreline superelevation. For example, for bays along Curlew Bay on the island's southwestern shore, shoreline superelevation increases progressively north to south and shoreline debris is stacked at the southern end of the bay (Figure 4.13). The concentration of stacked floated debris is interpreted as evidence of strong winds that blow materials on the wave surface downwind (Figure 4.14). However, the stacked debris could indicate the direction of last strong winds rather than direction of strongest winds. Bay-scale distributions of stacked lumber and progressive shoreline superelevation at 29 locations are interpreted as two lines of evidence of direction of strong wave energy (Figure 4.15). In general, on the west side of Antelope Island, bay-scale geomorphic evidence of stacked flotsam and progressively increasing shoreline superelevation indicates that both strong wave energy and strongest winds arrived from the northwest. For the east side of the island, bay-scale patterns indicate transport generally from the north but with exceptions. This evidence of wind-blown debris tends to corroborate island-scale patterns of associations of high shoreline superelevation with high-energy wave environments and direction of strong winds from the west and northwest.

Shorezone Slope and Shoreline Superelevation

Slope across shorezone profiles is not constant. For Antelope Island, the lower-shorezone slope, the slope between the 4195 and 4200 ft (1278.6 and 1280.2 m) a.s.l.

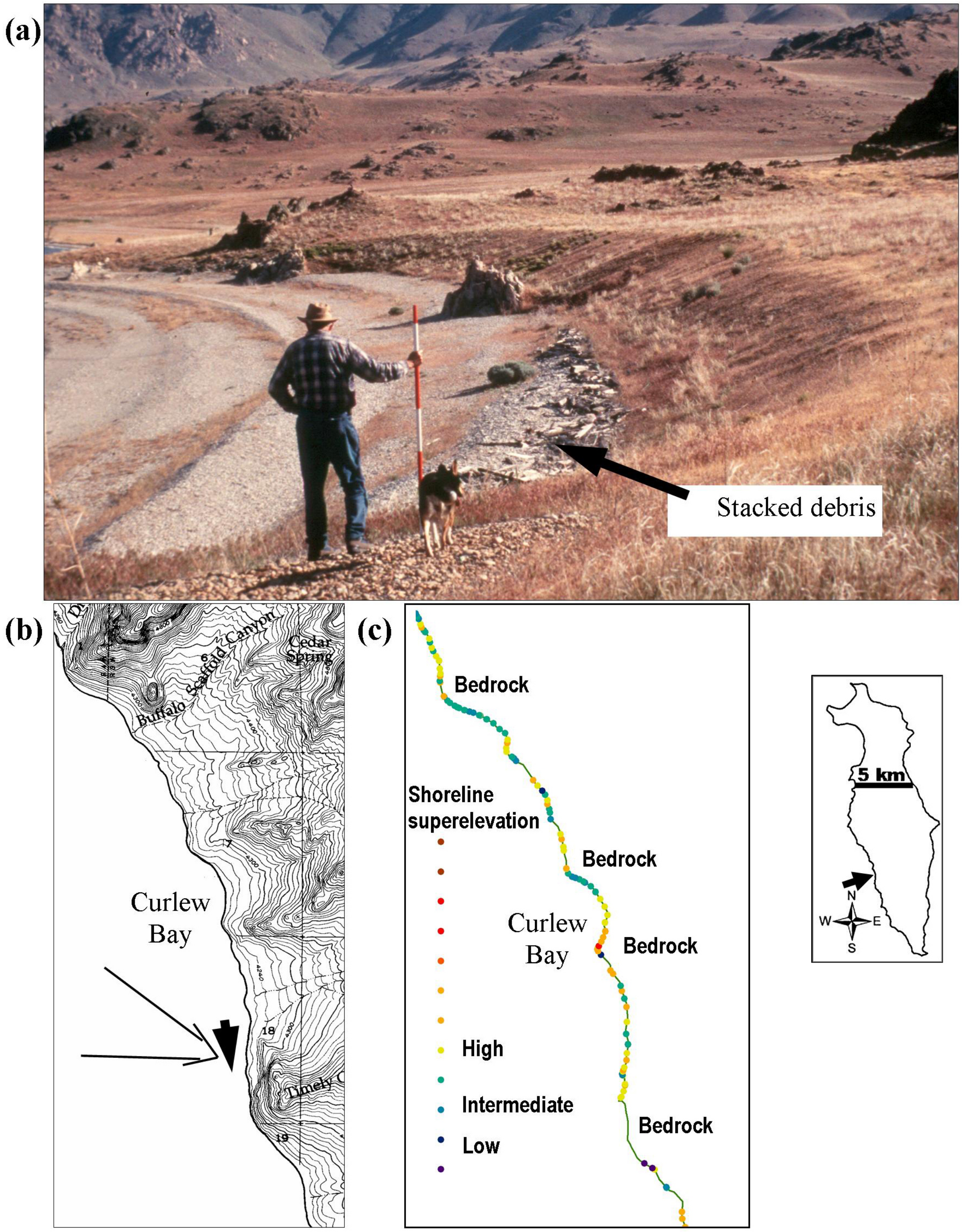


Figure 4.13. Bay-scale pattern of floated debris.
Photograph (a) shows debris stacked toward the south of Curlew Bay. Stacked debris is interpreted as evidence of wave transport direction. Arrows on map (b) show inferred wind direction (open arrow) and along shore transport (solid arrow). Map (c) shows shoreline superelevation in 1 ft (0.3 m) increments. Superelevation is lower in the lee of bedrock points than along shores facing into the wind. Source of base map: Utah State Parks and Recreation, 1991.

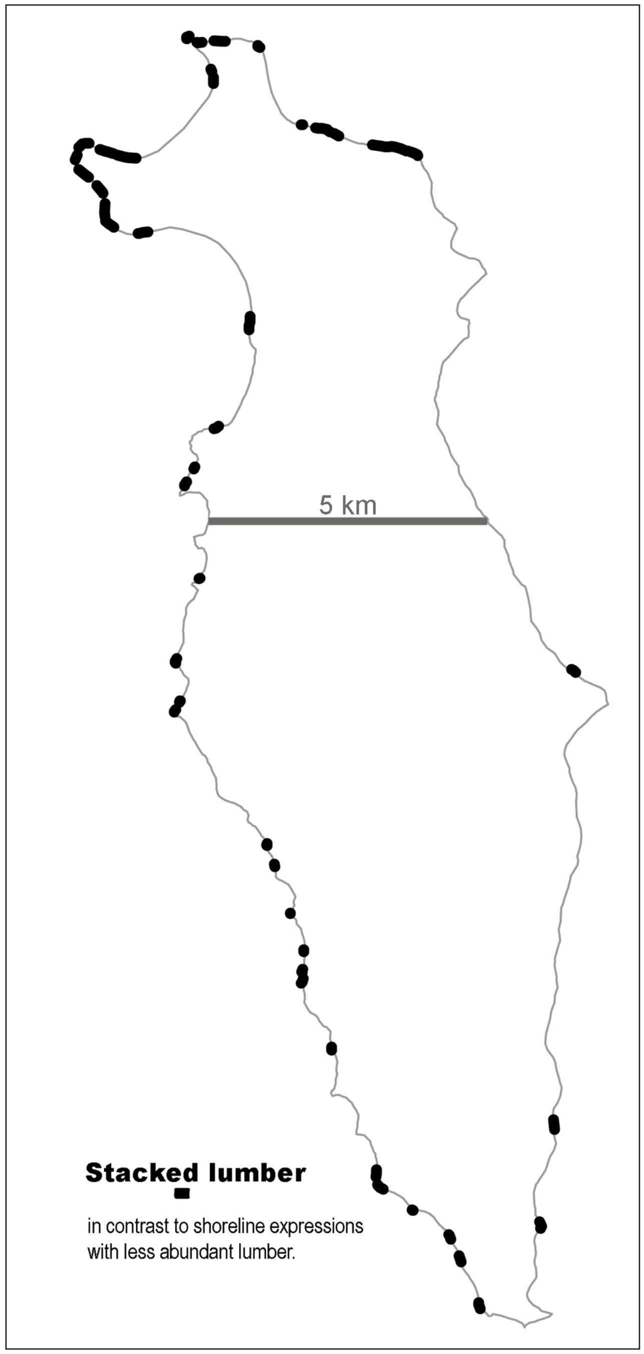


Figure 4.14. Distribution of stacked, floated, lumber debris.
Map shows shoreline stretches where waves deposited stacks of lumber along expressions of the 1986/87 shoreline. Patterns of stacked debris, in contrast to less abundant debris, are interpreted as evidence of direction of strongest wind.

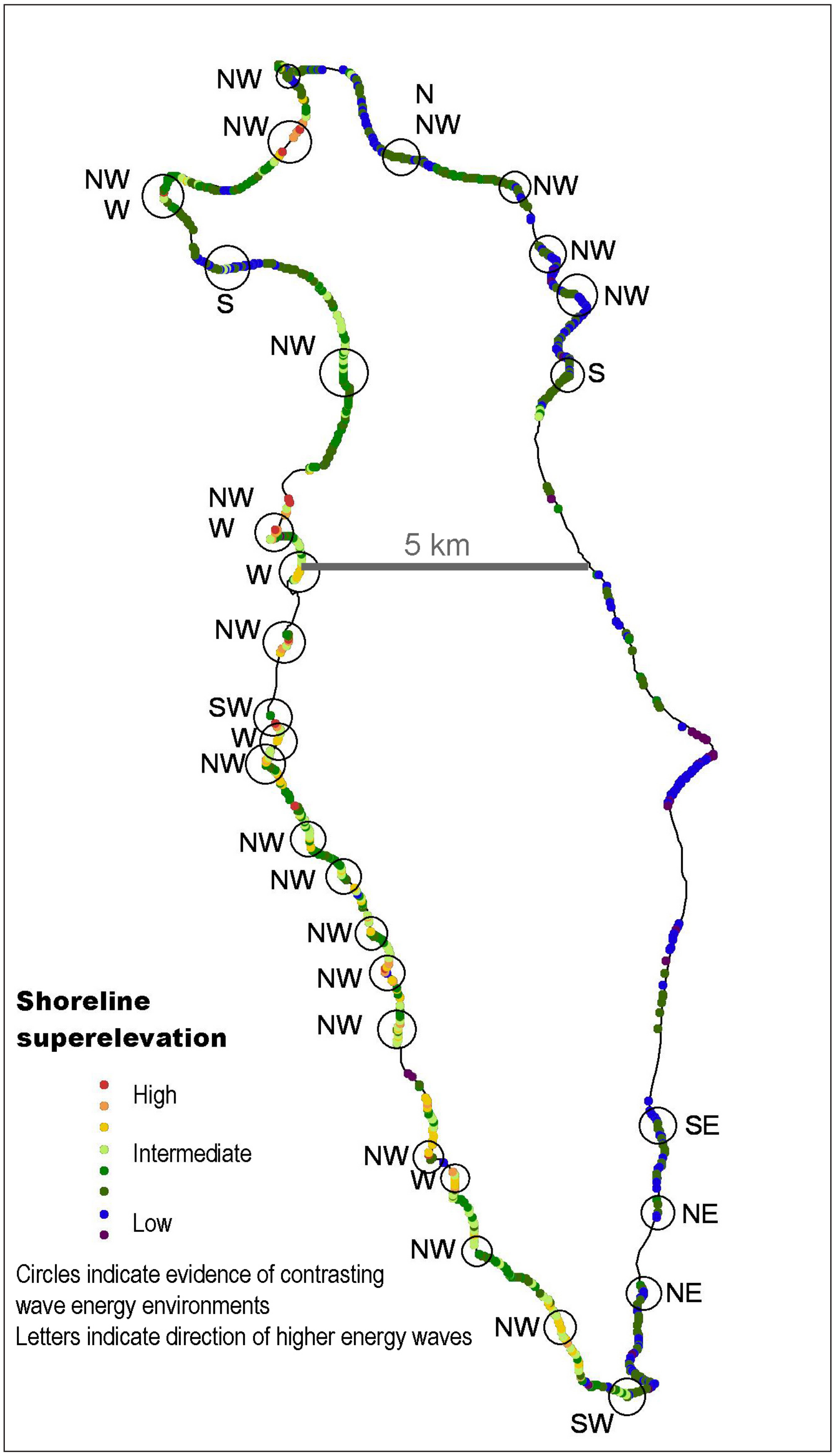


Figure 4.15. Places with evidence of direction of high-energy waves.
Progressive or contrasting patterns of shoreline superelevation and distribution of flotsam provide evidence of direction of high-energy waves at 29 locations around the island. The map shows shoreline superelevation as eight increments and the key relates the increments to high, intermediate, and low shoreline superelevation.

contours, tends to be low-gradient. Upper-shorezone slope, the slope between the 4200 and 4220 ft (1280.2 and 1286.3 m) a.s.l. contours, tends to be steeper gradient (4.3° average slope) than lower-shorezone slope (0.5° average slope). In general, steeper slopes are on the west side of the island, and gentler slopes are on the east side of the island for both the upper shorezone and lower shorezone (Figure 4.4).

High superelevation is associated with steeper upper-shorezone slope when upper-shorezone slope is classified using three classes: (a) > 6°, (b) 2-6°, and (c) < 2° (Figure 4.16). Higher superelevation is associated with steeper slopes when lower-shorezone slope is classified using three classes: (a) > 1°, (b) 0.1-1°, and (c) < 0.1° (Figure 4.16). In general, places with low shoreline superelevation have gentle lower-shorezone slope. Specifically, for the 414 surveyed locations with low superelevation, 64 percent have lower-shorezone slope < 0.1°. A scatterplot of shorezone slope against shoreline superelevation also indicates that steeper upper-shorezone slopes are associated with higher shoreline superelevation although the scatter is broad (Figure 4.17). For the 299 surveyed locations with upper-shorezone slope > 6°, 55 percent have high shoreline superelevation, 27 percent have intermediate, and 18 percent have low superelevation.

Shorezone Materials and Shoreline Superelevation

Shorezone materials are unexpectedly poorly associated with shoreline superelevation. Each of the following five attributes characterizing shorezone materials was expected to vary with differences in wave-energy environments around the island and, therefore, be associated with relative shoreline superelevation: (1) beach zone materials, (2) relative abundance of sand, (3) relative abundance of gravel, (4) largest particles moved, and (5) type of shorezone (erosional, depositional, or both). It was expected that high-energy wave environments and, therefore, high shoreline

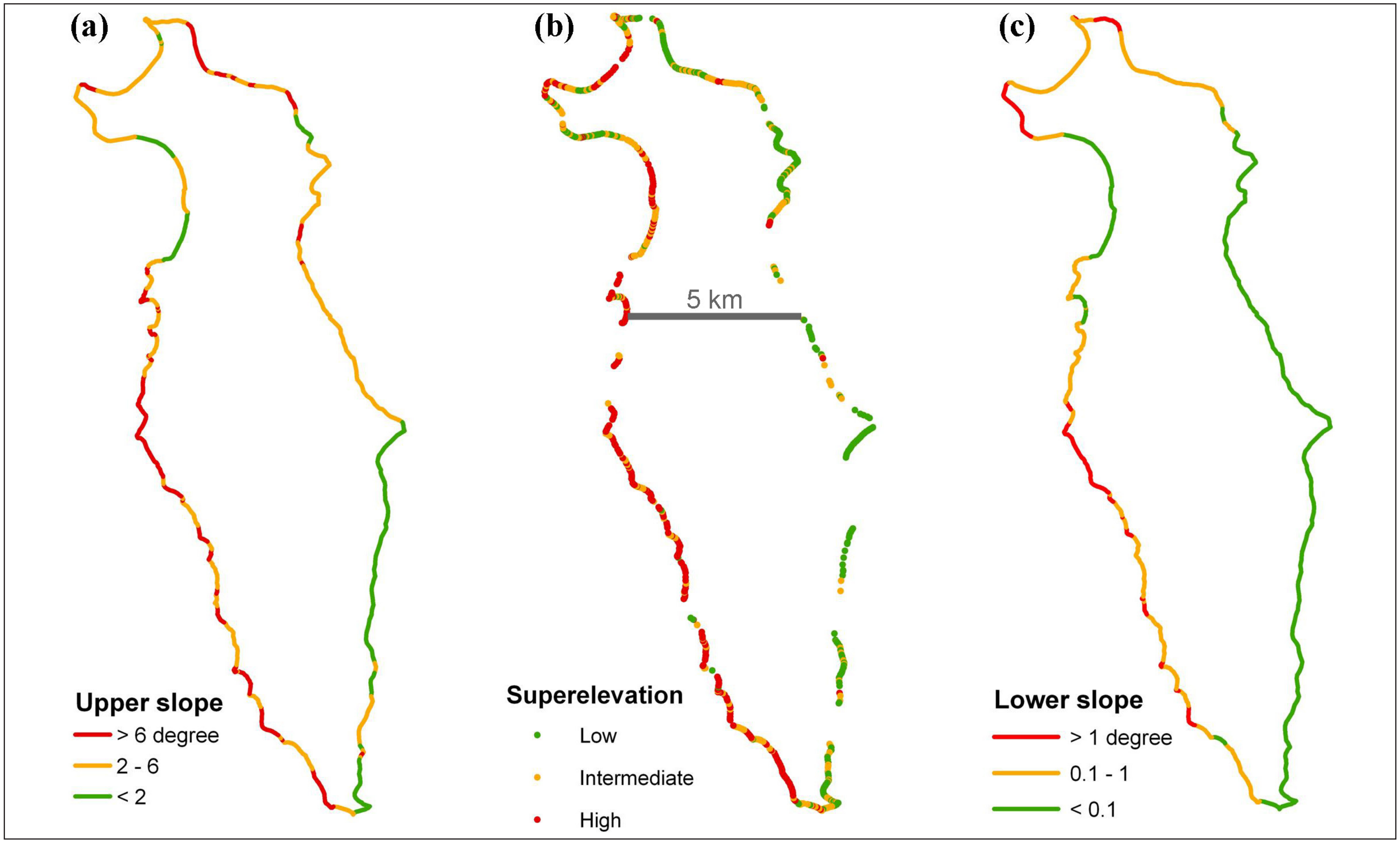


Figure 4.16. Shorezone slope and shoreline superelevation.
Map (a) shows upper-shorezone slope in three classes that generally resemble the patterns of shoreline superelevation shown in map (b). Map (c) shows lower-shorezone slope also in the three classes that resemble patterns of shoreline superelevation. In general, steep upper-shorezone slope is associated with high shoreline superelevation and gentle, low gradient, lower-shorezone slope is associated with low shoreline superelevation.

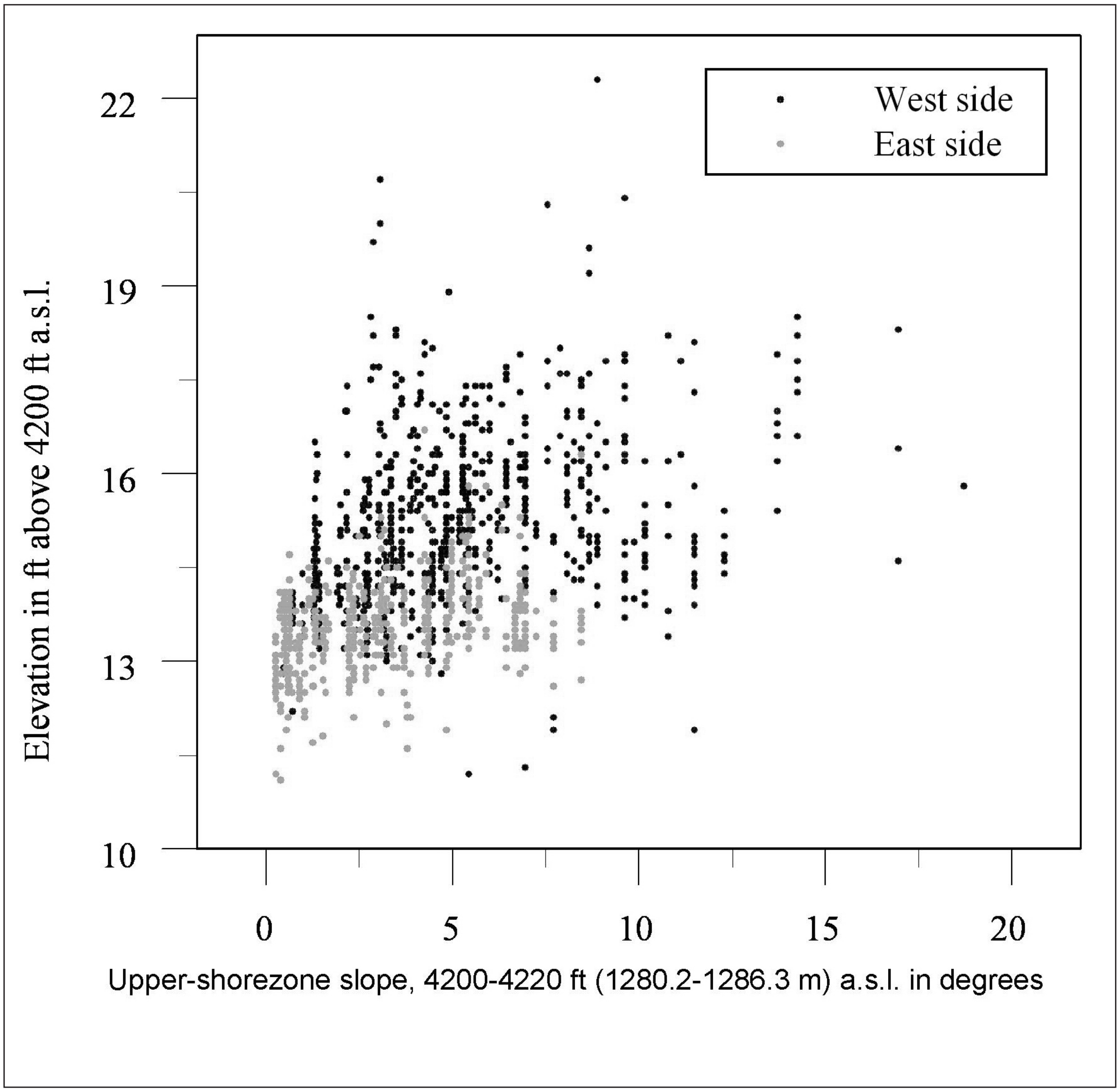


Figure 4.17. Plots of upper-shorezone slope and shoreline superelevation. Scatterplots show that east side, upper-shorezone slopes are gentler than those of the west side. Steeper slopes on both sides of the island are associated with higher shoreline superelevation.

superelevation would be associated with coarse debris and erosional shorelines.

Patterns of shoreline superelevation do not generally resemble patterns of materials of the shorezone. For example, it was expected that cobble-dominated beach zones would be associated with high shoreline superelevation and that 1986/87 beaches dominated by sand would have lower shoreline superelevation, but associations are not consistent (Figure 4.18). Of 106 surveyed locations with beach zone dominated by cobbles, 27 percent have high shoreline superelevation, 42 percent intermediate, and 35 percent low superelevation.

It was anticipated that contrasts of patterns of abundance of sand versus gravel might be associated with shoreline superelevation, with abundant gravel associated with higher shoreline superelevation than abundant sand. Increasing abundance of gravel was not associated with higher shoreline superelevation. Decreasing abundance of sand was associated higher shoreline superelevation (Figure 4.19). The decrease of sand associated with higher shoreline superelevation is explained as the effects of higher energy waves entraining sand and transporting it from the shore. The size of largest particles moved was not consistently associated with high shoreline superelevation (Figure 4.20 and box and whisker plot of Figure 4.21). For 351 surveyed locations along shores with evidence that cobbles were the largest particles moved during 1986-1987, less than half (48 percent) have high shoreline superelevation. For 486 surveyed locations where coarse gravel was the largest particle moved, 32 percent have high shoreline superelevation, 37 percent have intermediate, and 31 percent have low superelevation.

Coastal Landforms and Shoreline Superelevation

It was thought that erosional shorezones might be associated with high shoreline superelevation, but erosional shorezones have generally the same range

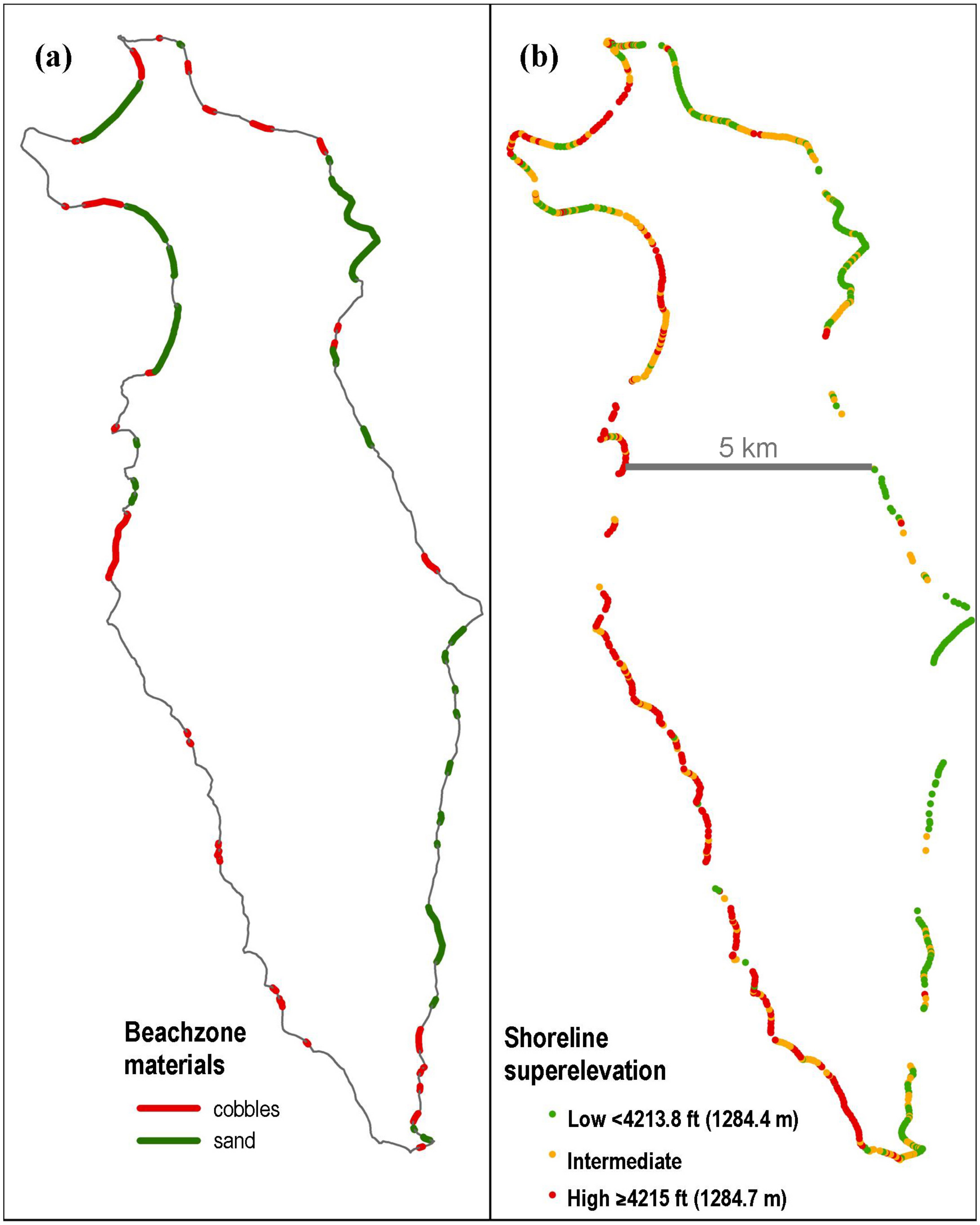


Figure 4.18. Beach materials and shoreline superelevation.
Map (a) shows cobble-dominated shorezones and sand-dominated shorezones. It was expected that coarse shorezone materials, such as cobbles, would be associated with high shoreline superelevation and that fine shorezone materials, such as sand, would be associated with low superelevation. However, associations are inconsistent. Grain size of shorezone materials is not a good indicator of shoreline superelevation for shores of Antelope Island and, therefore, not a reliable indicator of wave energy or wind strength.

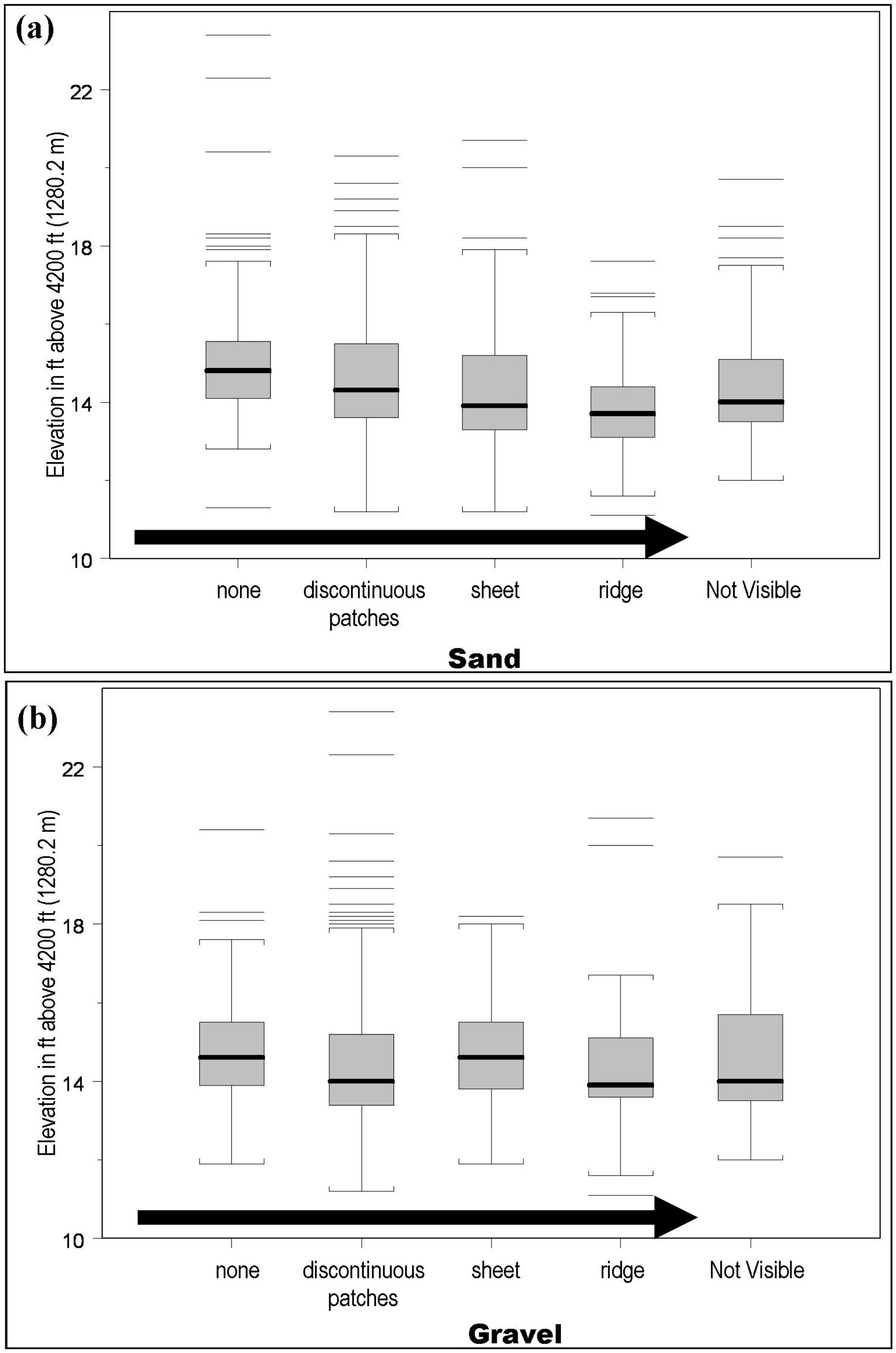


Figure 4.19. Plots of abundance of sand and gravel and shoreline superelevation. Arrows indicate increasing abundance of sand and gravel along the inundation shoreline expression. For approximately 5 percent of the shore, materials were not visible due, for example, to wetland vegetation. Plot (a) indicates that increased sand is associated with lower shoreline superelevation. Plot (b) does not show an association between abundance of gravel and shoreline superelevation.

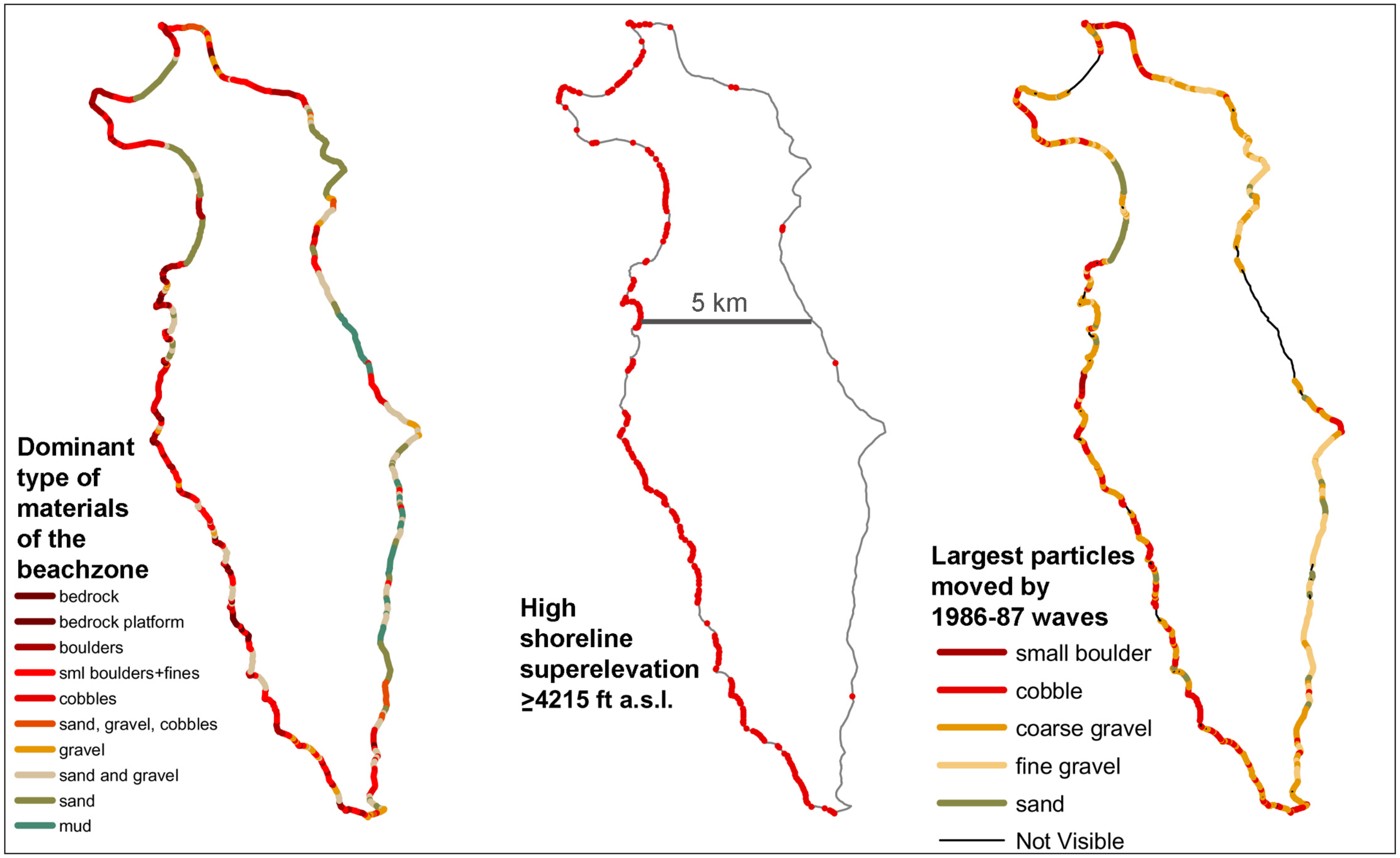


Figure 4.20. Shorezone materials and shoreline superelevation.
Map (a) displays the types of materials that dominate the 1986/87 beach zone. Map (b) shows only high shoreline superelevation. Map (c) shows observed patterns of largest materials moved by shore processes during 1986-1987. The hues and saturation of symbols of maps (a) and (c) indicate expected relationships of increasing size with higher shoreline superelevation. However, the patterns of maps (a) and (c) are not those of map (b). Size and type of shorezone materials are not consistently associated with superelevation..

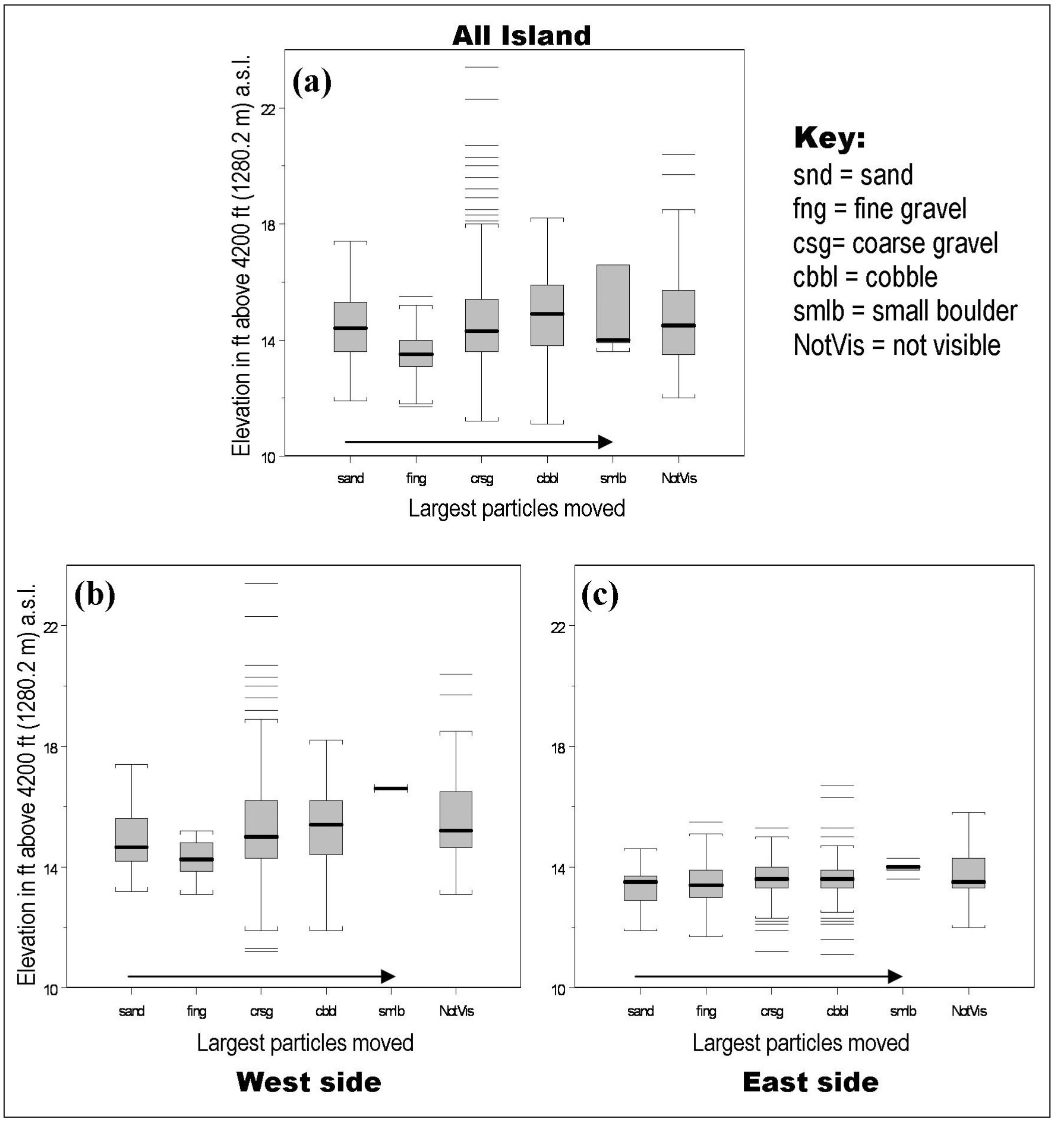


Figure 4.21. Plots of largest particles moved and shoreline superelevation. Largest particle moved was determined by observing the general class of materials that had been mobilized along the 1986/87 beach face and along inundation shoreline expressions. Arrows indicate increasing size of shorezone materials. Size of materials moved was not associated with high shoreline superelevation for the island as a whole, plot (a), or for either the east or west sides of the island, plots (b) and (c).

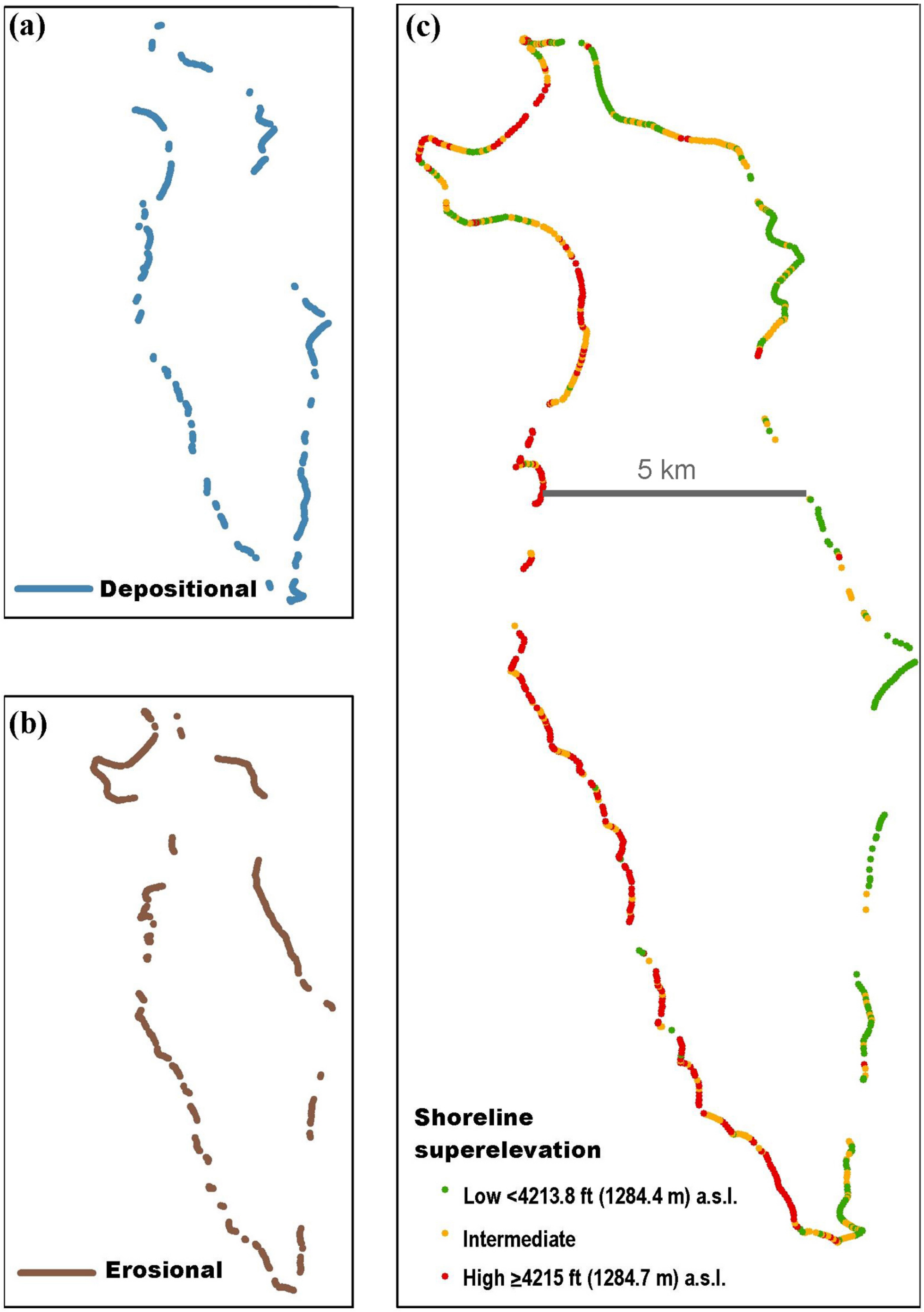


Figure 4.22. Erosional and depositional shorelines and shoreline superelevation. Patterns of erosional shorezone stretches of shoreline expressions of 1986/87 shown in map (a) and deposition shorezone stretches shown in map (b) do not indicate an association with shoreline superelevation shown in map (c).

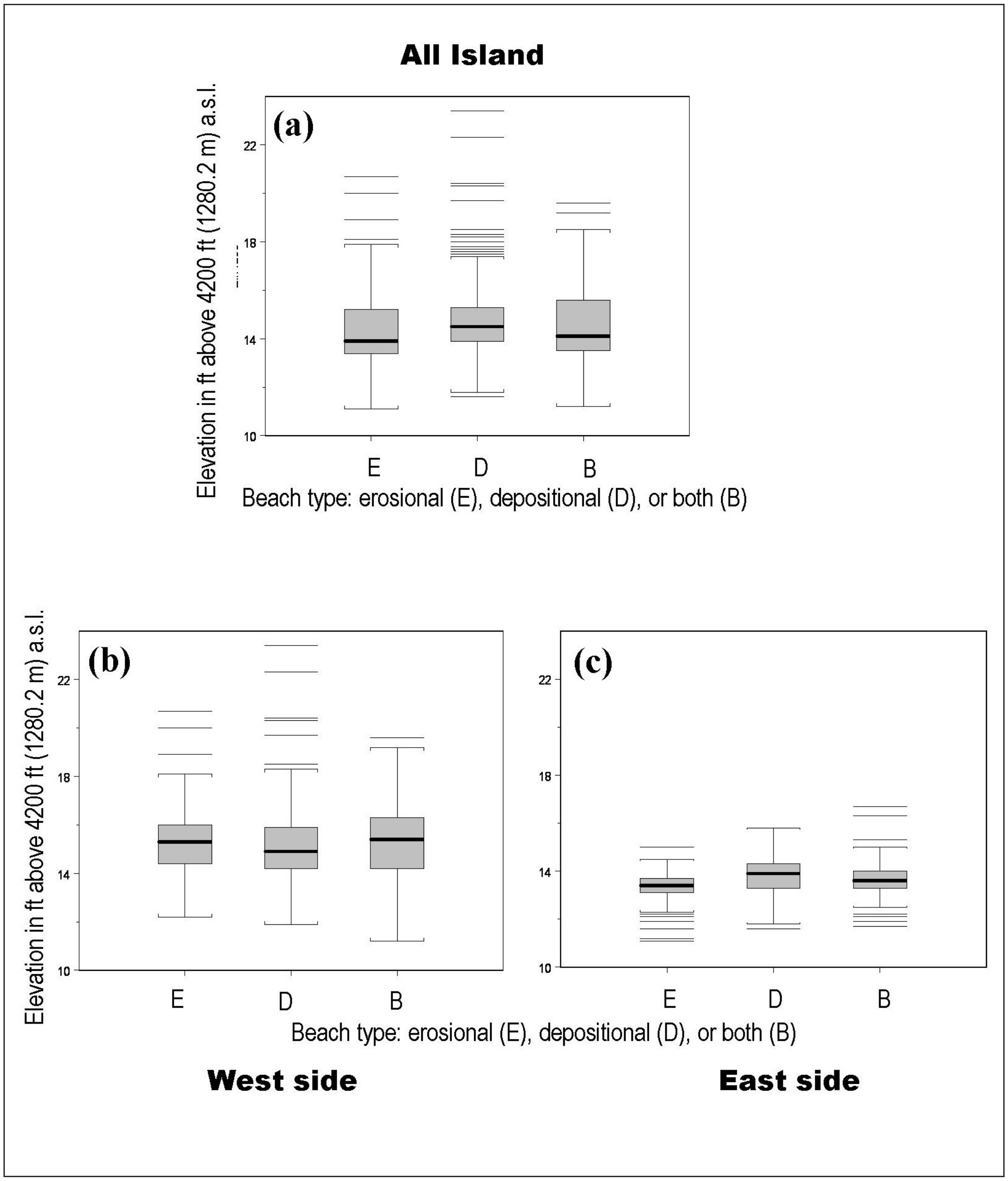


Figure 4.23. Plots of beach type and shoreline superelevation.
Shorezones were mapped as (1) erosional, (2) depositional, or (3) both erosional and depositional. Box and whisker plots indicate that the three beach types are not associated with shoreline superelevation. Plot (a) is the island as a whole, (b) is the west side, and plot (c) is the east side.

of shoreline superelevation as depositional shorezones and shorezones that are both depositional and erosional (Figure 4.22 and box and whisker plot of Figure 4.23). Of the 400 surveyed locations with high superelevation, 36 percent are along erosional shorezone segments, 36 percent are along depositional shorezone segments, and 28 percent are along shorezone segments with both erosional and depositional evidence of 1986/87 coastal processes. Both the west and east sides of the island have erosional and depositional shorezones.

Patterns of coastal landforms of the west side of the island differ from those of the east side. Landforms that jut into the lake along the west side of the island are generally erosional landforms in contrast to those of the east side that are generally accretional. Contrasting patterns of high versus low shoreline superelevation of the west and east sides of the island generally resemble the contrasting patterns of exposed bedrock headlands of the west side of the island and extensive mudflats of the east side of the island (Figure 4.24). The eastern coast of the island is smooth compared to the western coast. The western coast is broken by 27 headlands, points, and bedrock exposures compared to 18 points on the east. Thus, west-side circulation cells are smaller and transport distances are shorter than for circulation cells of the east side.

Patterns of sediments and their associated landforms are additional evidence of associations of directions of strong storm winds. General patterns of onshore and offshore currents caused by wind physically blowing the surface of the lake (Figure 4.3) are partly responsible for contrasting patterns of sedimentation. Shores that face into strong winds have sediment patterns of offshore currents, such as lag deposits of gravels and cobbles. In contrast, shores exposed to offshore winds have fine sediments in place, due, in part, to onshore currents and also due to the lack of offshore currents (Allen, 1984; Masselink and Hughes, 2003). Along-shore currents also are important transport agents, particularly for coastal systems dominated by wave trains arriving

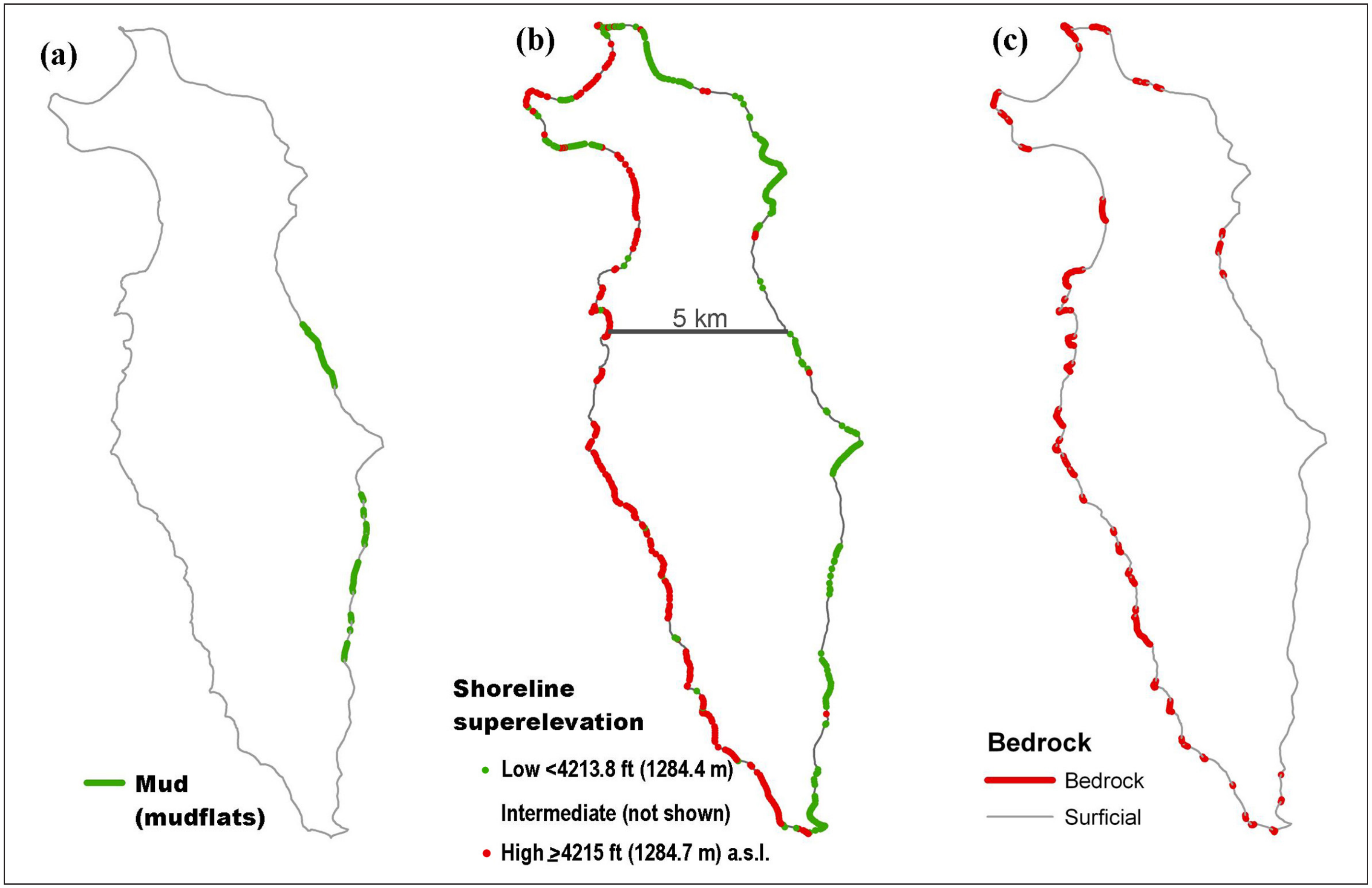


Figure 4.24. Landforms and shoreline superelevation.
Map (a) shows shorezone stretches dominated by mud. Map (b) shows shoreline superelevation. Map (c) shows shoreline stretches dominated by bedrock. Extensive mudflats are associated with low superelevation. Bedrock headlands are exposed bedrock along convex portions of the shoreline. They are associated with high superelevation. Contrasting patterns of bedrock headlands and mudflats indicate contrasting wave-energy environments.

oblique to shore (Komar, 1989). Effects of along-shore transport include the fining of grain size away from their bedrock source. These effects complicate interpretations of sediment patterns. Even so, offshore patterns of fine sediments on low-gradient shorezone slopes of the east side of Antelope Island contrast with erosional shorezones and steeper gradients offshore of the island's west shore. Of 21 surveyed locations with beach zone dominated by mud, all are on the east side of the island and 86 percent have low shoreline superelevation. These patterns of accretional landforms on the east side of the island and erosional landforms on the west side of the island are consistent with a pattern of strong onshore winds from the west causing downward, offshore lake currents off the west shore of the island and causing upwelling onshore lake currents onto the east shore of the island (Figure 4.3).

It was thought that planform shape, for example, whether shoreline shape is concave or convex, might be associated with shoreline superelevation. Headlands refract swell and focus wave energy, and pocket beaches trap on-rushing water of in-coming waves along some marine coasts (Komar, 1998). Neither concave nor convex planform shape is consistently associated with high or low shoreline superelevation for the island as a whole, for the east side, or for the west side (Figure 4.25). For 678 shore segments with concave planform shape, 35 percent have high shoreline superelevation, 35 percent have intermediate, and 30 have low superelevation. Bedrock headlands and pocket beaches are features of the west shore of the island which generally has high shoreline superelevation. The phenomenon of wave refraction of individual wind waves was not observed during storms, although refracted wave trains of swell consisting of organized waves of lesser energy than storm waves were observed particularly along the east side of the island, specifically along Sea Gull and Unicorn Points.

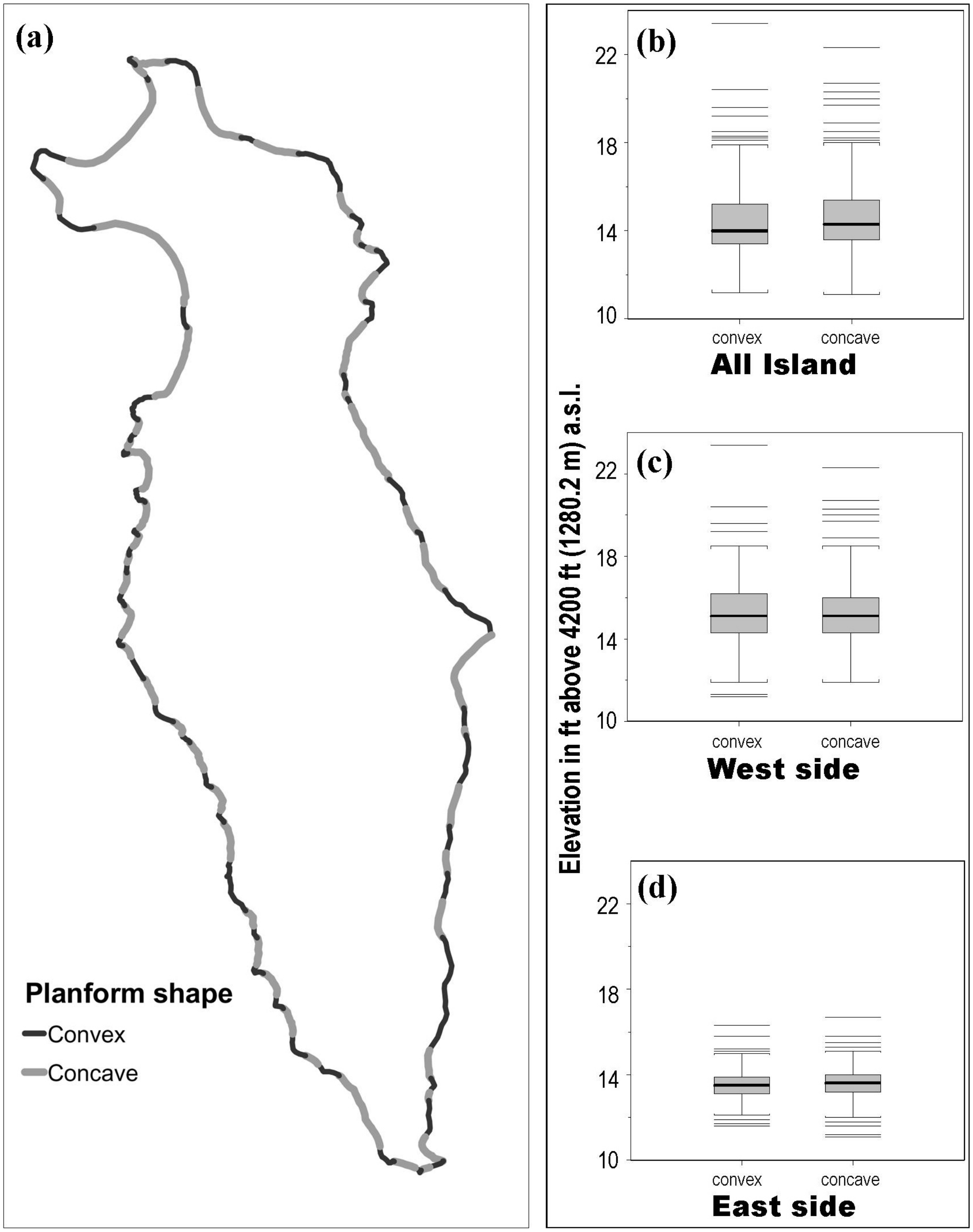


Figure 4.25. Planform shape of the shore and shoreline superelevation.
Map (a) shows the shore-route divided into 94 segments classified as dominantly convex or concave. Box and whisker plots (b), (c), and (d) indicate that neither concave nor convex shorelines are associated with shoreline superelevation for the island as a whole or for the west or east sides.

Discussion

With respect to the third set of statements of Table 1.1 concerning relationships among coastal conditions, shoreline superelevation, and wave energy, the Antelope Island data set clarifies some relationships and not others. Specifically, the data set confirms that shorezone slope and coastal landforms are associated with shoreline superelevation and, therefore, with wave energy. However, coarse beach materials are not good indicators of high-energy wave environments for Antelope Island. Implications of these associations will be discussed later in this chapter. The Antelope Island data set does not resolve the relative contributions of fetch and wind strength to relative energies of waves that run up the island's shores.

Fetch Versus Wind Strength

Differences in wave-energy environments cause differences in shoreline superelevation (Chapter 3). Antelope Island's location in Great Salt Lake precludes a definitive resolution of whether fetch, wind strength, or both cause the contrasts in wave-energy environments observed along the west versus east sides of the island. Antelope Island shoreline superelevation data and patterns of wind-blown debris are consistent with shoreline superelevation being related to direction of strong winds. The data also indicate that relative shoreline superelevation is associated with increase fetch length. Empirical research confirms that an increase in wind speed results in more than a linear increase in wave height and associated wave energy (Komar, 1998). However, increases in wave height and wave energy are limited by the physical instability of waves and their capacity to gain height before they break.

Hypothetically, if a lake were very large, on the order of 700 km, and elongated north-south, with dominant storm direction from the west and relatively weaker winds from the north, both the dominant storm winds and the relatively weaker winds would cause high shoreline superelevation. Shoreline superelevation would indicate high-energy wave environments but would not indicate direction of strongest wind. This is the phenomenon discussed in Gilbert (1890) and Johnson (1919). However, for a lake 30 km in diameter, differences in wind strength due to a dominant pattern of storm winds would cause differences in wave-energy environments. For such an idealized, hypothetical, fetch-limited, circular lake, with strongest wind from the northwest, shoreline superelevation would be higher on the southeastern, downwind shores facing into the direction of strongest storm winds. Relative shoreline superelevation would not only indicate wave energy, but it also would indicate direction of strongest wind.

Great Salt Lake is a fetch-limited system, meaning it is not so large that fetch alone accounts for a fully arisen sea. Fetch-limited wave environments are ones “in which wave energy (or wave height) is limited by the size of the wave generation area (fetch)” (USACE, 2003, p. A-30). For fetch lengths of less than 60 km, typical of shores of Antelope Island, the nomograph of Figure 1.8 predicts that wave height increases as fetch increases and also with increases in wind strength and storm duration.

The coastal environment of Great Salt Lake, because it is fetch-limited, contrasts with marine coasts where swell arrives on shore from fully arisen seas as series of waves of relatively similar height, wave length, and direction. A sea surface that is not fully arisen consists of individual wind waves of diverse energies heading in diverse directions, although generally downwind (Komar, 1998). Patterns of variability of superelevation observed on Antelope Island are consistent with wave runup of individual wind waves of a disorganized sea encountering diverse coastal conditions, including shorezones of differing steepness and shore materials. Shorezone slope, shore aspect, and planform shape are more variable on the west side than east side. This contributes to the greater variability of shoreline superelevation on the west side of the island.

Further research on Great Salt Lake could clarify relationships among fetch, direction of strong winds, and shoreline superelevation. One way to isolate effects of fetch from wind strength is to compare superelevation for pairs of locations, as suggested by Gilbert (1890). Shoreline superelevation at locations on opposite sides of a bay could be compared where one shore is on the upwind side of the lake and the other is on the downwind side.

If shoreline superelevation is a function of fetch and wind strength, then

$$Z_{in} = (Z_{fetch} + Z_{windstrength}) + c$$

where

Z_{in} = shoreline superelevation,

Z_{fetch} = superelevation attributable to fetch,

$Z_{windstrength}$ = superelevation attributable to wind strength,

and

C = other factors.

With Z_{fetch} held constant, differences in Z_{in} are due to $Z_{windstrength}$ plus other factors, such as shorezone slope. Chapter 5 reports initial findings from Gunnison Bay regarding the specific question of fetch versus wind strength and the relative contribution of other factors, such as shorezone slope.

Further research also could explore the sensitivity of shoreline superelevation to fetch length. If the signal of fetch can be quantified and isolated from the total wave-energy signal, the net effect of other factors can be quantified. One way to quantify effects of diminished fetch is to document evidence of shoreline superelevation at locations with evidence of both the 1986/87 and 1860s-70s shorelines. Construction of the Southern Pacific solid-fill causeway from Promontory Point to Lakeside in 1959 cut the west part of the lake virtually in half, reduced fetch markedly for most of the lake's shore, and reduced it dramatically at some locations. Field work during 2003 at Lakeside and at places along the east shores of Gunnison Bay identified evidence of landforms and debris that demarcates the two historic highstands and documents differences in shoreline superelevation Figure 4.26.

Further research could classify landforms around Great Salt Lake to test associations found around Antelope Island with contrasting sediments, accretional landforms, and erosional landforms. If Fremont Island, Stansbury Island, and Carrington Island all have upwind, leeward features along eastern and southeastern exposures, in spite of significant differences in fetch, then contrasts of accretional versus erosional coastal landforms would suggest that storm-wind conditions, not simply fetch, determine relative wave energy.

Another area for future research concerns ways to quantify the wave-generating surface of lakes. Calculating fetch as a vector may be too simplistic for a shallow, closed-basin lake, such as Great Salt Lake. Evidence of shoreline superelevation around the shores of Great Salt Lake could be used to test alternative methods of calculating effective fetch. Such an investigation could explore advantages and disadvantages of calculating fetch as a vector or as surface area. Calculations of fetch as a surface area have been shown to be no more accurate in determining effective fetch for marine, tropical depressions than those calculating fetch as a straight line vector (USACE, 2002, p. II-2-45). Modified vector methods for calculating fetch have been developed by USACE (1989) as part of calculating wind wave generation for elongate waterbodies, such as Puget Sound and large reservoirs. GIS techniques could be used to incorporate effective fetch into predictions of location-specific inundation hazards of shallow, fetch-limited lakes, such as Great Salt Lake. GIS techniques also have capabilities to incorporate spatial complexities of Great Salt Lake that change with lake fluctuations. Islands, landmasses, and submerged topographic features

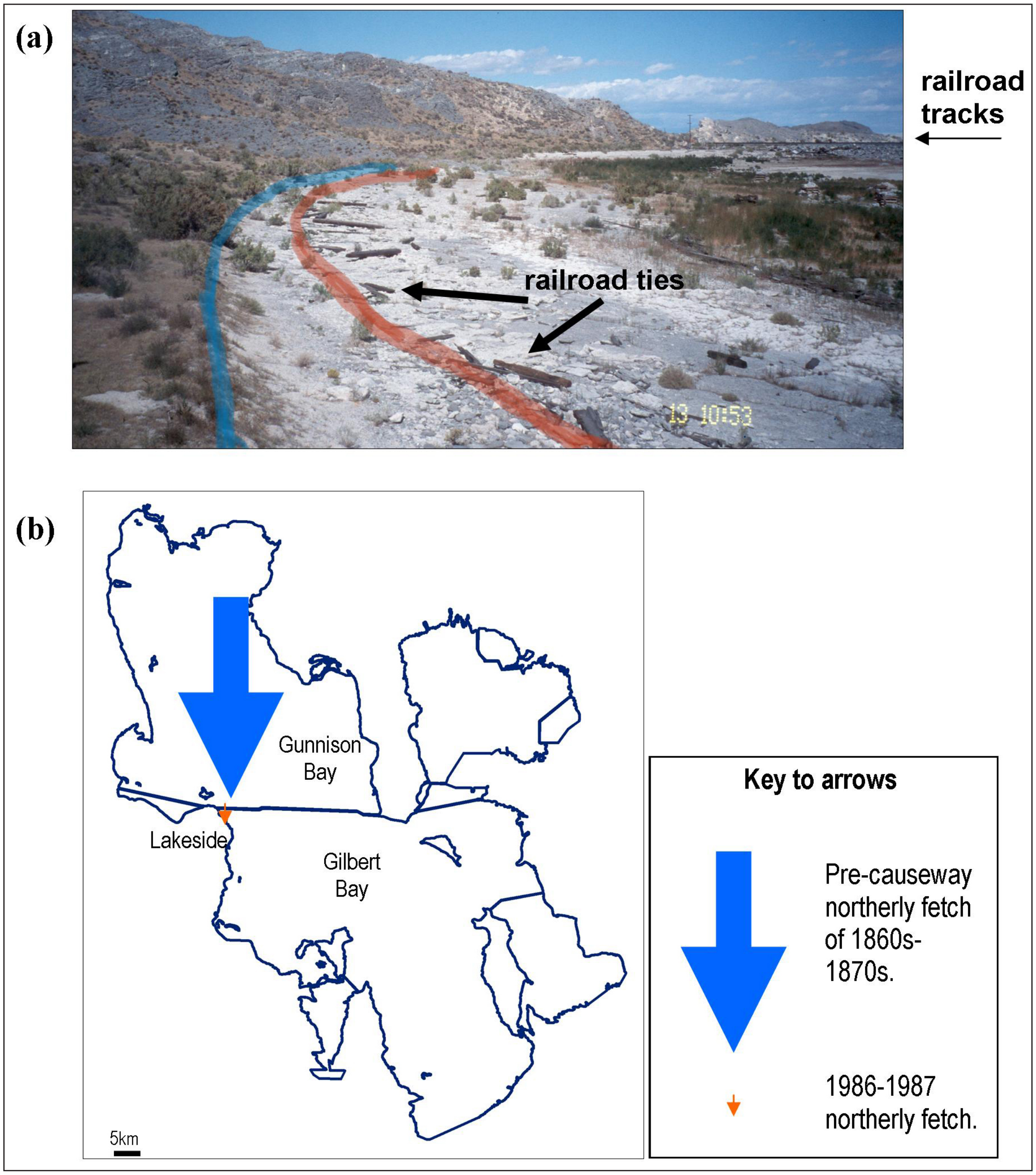


Figure 4.26. Evidence of diminished fetch.
Photograph (a) looks north to the railroad causeway immediately east of Lakeside. The red line highlights the approximate location of the inundation expression of the 1986/87 shoreline. The blue line highlights a prominent older shoreline expression interpreted to be an expression of the 1860s-70s lake highstand. Railroad ties indicate scale. Causeway construction of the railroad trestle and solid fill began in 1902. The solid-fill causeway completed in 1959 dramatically diminished maximum fetch to many shorezones including northwesterly facing shorezones of Antelope Island. Diminished fetch is shown schematically in map (b). Before the causeway, northerly fetch to this shore was greater than 50 km. Today, northerly fetch is less than 1 km.

complicate effective fetch (USACE, 2002). Density differences of brine layers influence seiches (Gill, 1982; Open University Oceanography Course Team, 1989) and may influence effective fetch.

At least three research projects could diminish uncertainty concerning direction of strongest storm winds across Great Salt Lake during 1986/87 and associations with shoreline superelevation. First, a research project could test whether aspect is a reasonable proxy for direction of strong winds. Weather stations on and around the lake monitor wind direction and wind strength in real-time. Instrumentation and remote sensing can record wave patterns and currents (EOS, 2005). Instrumentation along the west shore of Antelope Island could document whether aspect is, indeed, a general approximation of the direction of strongest winds that affect the shorezone.

Second, advances in remote sensing technology and satellite coverage will make it feasible to capture the evolution of lake set-up due to storm winds in real time. Real-time monitoring has documented currents and sediment transport in the Adriatic Sea in response to wintertime storm events (EOS, 2005). Remote sensing that captures elevation differences across the lake surface through storm events could provide a systems view vastly more informative than the two lake-surface monitoring gages on Gilbert and Gunnison Bays. Research that documents biological systems (Baxter and others, 2005), bathymetry (Baskin and Allen, 2005), and pollutants of Great Salt Lake (Naftz and others, 2005) highlights the need for a greater understanding of lake circulation patterns and their driving mechanisms, including lake set-up from storm winds.

Third, even without the benefit of modern technology, a research project could better define storm conditions of 1986/87. Major storms of 1986/87 have been identified using lake-monitoring records that show seiches of Gilbert Bay. Wind patterns can be hindcast using post-1990s analogues (J. Steenburgh and P. Jewell, oral commun., 2002).

Indicators of Wave Energy and Wind Direction

Shoreline superelevation is measurable evidence of wave energy and may indicate direction of strong winds for fetch-limited lakes. However, shoreline superelevation is difficult to measure for all but exceptional shorelines, and it is rarely possible to precisely survey extensive stretches of paleoshorelines with tightly constrained age. A more readily recognizable shorezone attribute, such as shorezone slope or a set of coastal landforms, could help identify relative wave-energy environments.

The Antelope Island data set gives mixed evidence of the utility of slope as a reliable indicator of wave-energy environments. Unlike fetch and wind strength that largely control the input of energy from wind into the lake surface, slope is related to energy dissipation as waves arrive onshore (Komar, 1998). The relationship is complicated because wave runup affects shorezone slope and shorezone slope affects wave runup (Komar, 1998). Research on marine coastal processes further indicates that the relationship of slope and wave energy is affected by properties of waves, such as their steepness; properties of the beach face, such as permeability; and properties of the returning backwash (Komar, 1998). The association of gentle shorezone slopes with marine, low-energy wave environments has notable exceptions, such as extensive, cobble-armored, gently sloping, high-energy wave environments of the Oregon coast (Komar, 1998).

For Antelope Island, island-scale patterns of shorezone slope are associated with island-scale patterns of superelevation. Gentler slopes of the east side of the island are generally associated with low shoreline superelevation, and steep slopes of the west side of the island are generally associated with high shoreline superelevation;

however, the data are broadly scattered. The association of shorezone slope and wave energy assumes a causal connection. The utility of shorezone slope as an indicator of wave energy will be compromised to the extent that underlying geologic rock type or structure, not coastal processes, determine shorezone slope. For example, it is not certain that shorezone slope on Antelope Island is independent of geologic structure. Geologic bedrock and structures of the island trend north-south and result in contrasting west-side versus east-side rock types (Figure 4.27). The west side of Antelope Island is bounded by an active fault (Doelling and others, 1990; Dinter and Pechmann, 1999; Hecker and Case, 2000), whereas the east side of the island borders Farmington Bay and the delta of the Jordan River.

Shorezone materials have been proposed as a possible indicator of wave-energy environments. For example, Adams (2003) uses beach particles of the shores of Antelope Island to correlate particle size with storm winds on Great Salt Lake, extrapolates the technique to shores of Lake Lahontan, and concludes that Late Pleistocene climate during highstands of Lake Lahontan was windier than present Great Basin climate. However, findings from Antelope Island, presented here, suggest that the use of beach particle size as a proxy for wave energy is overly simplistic. The poor relationship between shoreline superelevation and attributes of shorezone materials of the 1986/87 shoreline expressions suggests that beach particle size is a poor indicator of (1) shoreline superelevation and, therefore, for (2) wave energy and (3) wind strength, assuming wind strength is related to wave energy.

An explanation for the poor association between coarse particle size and high shoreline superelevation along highstand shorezones of Antelope Island is that particle size along 1986/87 beaches is as much a function of provenance as of wave energy. Waves can only affect grain sizes already present in the shorezone, regardless of energy. Along the west side of Antelope Island, many high-energy shore stretches have

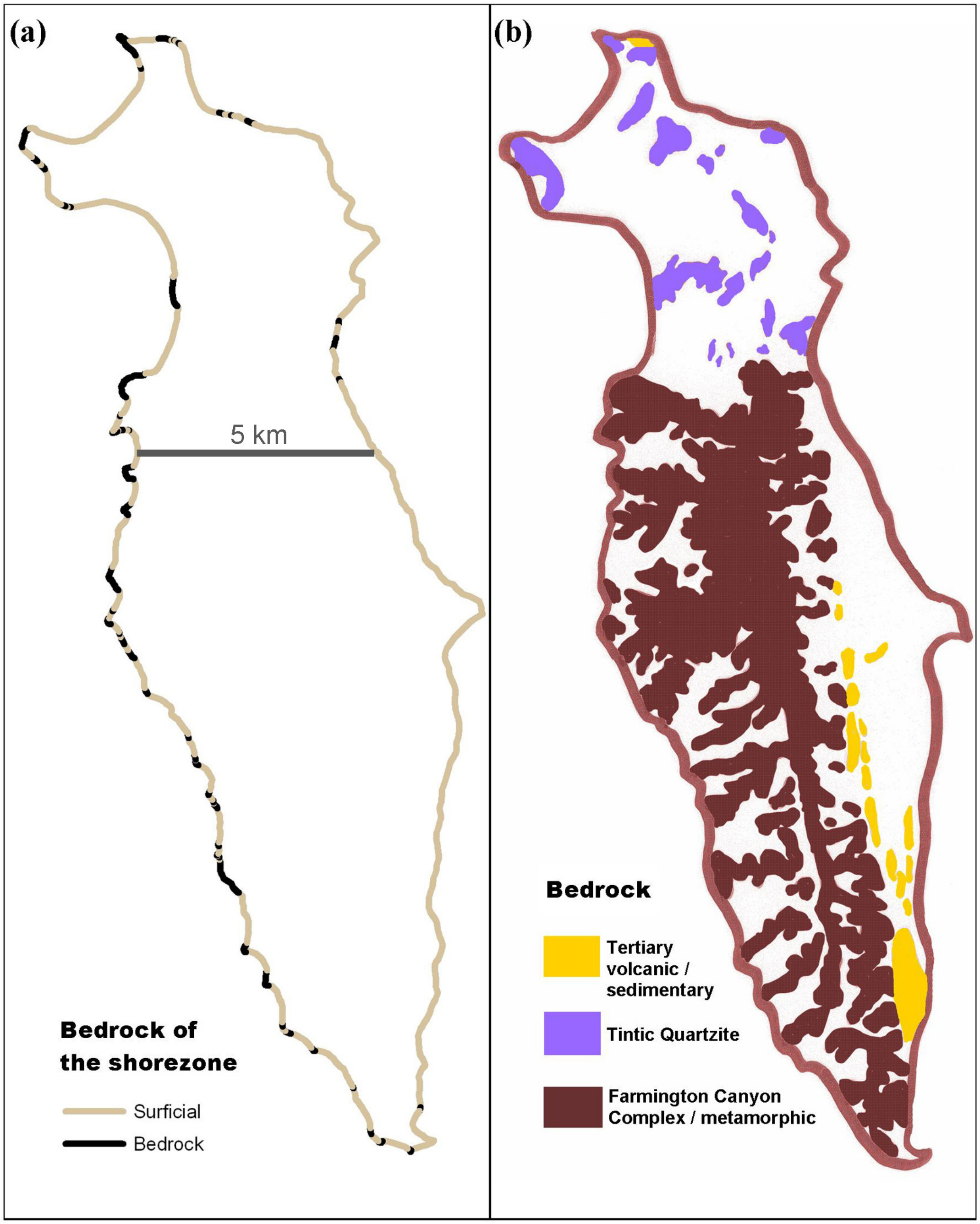


Figure 4.27. Bedrock of Antelope Island.
Map (a) displays shorezone materials classified as bedrock or surficial materials based on boundaries digitized from Doelling and others (1990). Map (b) shows the three major bedrock types of Antelope Island, adapted from Doelling and others (1988). Bedrock of the west side of the island generally is exposed at points jutting into Gilbert Bay, in contrast to bedrock of the east side that is less significant and generally exposed along bays.

cobble beaches and are near exposed bedrock. At the scale of individual bays, beach materials diminish in size with increased distance from bedrock headland exposures Figure 4.28. Shorezones of low energy have cobbles at the surface where shore deposits are nourished by debris flow outflow. Three examples of debris flow deposits along the 1986/87 shoreline are (1) north of the Ranch House along the eastern side of the island, (2) along the northwest shore of Buffalo Point, and (3) along the ranch road near Dairy Springs where a debris flow on August 2, 2005, carried cobbles across the Ranch Road (Figure 4.29) and beyond 1986/87 shoreline expressions.

Future research could explore the relationship of time, sediment size, sorting of beach materials, and wave energy along shores of shallow closed-basin lakes. The finding that shorezone materials are poorly associated with shoreline superelevation was unexpected. Particle size has been used as a general indicator of marine wave-energy environments in the geologic record (Folk, 1968). Perhaps the difference between well-sorted, coarse deposits of marine shores and the cobble-strewn shores of Antelope Island is the relatively short exposure-time of shores of Antelope Island to wave processes. Fewer than 60 days of storm waves in over a century have modified the historic highstand shoreline expressions of Great Salt Lake, conservatively assuming a dozen large storm events for 1986/87 highstand conditions and a similar number for the 1860s-70s highstand. Materials on shores of Antelope Island have not had sufficient exposure to wave conditions to become well-sorted evidence of wave action. Particle size in the beach zone is not entirely due to coastal processes but also is due to terrestrial processes. Therefore, the assumption that particle size reflects only coastal conditions and wave processes is flawed.

Another indicator of paleoshoreline wave-energy environments are patterns of coastal landforms. Findings of marine and Lake Bonneville research concerning associations of coastal landforms and wave-energy environments include (1) rocky

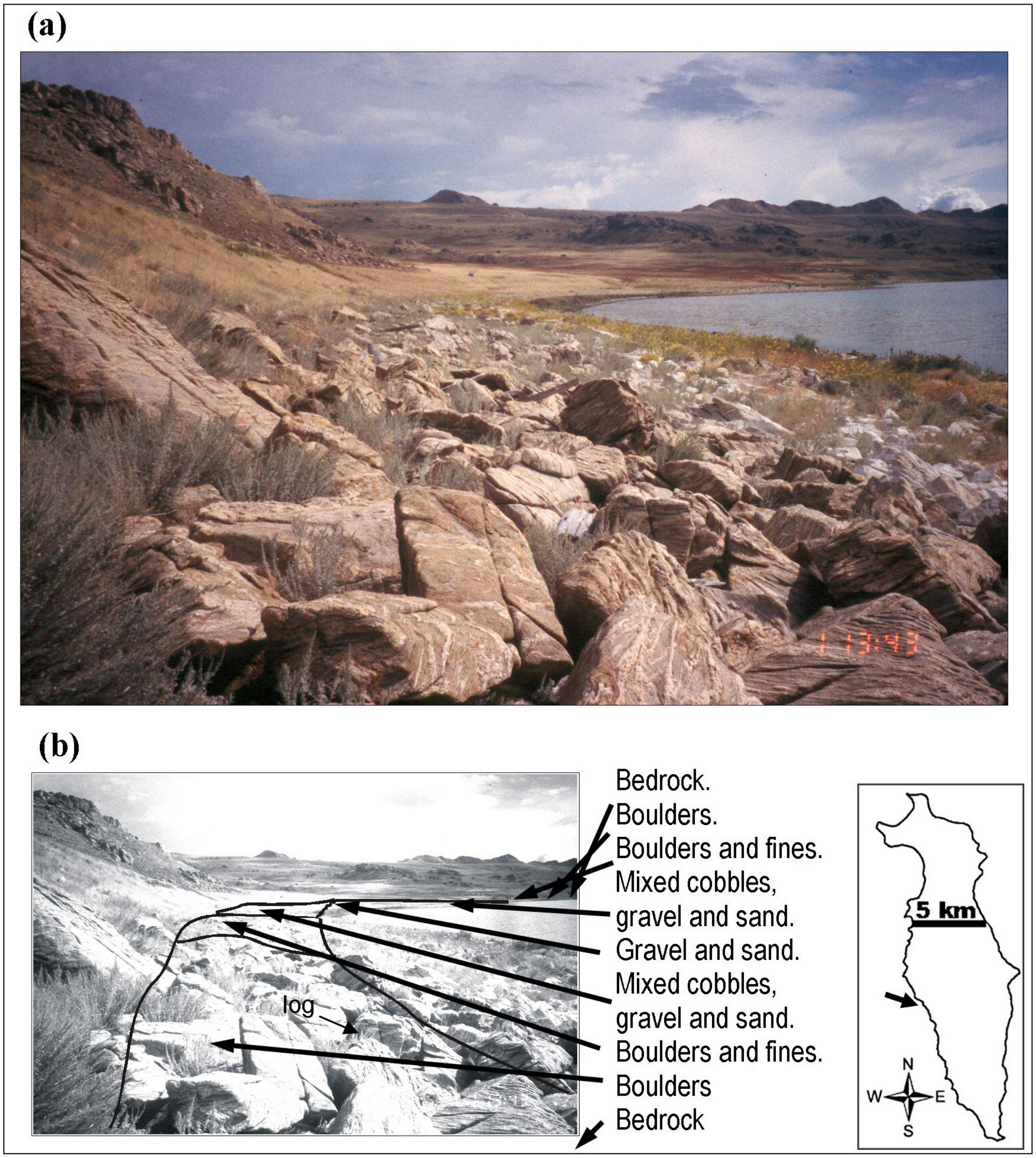


Figure 4.28. Sediment sequence from headland to headland.
Photograph (a) taken in 1998 looks south along Buffalo Scaffold Bay, a west-side bay. Log near center of the photo is approximately 1 ft (0.3 m) wide. Size of beach materials diminishes toward the back of the bay with distance from bedrock headlands. Size of largest particles moved during 1986-1987 also generally diminishes with size of beach materials. Annotated photograph (b) shows progression of materials from north to south, from headland to headland: from bedrock, to boulders, to small boulders with fines including sand, to cobbles and gravel, to gravel and sand of the back bay barrier beach, to cobbles and gravel, to small boulders with fines, to boulders, and to bedrock of the southern headland.

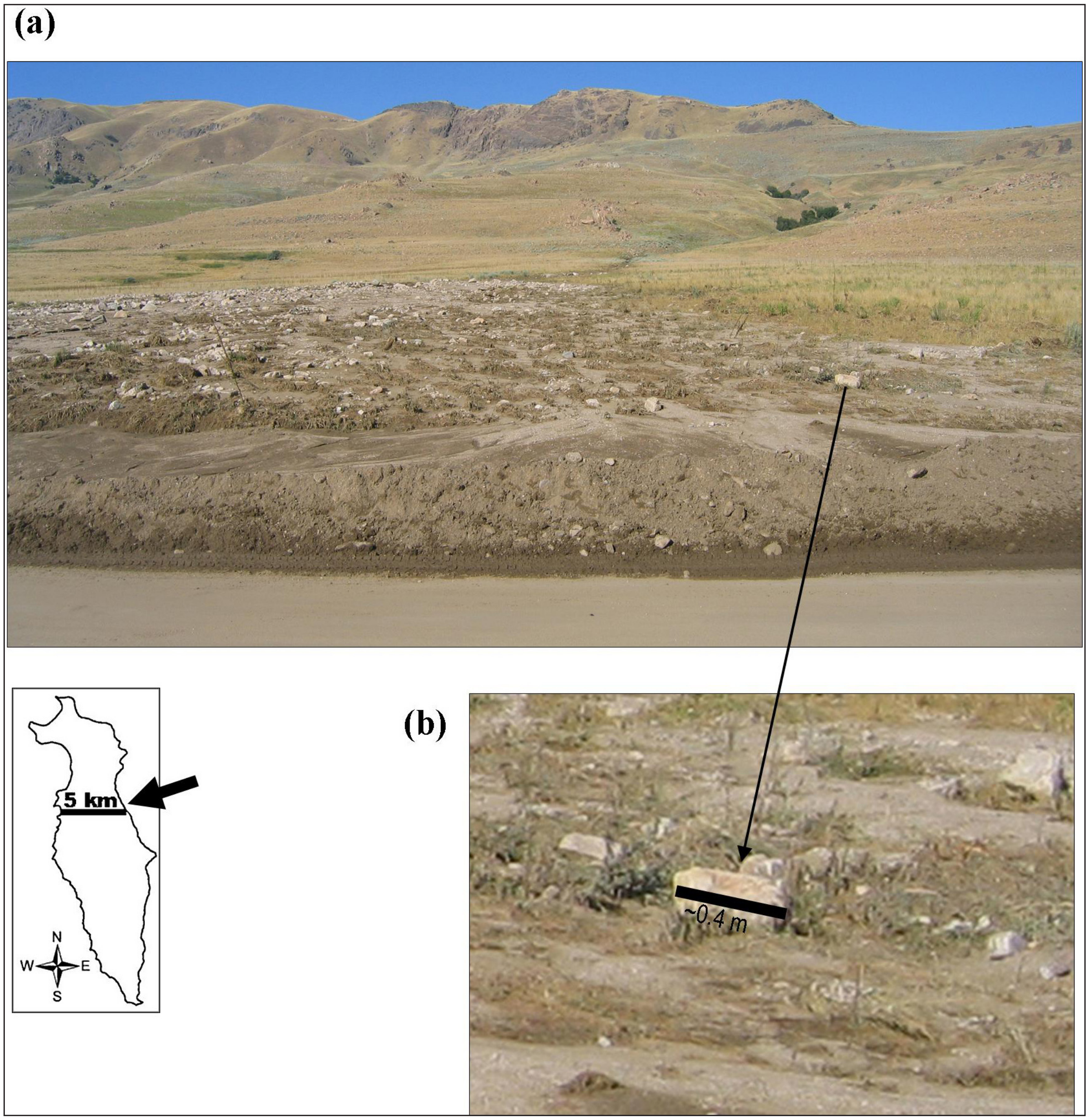


Figure 4.29. Debris flow nourishment of the sediments of the shorezone. Photograph (a) taken from the ranch road, September 4, 2005, looking west across debris flow materials from the Dairy Springs drainage. The debris flow resulted from a localized, intense precipitation associated with a tornado that crossed the island west to east the evening of September 2, 2005. Debris flow materials, including cobbles, were transported across the road to the ranch, foreground, beyond 1986/87 shoreline expressions which are downslope of the road, not shown. The long axis of the rock in photograph (b), a detail of photograph (a), is 15 in (38 cm).

headlands are associated with high-energy waves (Gilbert, 1890; Komar, 1998); (2) headlands focus and reflect wave energy (Komar, 1998); (3) shelves of wave-abraded platforms have high shoreline superelevation (Gilbert, 1890); (4) however, broad flats of fine sediments dissipate energy (Komar, 1998); (5) complexes of barrier beaches are associated with accreting shorelines (Gilbert 1890; Komar, 1998); (6) undercut sea cliffs are associated with high-energy waves (Gilbert, 1890; Komar, 1998); (7) alignment of spits is controlled by along-shore currents, in turn controlled by wind patterns (Jewell, 2005); and (8) the shapes of islands of western portions of Lake Bonneville include steep headlands that face into energetic waves and trailing, gentle profiles in the lee of the steep headlands (Felton, 2003).

The Antelope Island data corroborate several, but not all, of these observations. Specifically, bedrock headlands along the 1986/87 shore of Antelope Island are associated with high shoreline superelevation and, therefore, high-energy waves. Extensive mudflats are associated with low shoreline superelevation and low-energy waves. Using classifications of Komar (1998), the western side of Antelope Island facing into strong winds is an erosional coast, and the leeward, east side of the island is an accretional coast. The eastern side of the island has complexes of barrier beaches (e.g., Sea Gull Point); lagoons (e.g., Tin Lambing Shed); mudflats and offshore barriers (e.g., southeast of Sea Gull Point); cuspate forelands (e.g., Sea Gull Point); low-profile beaches; wetlands; and marshes. The western side of the island has wave-cut platforms (e.g., off Buffalo Point); sea cliffs (e.g., Cambria Point); numerous rocky headlands; undercut cliffs; pocket beaches; and steep-profile beaches. The large landforms that jut into Great Salt Lake on the western side of the island are bedrock, erosional features, such as Cambria Point. The large landforms that jut into Farmington Bay from the eastern side of the island are depositional, accretional features, such as Sea Gull Point. The association of accretional landforms with shores facing into the wind has exceptions. For example, the intermediate and high shoreline expressions of White Rock Bay on the northwest of the island have extensive mudflats off shore. However the general, contrasting pattern of bedrock headlands on the side of the island facing into strong winds and long fetch versus mudflats in the lee of the island appears to be associated with island-scale patterns of wave-energy environments and shoreline superelevation.

Research to examine associations of patterns of landforms should include the context of tectonic setting and sediment budgets. Coastal processes act on landscapes largely determined by tectonics, rock type, and sediment influx (Komar, 1998). Antelope Island is a range of the Basin and Range physiographic province, in a tectonically active region characterized by thick accumulations of sediments in closed basins. Landforms have inherited characteristics of their geologic past that should not be confused with characteristics caused by coastal processes.

Based on Antelope Island shoreline superelevation data, patterns of landforms appear to offer the most promise as reliable indicators of shoreline superelevation. Specifically the contrast of extensive mudflats and high elevation lake bottom versus bedrock headlands appears to be evidence of relative wave energies of modern closed-basin lakes and suggests the relationship as a tool to ascertain direction of paleostorm winds of paleolakes.

The following chapter summarizes results of field checking findings of Antelope Island shoreline superelevation research at places around Great Salt Lake. It also reports initial research results concerning associations of superelevation, wind strength, and wave energy at places around Great Salt Lake in addition to Antelope Island.

CHAPTER 5

SHORELINE SUPERELEVATION AROUND GREAT SALT LAKE

In 2003, findings of Antelope Island superelevation research, summarized in Table 1.1, were tested at places around Great Salt Lake. Elevations of expression of the 1986/87 shoreline were surveyed at 608 locations, grouped into 20 contrasting surveyed shores, along 10 shore regions around Great Salt Lake (Figures 5.1, and 5.2, and Table 5.1). Field investigations were designed to test (1) whether shoreline superelevation could be determined for places around the lake other than Antelope Island, (2) whether patterns of superelevation around the lake were analogous to those on Antelope Island, and (3) whether relationships between shoreline superelevation and coastal conditions investigated on Antelope Island would be invalidated by evidence from other places around the lake. Specifically, the following findings from Antelope Island were explored:

- relative shoreline superelevation is evidence of relative wave energy arriving onshore;
- the signal of lake set-up cannot be isolated in the signal of shoreline superelevation and it is not a simple tilt of the lake's surface;
- greater shoreline superelevation is associated with direction of longest fetch;
- greater shoreline superelevation is associated with direction of strong storm winds;
- steep shorezone slope is associated with high shoreline superelevation;
- very gentle offshore slope and extensive offshore, shallow water are associated

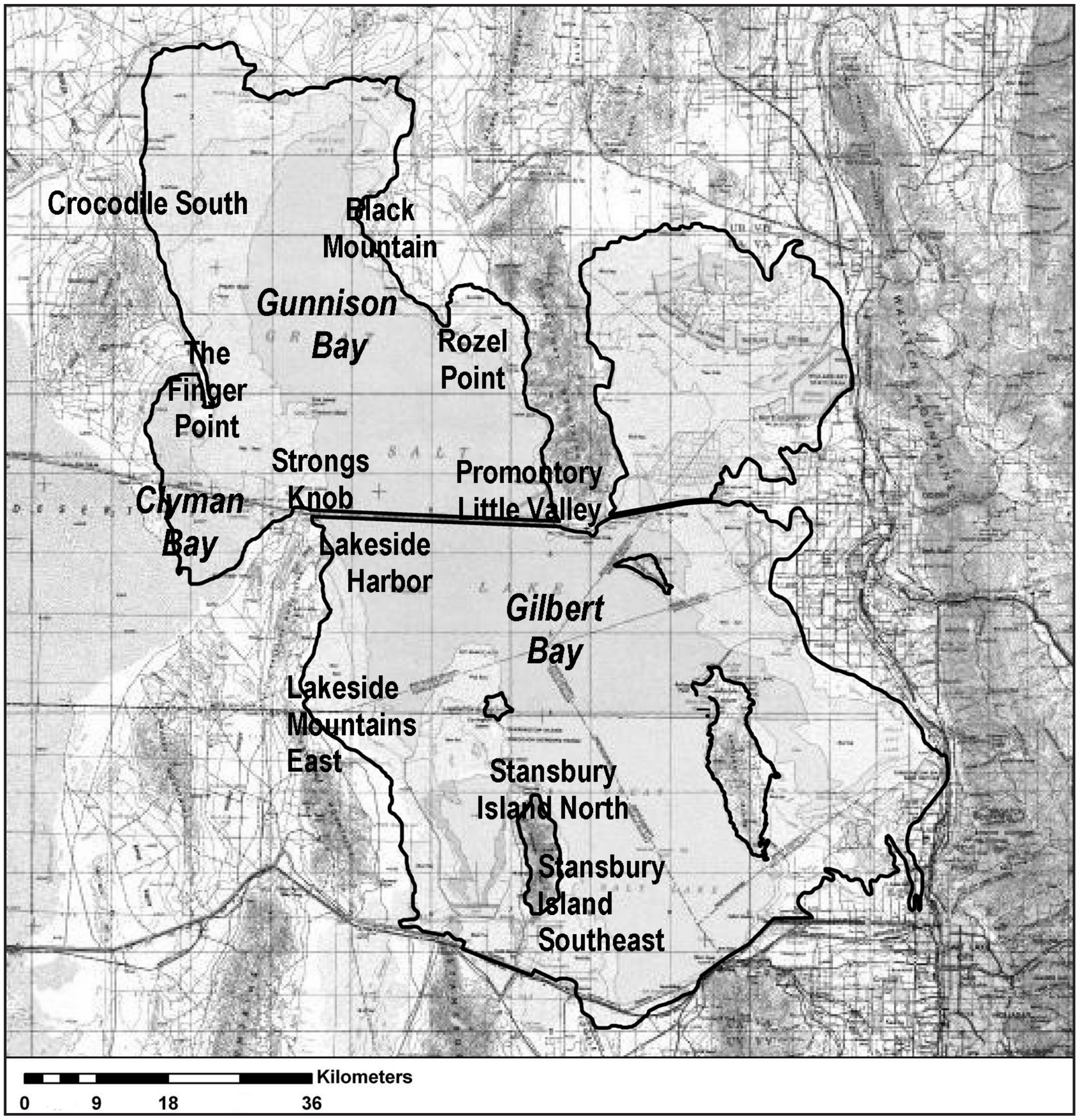


Figure 5.1. Map of the 10 shore areas of the Great Salt Lake elevation survey. Ten shore area were selected to explore findings of Antelope Island superelevation research. The 10 shore areas consist of 20 contrasting surveyed shores with diverse conditions of aspect, fetch and slope. See Figure 5.2 for locations of the 20 surveyed shores and Table 5.1 for a summary of shore characteristics of the 20 surveyed shores. Expressions of the 1986/87 shoreline were surveyed at 608 places. Survey data are presented in Appendix B.

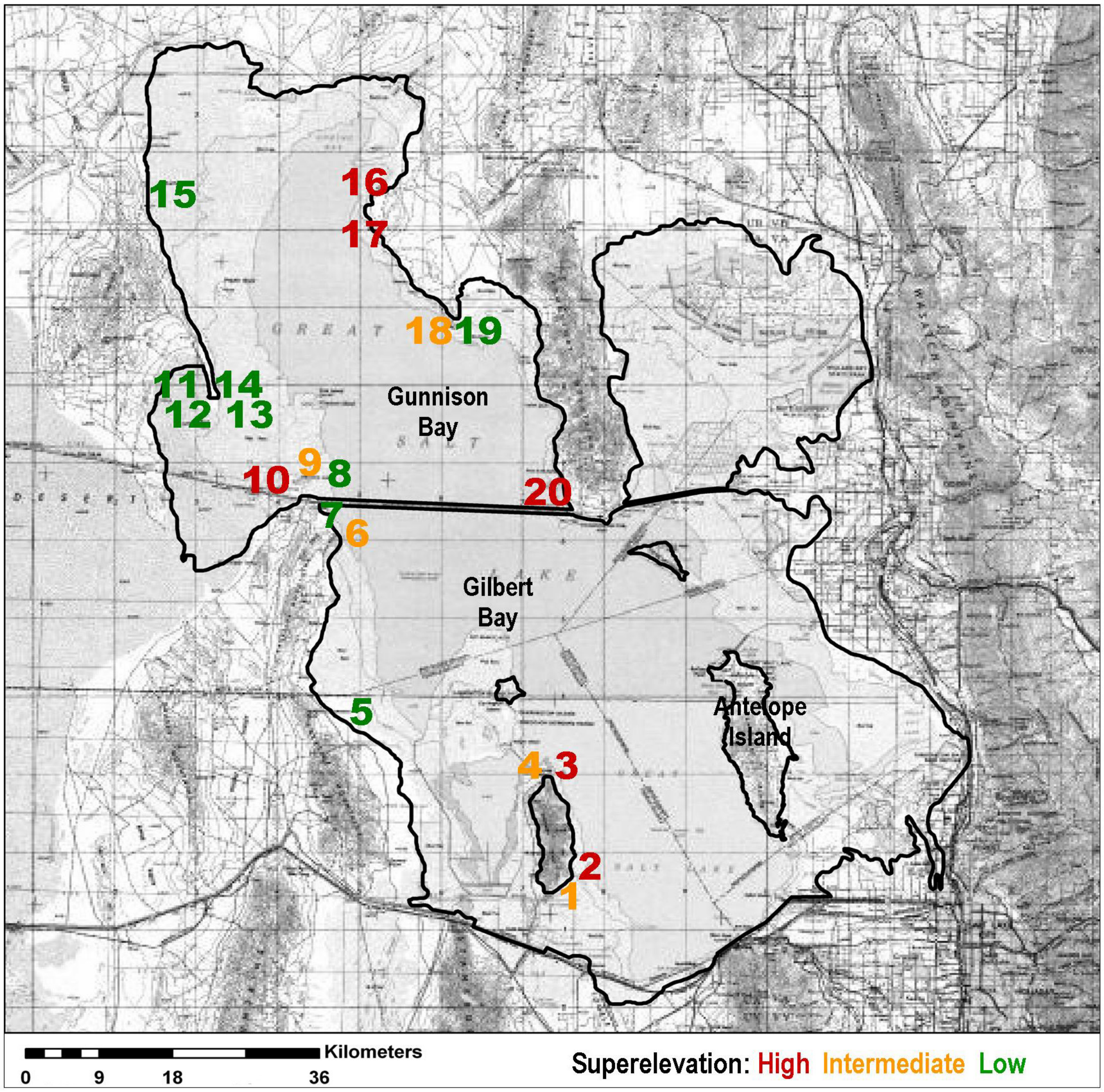


Figure 5.2. Map and generalized superelevation of Great Salt Lake surveyed shores. Elevations were surveyed at 10 shore areas along 20 shores with contrasting exposures. The 20 surveyed shores were classified as generally high, intermediate, or low based on patterns of shoreline superelevation and data plots.

Table 5.1. Summary of characteristics of surveyed shores of Great Salt Lake.

	Surveyed shore	Generalized superelevation	Fetch (km)	Direction of maximum fetch	Aspect	Fetch to N+W (km)	Lake set-up	Shore slope in degrees	Elevation of lakebed in ft a.s.l.	Bedrock in shorezone	Accretion vs. erosion
1	Stansbury Island SE	Intermediate	53	NNE	E	NA	Mid-bay	1.59	4195	3%	Mixed
2	Stansbury Island Shanty Sp	High	52	NNE	NNE	43	Mid-bay	4.98	4195	20%	Mixed
3	Stansbury Island NE	High	38	NE	NE	30	Node	5.80	4193	40%	Erosional
4	Stansbury Island NW	Intermediate	43	NNW	W	43	Node	1.16	4200	15%	Mixed
5	Lakeside Mountains E	Low	50	ESE	E	NA	Mid-bay	0.05	4207	0%	Mixed
6	Lakeside harbor E	Intermediate	73	SE	E	NA	Edge	3.49	4196	3%	Mixed
7	Lakeside harbor bay	Low	60	E	N	2	Edge	2.33	4199	0%	Accretional
8	Strongs Knob SE	Low	32	E	SE	NA	Edge	2.00	4199	0%	Accretional
9	Strongs Knob N bay	Intermediate	55	NNW	N	55	Edge	1.16	4198	0%	Mixed
10	Strongs Knob NE	High	52	NNE	NE	50	Edge	9.88	4198	40%	Erosional
11	Finger joint W	Low	24	S	W	5	Edge	0.03	4207	0%	Accretional
12	Finger tip SW	Low	22	S	SW	NA	Mid-bay	0.17	4205	0%	Accretional
13	Finger tip SE	Low	44	ESE	ESE	NA	Mid-bay	0.35	4199	0%	Accretional
14	Finger tip E	Low	47	SE	E	43	Mid-bay	1.66	4199	0%	Accretional
15	Crocodile south	Low	63	SE	E	NA	Mid-bay	0.06	4206	0%	Accretional
16	Black Mountain N	High	32	NW	NW	32	Mid-bay	9.11	4197	10%	Erosional
17	Black Mountain S	High	37	SSW	WSW	32	Mid-bay	3.87	4197	10%	Erosional
18	Rozel Point W	Intermediate	47	NW	SW	47	Mid-bay	8.67	4193	60%	Erosional
19	Rozel Point E	Low	28	SSE	SE	NA	Node	0.44	4205	0%	Accretional
20	Promontory-Little Valley	High	73	NW	W	73	Edge	4.65	4199	30%	Erosional

Numbers refer to locations of surveyed shores shown on Figures 5.2.
Appendix B presents elevation data and summary of coastal conditions for each surveyed shore.

with low shoreline superelevation; and,

- patterns of contrasting erosional versus accretional coastal landforms indicate direction and relative energy of waves and wind.

The question of whether fetch or wind strength or both determine the transfer of wind energy into the lake surface and to wave energy onto shore is of more than theoretical interest. If relative shoreline superelevation documents direction of storm winds for fetch-limited lakes, then superelevation of paleoshorelines for fetch-limited water bodies has potential to be evidence of direction of strong paleowinds. Conversely, if wind strength does not contribute significantly to wave energy and fetch alone explains shoreline superelevation, then modeling of shorezone wave environments and associated inundation hazards is greatly simplified because fetch is an easily quantified coastal variable.

Methods

As with Antelope Island, absolute superelevation of 1986/87 shoreline expressions at places around Great Salt Lake could be established where shoreline expressions could be positively identified as inundation shoreline expressions of 1986/87, where still-water lake elevation was gaged during 1986/87, and where accurate surveying of shoreline expressions was possible. A set of reconnaissance field trips during 2003 determined that evidence of the 1986/87 shoreline at many places around Gilbert and Gunnison Bay had survived 16 years of human and natural degradation; however, evidence had not survived around the more-developed Farmington Bay. As with evidence on Antelope Island, small fragments of organic matter and subtle geomorphic features had been destroyed or modified by natural processes. Fire had destroyed lumber and plastic essential for unequivocal identification of historic shorelines along some shore sections, such as along portions of the northern shore of Gunnison Bay. Human activities had destroyed or changed entire sections of shorelines in agricultural, industrial, recreational, and residential areas, including virtually all of the shores of Farmington Bay.

Concerns about the determination of still-water lake elevation for field investigations around Great Salt Lake are similar to those for Antelope Island with the added complexity of two bays, rather than one bay, and three, rather than two, gaging stations (USGS, 2001). USGS-revised lake elevations were used as still-water lake elevation for determining absolute shoreline superelevation (USGS, 2004). The elevation used for Gilbert Bay for highstand still-water elevation is 4211.6 ft (1283.7 m) a.s.l. and for Gunnison Bay is 4211.1 ft (1283.5 m) a.s.l.

Vertical control for surveying elevations around Great Salt Lake is of concern. Four types of vertical control were used: real-time lake-level monitoring, surveyed benchmarks, locations surveyed by salt extraction companies, and triangulation stations. Lake level on a still day was the preferred vertical control because, although the lake was not always accessible, lake surface is a consistent horizontal datum monitored real-time by the USGS for Gunnison and Gilbert Bays. In 2003 the lake's low elevation resulted in long distances, up to 8 km, between some expressions of the 1986/87 shoreline and the lake's 2003 shoreline. Only steep shorezones of 1986/87 were within 0.1 km of the 2003 shoreline. If lake surface had been used as the only control, surveyed shores would not have been representative of the geomorphic diversity of the lake's shore.

Benchmarks were the next preferred control. Difficulties with benchmarks include their scarcity and associated lack of redundant control. Only a dozen general areas around the lake have reliable vertical control from National Geodetic Service surveyed benchmarks. Change in elevations of benchmarks is of concern as indicated by the use of benchmarks of the region to analyze tectonic and isostatic changes of

Basin and Range terrain over the past 150 years (Crittenden, 1963). Not all of the region's benchmarks have been resurveyed even in the past three decades (National Geodetic Service, 2005). The third type of vertical control relied on elevation markers surveyed as part of salt extraction operations, such as company-surveyed markers at pump stations or on evaporation ponds. Salt extraction companies closely monitor water levels of ponds relative to pumps and canals. The challenge is to tie salt company vertical control to USGS-monitored levels of Great Salt Lake. The fourth, least acceptable, basis of vertical control was triangulation stations. Precision of triangulations stations is to 1 ft (0.3 m) vertical, insufficient precision for shoreline superelevation surveys, although useful for redundancy.

The purpose of the Great Salt Lake elevation survey was to document elevation of shoreline expressions for each shore region reliably and efficiently and to gather information to test findings of Antelope Island research. Some locations, such as Fremont and Carrington Islands, were impractical shore regions to survey in a limited period of time. Ten shore regions around the lake were chosen as survey areas (Figures 5.1 and 5.2). The 10 shore areas represent 20 contrasting geomorphic expressions (Figures 5.2; and referenced by number in following discussions). For example, Rozel Point has two contrasting shores: one dominated by exposed bedrock (#18), the other characterized by a series of barrier beaches and lagoons (#19). Field investigations around Great Salt Lake used the survey equipment and survey procedures of the Antelope Island elevation survey. Field data were referenced to National Geodetic Vertical Datum of 1929 (NGVD 29) in feet above sea level (ft a.s.l.). Results are presented in Appendix B.

Six hundred eight locations on inundation shoreline expressions were surveyed in short, sometimes discontinuous, shore segments (Appendix B). This field procedure contrasts with the near-continuous survey coverage of Antelope Island. The Antelope

Island survey represents nearly complete documentation of all shore environments around the island, including difficult places to survey, such as undercut cliffs and bouldery terrain. Shores with potential for elevation outliers were documented for Antelope Island research. In contrast, surveying of shoreline expressions of Great Salt Lake was designed to collect sufficient elevation data to test island-scale patterns observed on Antelope Island.

Surveyed elevations are classified as high, intermediate, and low using the classification breaks of Antelope Island (see Chapter 3). Each of the 20 contrasting surveyed shores was classified as a single unit as generally high, generally intermediate, or generally low shoreline superelevation based on general patterns displayed on maps of each shore area (Appendix B) and plots of the data (Figure 5.3). For some shores, such as Crocodile south (#15), elevations are consistently low and classification is straightforward. However, for some stretches, such as north and south Black Mountain, elevations are variable and a single superelevation classification is an oversimplification for purposes beyond those of the Great Salt Lake elevation survey. As with Antelope Island, shores with high values of shoreline superelevation also are shores with more variable superelevation (Figure 5.3).

The Great Salt Lake shore elevation survey was not intended to present a complete picture of the magnitude and distribution of superelevation of shoreline expressions around the lake. The 10 shore areas were not selected randomly although they were chosen for spatial distribution around the Gilbert and Gunnison Bays. Accessible vertical control largely determined shore regions to survey. Of the 20 contrasting surveyed shores, 7 are in Gilbert Bay (#1-7), 12 in Gunnison Bay (#8-10, #12-20), and 1 in Clyman Bay (#11); 6 are classified as high shoreline superelevation (#2, 3, 10, 16, 17, and 20), 5 as intermediate shoreline superelevation (#1, 4, 6, 9, and 18), and 9 as low shoreline superelevation (#5, 7, 8, 11-15, and 19); 7 are on islands

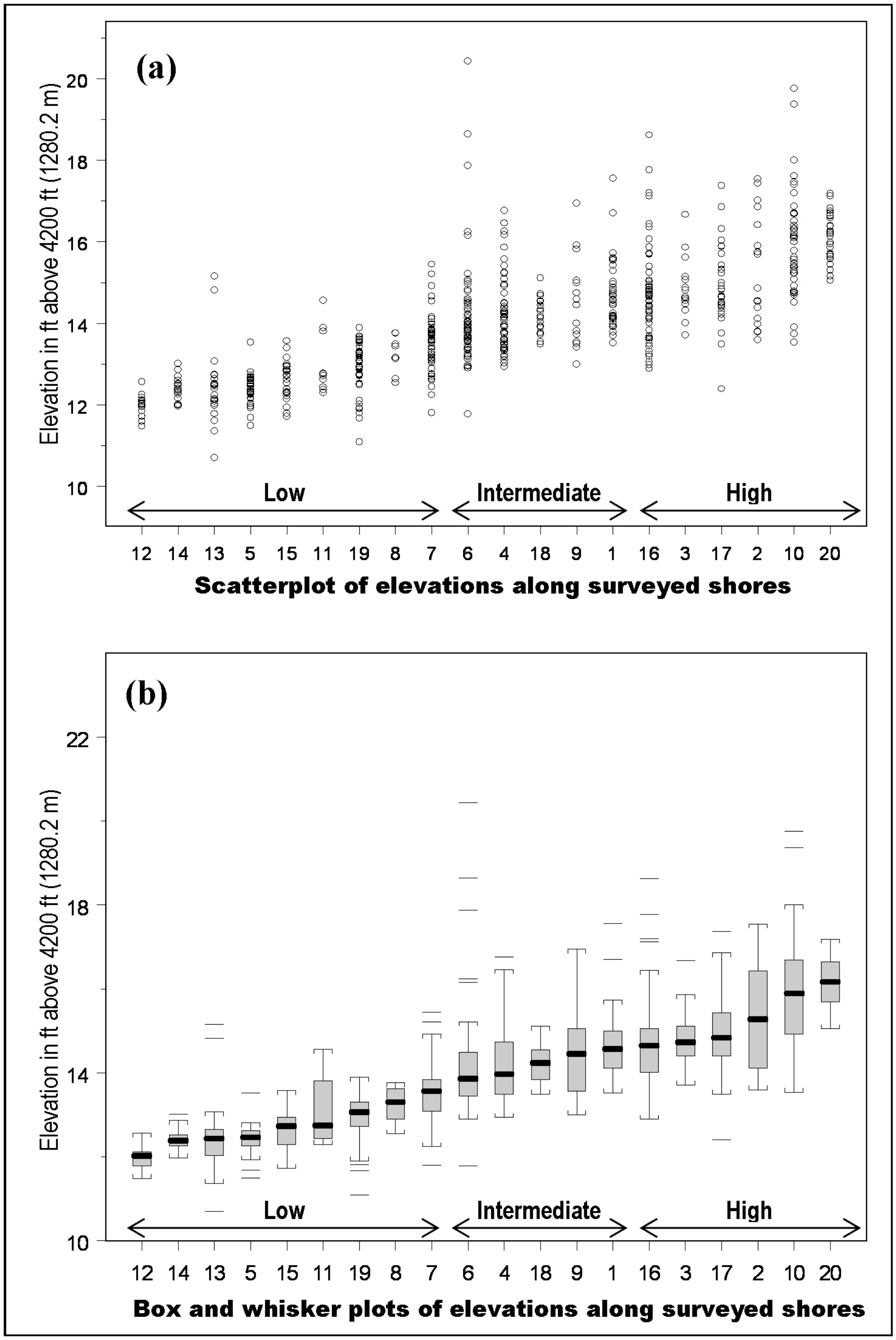


Figure 5.3. Plots of elevation data of surveyed shores.
Scatterplot (a) and box and whisker plots (b) present elevation data for the 20 surveyed shores of the Great Salt Lake. Numbers refer to shores of Figure 5.2. Surveyed shores are ordered based on median value. The surveyed shores are classified as generally high, intermediate, or low shoreline superelevation based on these plots and on patterns of superelevation data presented in Appendix B.

(#1-4 and 8-10), and 13 are on the mainland (#5-7, 11-20). In Gilbert Bay, all 7 (#1-7) are on the western side of the bay. In Gunnison Bay no stretches of shore with adequate survey control and abundant, continuous, debris, unequivocally dating to 1986/87 were found along the northern or southern boundaries of the bay, 7 locations (#8-10, 12-14) are on the west side of the bay and 5 (#16-20) are on the east side.

Field investigations around Great Salt Lake simplified the operational definitions developed for Antelope Island to test findings of Antelope Island research. For example, lake set-up potential is described as three general classes (node, mid-bay, or edge) based on visual inspection of USGS (1988) map of Great Salt Lake (Figure 5.4) in contrast to the continuum of UTM northings used for Antelope Island research. As with Antelope Island, fetch, aspect, and shorezone slope were measured digitally from source maps originally at 1:500,000 scale (USGS, 1988) and from USGS topographic 7.5-minute quadrangle maps. However, measurement of fetch length was determined by digital calculation of hand-drawn fetch vectors for 16 compass directions rather than the 24 fetch vectors measured for Antelope Island research because the purpose of the Great Salt Lake investigation was to identify maximum fetch length for generalized compass directions. The 16-direction hand-digitized technique, although less precise than the 24-direction GIS-generated vectors, captured the information specific to test findings from Antelope Island concerning longest fetch to the west and northwest. Aspect of Great Salt Lake shores was determined by visual inspection of 1:24,000 scale topographic maps. Shorezone slope was calculated from digital measurements of distance between the 4200 ft (1280.2 m) a.s.l. and 4220 ft (1286.3 m) a.s.l. contour intervals. Elevation of extensive, offshore, shallow water during 1986/87 was identified as near-horizontal, offshore lake bed topography and mudflats from USGS 7.5-minute topographic quadrangle maps. Except for bedrock and mudflats, materials of the shorezone were not categorized. Abundance and presence

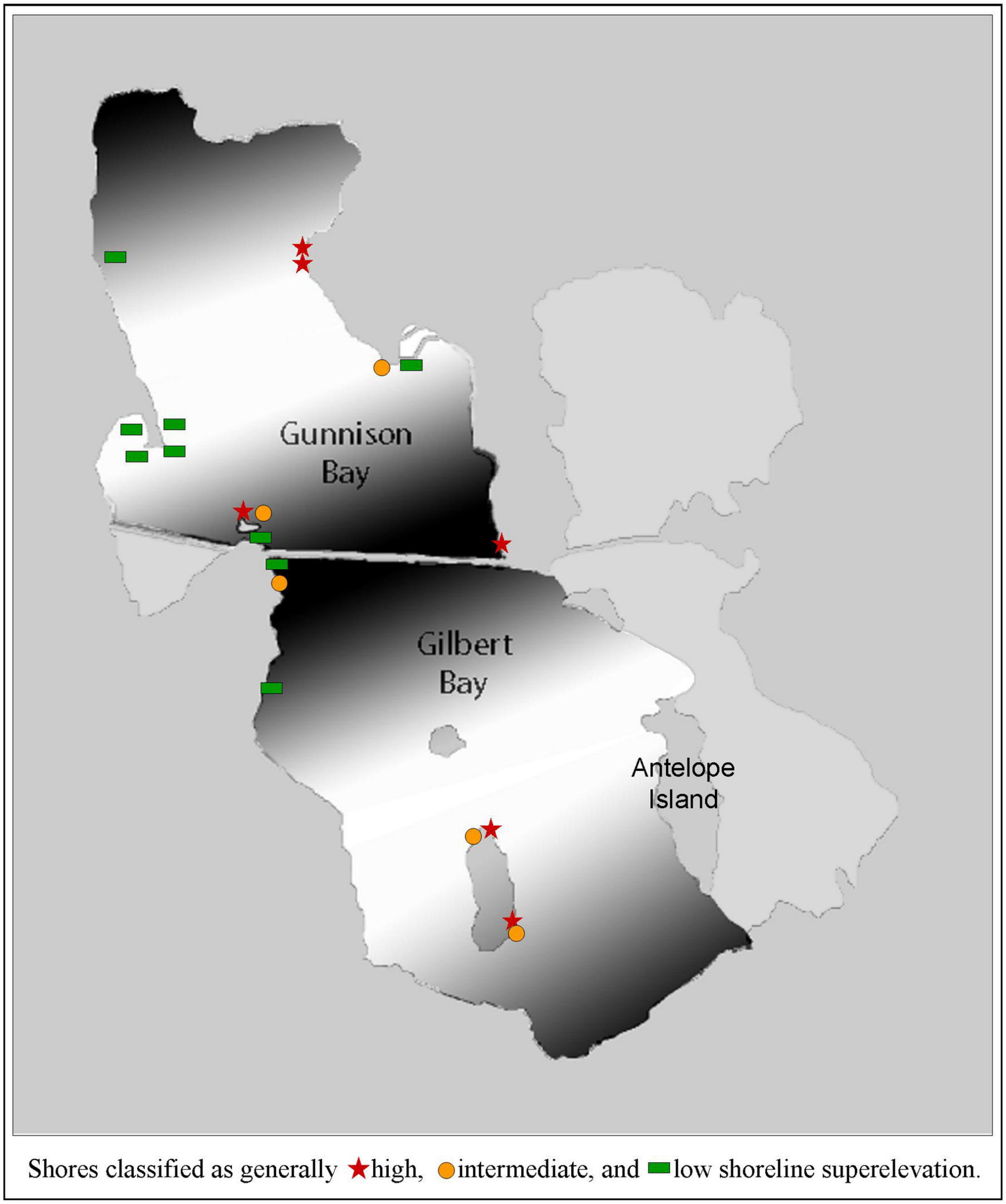


Figure 5.4. Potential for tilted-surface lake set-up.
Map of Gilbert and Gunnison Bays shows hypothetical progression of lake set-up assuming a tilted lake surface along the long axes of the bays. Darker gradients indicate greater lake set-up. Shoreline superelevation on Antelope Island and around Great Salt Lake does not provide evidence of gradually increasing north to south lake set-up as a tilted lake surface.

of exposed bedrock along the shores of surveyed stretches and mudflats offshore from surveyed stretches were estimated in the field. Beach type (erosional, depositional, or both) and abundance of beach materials were not mapped.

Evidence of Shoreline Superelevation

Debris of the 1986/87 shoreline was unexpectedly intact at many places around western and northern shores of the lake, along the Promontory Mountains, and on islands, such as Strongs Knob (#8, 9, and 10) at the southwestern corner of Gunnison Bay and Stansbury Island in Gilbert Bay. Strongs Knob has the most diverse shoreline evidence and most diverse shoreline exposures for a compact area. Strongs Knob illustrates the utility of island exposures for geomorphic analysis of contrasting shore conditions. Stansbury Island (#1-4) has diverse conditions and good preservation. However, its western shore was not surveyed because shores along evaporation ponds of Stansbury Bay experienced a history of 1980s flooding that differed from other shores of Gilbert Bay and those of Antelope Island, specifically, inundation by a single, major storm.

As with Antelope Island, three types of features suffered the most degradation from natural causes from 1986/87 to field work of 2003: (1) erosional scarps lost their near vertical slopes, primarily by slumping and by burrowing animals; (2) sand ridges lost the upper 1-3 in (0.03-0.07 m) of their classic asymmetric morphology of wash-over ridges and crests; and (3) debris lines of brine fly pupae cases disintegrated. Fresh windrows of pupae and other fine organic matter clearly distinguished 1986/87 shorelines for a few years following highstand flooding. By 2003, this type of readily identifiable debris of 1986/87 was not available to positively demarcate 1986/87 shoreline expressions. The loss of evidence of 1986/87 vegetative and brine fly debris is regrettable in Gunnison Bay where a subtle, older shoreline, interpreted to be from the lake's 1860-70s highstand, is approximately 0.5–1.0 ft (0.2–0.3 m) above 1986/87 shoreline evidence and can be mistaken for it. In places, such as along Promontory-Little Valley (#20), rough-cut lumber and wooden debris of this older shoreline were identified as pre-1980s by their square nails. This potential for mistaken identity of 19th-century shoreline evidence is not a concern for Antelope Island because the still-water highstand lake elevation of 1986/87 of Gilbert Bay equaled that of the 1860s-70s Great Salt Lake (Mabey, 1986). However, the still-water elevation of Gunnison Bay in the 1860s-70s was higher than for 1986/87 due to 20th-century hydrologic impacts caused by the solid-fill railroad causeway.

Table 5.1 summarizes characteristics of the 20 contrasting surveyed shores of Great Salt Lake used to test findings of the Antelope Island research. Values of superelevation range across approximately 9 ft (2.7 m): from low elevations 0.5 ft (0.2 m) below still-water lake elevation to high elevations greater than 8 ft (2.4 m) above still-water lake elevation. Surveyed shores with higher shoreline superelevation have greater shoreline superelevation variability although the association of greater variability with high shoreline superelevation is not as strong for Great Salt Lake shores as for Antelope Island (compare Figure 5.3 with Figure 2.10). Of the 608 surveyed locations, six were below still-water lake elevation. The lowest is 0.9 ft (0.3 m) below official still-water lake elevation and is anomalously low. Judging from its position, the shoreline evidence may have been flotsam stranded in a lagoon and not flotsam marking the highest, inland, inundation shoreline expression. The five other low values are within 0.5 ft (0.2 m) of official still-water lake elevation and represent low-energy wave environments perhaps analogous to places with very low values on Antelope Island characterized by wetland vegetation.

The general magnitude of shoreline superelevation for shores of Great Salt Lake resembles that of Antelope Island with some qualifications. Highest shoreline expressions surveyed during the Great Salt Lake shore elevation survey are not as high as the highest surveyed on Antelope Island. This does not contradict findings of Antelope Island research. Not all exposures of shores of mainland Great Salt Lake were surveyed. If only 20 of the most accessible shores with vertical survey control and contrasting exposures had been surveyed on Antelope Island, the range of magnitudes of shoreline superelevation might well have been less than for the nearly complete shore survey. Highest debris on Antelope Island is found along rugged bedrock headlands, shoreline expressions that are relatively unusual along the mainland coast and ones that generally were not surveyed during the Great Salt Lake shore elevation survey due to time constraints or lack of vertical control.

Results and Discussion

West-East Patterns

On Antelope Island, the general pattern of shoreline superelevation is high superelevation on the west side of the island in contrast to low superelevation on the east side. West versus east patterns of shoreline superelevation for Great Salt Lake may initially appear less distinctive at a lake-scale (Figure 5.2) than for the Antelope Island data set at an island-scale (Figure 2.7). Islands have spatial relationships of windward versus leeward shores that mirror their mainland counterparts. This results in patterns of shoreline superelevation that may appear contradictory, but actually are generally consistent with those of Antelope Island. The 13 mainland shores (#5-7, 11-20) generally have high superelevation along the eastern shores of Great Salt Lake that face into storm winds. Along the western side of the lake, in the lee of land, shoreline superelevation is generally low. The three surveyed shores on Strongs Knob (#8-10), an island, generally have the west-high and east-low shoreline superelevation pattern that resembles that of Antelope Island (Figure 5.2). However, patterns of Stansbury

Island (#1-4) are not those of Antelope Island. Shores in the lee of Stansbury Island (#1,2) along the island's southeastern shore, are intermediate and high shoreline superelevation in contrast to the southeast shore of Antelope Island characterized by very low shoreline superelevation.

Evidence of Lake Set-Up

Field investigations around Great Salt Lake confirm the finding of Antelope Island that lake set-up is not an identifiable, simple-tilt component of shoreline superelevation. Progressive increase in shoreline superelevation associated with location along the northwest-southeast long-axis of Gunnison or Gilbert Bays were not evident for surveyed shores of Great Salt Lake (Figure 5.5). Surveyed shores along the north and south ends of Gunnison and Gilbert Bays have high, intermediate, and low shoreline superelevation as do midbay locations. Locations along the expected node of minimum-expected lake set-up include low (#19), intermediate (#14), and high (#3) shoreline superelevation. Three shores located near the lake's north and south ends have high shoreline superelevation: Strongs Knob (#10) and Promontory-Little Valley (#20) at the south of Gunnison Bay, and Stansbury Island Shanty Springs (#2) at the southern edge of Gilbert Bay. However, nearby shores have intermediate or low shoreline superelevation, such as at Strongs Knob east (#8) and Stansbury Island southeast (#1).

Thus, neither shoreline superelevation of Antelope Island nor shoreline superelevation at places around Great Salt Lake validates a tilted-surface model of lake set-up in response to storm winds (Figure 3.1). Both the Antelope Island and Great Salt Lake data sets suggest that lake set-up (a) may be masked by greater effects of wave runup, or (b) is more complex than a tilted lake-surface.

	Location	Generalized superelevation	In-bay location	GSL observed	Set-up model
10	Strongs Knob NE	High	Edge	[red]	[red]
20	Promontory-Little Valley	High	Edge	[red]	[red]
6	Lakeside harbor E	Intermediate	Edge	[yellow]	[red]
9	Strongs Knob N bay	Intermediate	Edge	[yellow]	[red]
8	Strongs Knob SE	Low	Edge	[green]	[red]
7	Lakeside harbor bay	Low	Edge	[green]	[red]
11	Finger joint W	Low	Edge	[green]	[red]
2	Stansbury Island Shanty Springs	High	Mid-bay	[red]	[yellow]
16	Black Mountain N	High	Mid-bay	[red]	[yellow]
17	Black Mountain S	High	Mid-bay	[red]	[yellow]
1	Stansbury Island SE	Intermediate	Mid-bay	[yellow]	[yellow]
18	Rozel Point W	Intermediate	Mid-bay	[yellow]	[yellow]
5	Lakeside Mountains E	Low	Mid-bay	[green]	[yellow]
12	Finger tip SW	Low	Mid-bay	[green]	[yellow]
13	Finger tip SE	Low	Mid-bay	[green]	[yellow]
14	Finger joint E	Low	Mid-bay	[green]	[yellow]
15	Crocodile south	Low	Mid-bay	[green]	[yellow]
3	Stansbury Island NE	High	Node	[red]	[green]
4	Stansbury Island NW	Intermediate	Node	[yellow]	[green]
19	Rozel Point E	Low	Node	[green]	[green]

Figure 5.5. Lake set-up and Great Salt Lake surveyed shores.
Shores (left columns) are sorted based on assumptions of progressive, tilted lake set-up along the bays' long axes. If superelevation were explained by a tilted lake surface, locations along the northern and southern margins of bays would have high superelevation, as shown in the column farthest to the right. Generalized surveyed superelevation is shown in the column, GSL observed. Evidence of a tilted lake surface was not observed in patterns of superelevation around Antelope Island or around Great Salt Lake.

Fetch

Results of Antelope Island research indicate that fetch length is associated with shoreline superelevation, a phenomenon explained by increased opportunity of wind energy transfer into the lake surface as indicated by fetch. However, understanding associations of fetch and shoreline superelevation on Antelope Island is compromised by the island's location in Great Salt Lake. The question of the influence of fetch on shoreline superelevation was examined by ordering the 20 contrasting surveyed shores of Great Salt Lake from longest fetch to shortest fetch (Figure 5.6). Of the 5 shores with long fetch, fetch > 55 km, 1 was classified as generally high shoreline superelevation, 2 as intermediate, and 2 as low superelevation. Of the 5 shores with short fetch, fetch < 35 km, 4 are classified as generally low shoreline superelevation, none as intermediate, and 1 as high superelevation. The pattern confirms findings of Antelope Island research that short fetch, less than 35 km, is associated with low shoreline superelevation (Figure 5.6 and Table 5.1). The inference is that short fetch, indicative of limited wave-generating area, limits transfer of wind energy into the lake surface. Resulting wave-energy environments are low. However, the finding that long fetch is not consistently associated with high superelevation for surveyed shores around Great Salt Lake indicates that fetch alone does not explain relative wave-energy environments.

For Antelope Island, shoreline superelevation associated with ≥ 55 km fetch is consistently high and with ≥ 50 km fetch is generally high. For Great Salt Lake surveyed shores, fetch ≥ 50 km is not associated with shoreline superelevation: of 9 shores with ≥ 50 km fetch, 3 are high of which 2 face into storm winds; 3 are intermediate; and 3 are low and in the lee of land (Figure 5.6). The shore of west-facing Promontory-Little Valley (#20) is one of two Great Salt Lake shores with the longest fetch (73 km) and has high shoreline superelevation. However, Lakeside

	Location	Generalized superelevation	Fetch in km	GSL observed	Based on AI
20	Promontory-Little Valley	High	73		
6	Lakeside harbor E	Intermediate	73		
15	Crocodile south	Low	63		
7	Lakeside harbor bay	Low	60		
9	Strongs Knob N bay	Intermediate	55		
1	Stansbury Island SE	Intermediate	53		
2	Stansbury Island Shanty Springs	High	52		
10	Strongs Knob NE	High	52		
5	Lakeside Mountains E	Low	50		
18	Rozel Point W	Intermediate	47		
14	Finger joint E	Low	47		
13	Finger tip SE	Low	44		
4	Stansbury Island NW	Intermediate	43		
3	Stansbury Island NE	High	38		
17	Black Mountain S	High	37		
16	Black Mountain N	High	32		
8	Strongs Knob SE	Low	32		
19	Rozel Point E	Low	28		
11	Finger joint W	Low	24		
12	Finger tip SW	Low	22		

Figure 5.6. Fetch and Great Salt Lake surveyed shores.
Shores are indicated by number (left column) and name . They are sorted by fetch length. Column on far right presents relationships based on Antelope Island evidence that long fetch is associated with high superelevation and that short fetch is associated with low superelevation. For Great Salt Lake shores, (GSL observed) short fetch is generally associated with low superelevation. However, long fetch is not consistently associated with high superelevation.

harbor east (#6), with equally long fetch (73 km), but facing east, has intermediate shoreline superelevation. East-facing Crocodile south (#15) with 63-km fetch has low shoreline superelevation and is in the lee of land. Direction of strong storm winds, to be discussed later in this chapter, and shallow water explain these low values.

Aspect – Direction of Storm Winds

Antelope Island research indicates that superelevation of the 1986/87 shoreline is associated with shorezone aspect, with the caveat that the association could be coincidental and explained by fetch, not wind strength. Shorezones facing west and northwest on Antelope Island generally have higher shoreline superelevation than those facing east, southeast, south, and southwest.

Ordering the 20 contrasting surveyed shores of Great Salt Lake based on associations of shoreline superelevation and aspect observed on Antelope Island shows inconsistent relationships of aspect and shoreline superelevation (Figure 5.7). As with Antelope Island, Great Salt Lake surveyed shores that face east and southeast and are in the lee of land have lower shoreline superelevation than those facing northwest (Figure 5.3). Specifically, of the 8 shores with east and southeast aspect, 6 have generally low shoreline superelevation, 2 have intermediate, and none have high superelevation. However, for the 5 west and northwest facing shores, 3 have high shoreline superelevation, 1 has intermediate, and 1 has low superelevation. Mainland shores on the up-wind shores of Great Salt Lake include shores in the lee of land along the east side of the Lakeside Mountains (#5, 6, and 7) in Gilbert Bay, the west side of Gunnison Bay (#13-15), and the east side of Rozel Point (#19). These shores have low shoreline superelevation except for a shore of intermediate superelevation south of Lakeside (#6). However, there are exceptions to this general pattern of low superelevation associated with shores in the lee of land: lee exposures of southeastern

	Location	Generalized superelevation	Aspect	GSL observed	Based on AI
16	Black Mountain N	High	NW		
4	Stansbury Island NW	Intermediate	W		
11	Finger joint W	Low	W		
20	Promontory-Little Valley	High	W		
17	Black Mountain S	High	WSW		
7	Lakeside harbor bay	Low	N		
9	Strongs Knob N bay	Intermediate	N		
3	Stansbury Island NE	High	NE		
10	Strongs Knob N	High	NE		
2	Stansbury Island Shanty Springs	High	NNE		
12	Finger tip SW	Low	SW		
18	Roxel Point W	Intermediate	SW		
1	Stansbury Island SE	Intermediate	E		
6	Lakeside harbor E	Intermediate	E		
5	Lakeside Mountains E	Low	E		
14	Finger joint E	Low	E		
15	Crocodile south	Low	E		
13	Finger tip E	Low	ESE		
8	Strongs Knob SE	Low	SE		
19	Rozel Point E	Low	SE		

Figure 5.7. Aspect and Great Salt Lake surveyed shores.
Shores are sorted by aspect based on Antelope Island evidence that shores that face northwest, west, and north generally have high superelevation, and those facing east and southeast generally have low superelevation. For Great Salt Lake shores, (GSL observed) east and southeast facing shores have low or intermediate shoreline superelevation. However, association of high shoreline superelevation with west and north aspect is not consistent.

shores of Stansbury Island (#1, 2) have intermediate and high superelevation. Both of these shores are exposed to fetch > 50 km.

Downwind, mainland shores that face into storm winds from the west and northwest have high or intermediate shoreline superelevation, such as at Black Rock Point (#16, 17), the west side of Rozel Point (#18), and at Promontory-Little Valley (#20) with important exceptions: (1) Finger joint west (#11) faces west, has low shoreline superelevation, and is located on the east side of exceptionally shallow Clyman Bay; (2) Lakeside harbor bay (#7) faces north, but fetch to the north is exceptionally short, only 2 km. Northeast facing shores of Strongs Knob (#9) and Stansbury Island (#3) have high and intermediate shoreline superelevation, inconsistent with general patterns of Antelope Island, but perhaps explained by northerly and northeasterly winds associated with cyclonic systems as they move across the lake. Surveyed shores of Strongs Knob (#8-10) provide evidence of effects of wind exposure and fetch: in the lee of the island (#8) exposed to short fetch, shoreline superelevation is low; northeasterly (#9) and north (#10) exposures with fetch > 50 km and outside of the lee of the island have high and intermediate shoreline superelevation (Table 5.1). However, there are exceptions to this general pattern of low superelevation associated with shores in the lee of land: lee exposures of southeastern shores of Stansbury Island (#1, 2) have intermediate and high superelevation. Both shores are exposed to fetch > 50 km (Table 5.1).

Fetch and Wind

Field investigations around Great Salt Lake were designed to explore the relative role of wind strength and fetch in determining wave-energy environments and shoreline superelevation. The Antelope Island data set provides tantalizing but inconclusive evidence that relative shoreline superelevation indicates direction of strong winds. As suggested by Gilbert (1890), a way to test whether fetch alone accounts for elevated shorelines is to examine associations of direction of strong winds and relative shoreline superelevation where fetch is held constant. Gilbert (1890) observed that superelevation is approximately equal for pairings of Bonneville-level shorelines with equal fetch in opposite directions and concluded that differences in fetch, not differences in wind strength, explain differences in shoreline superelevation. The pattern of paired exposures of shoreline superelevation for Gunnison Bay indicates that direction of storm winds is more consistently associated with shoreline superelevation than fetch (Figure 5.8). If fetch were the dominant factor, the color patterns of the diagram would resemble concentric circles, with low values toward the center of the diagram, intermediate values with increasing fetch, and high values on the outside of the diagram. However, the pattern is low for shores to the northwest and high for shores on the southeast where they face into storm winds. Thus, evidence suggests that wind strength contributes more to shoreline superelevation than fetch for shores of Gunnison Bay.

The association of shoreline superelevation with both fetch and aspect for Great Salt Lake does not contradict Gilbert (1890) and is consistent with shore protection manuals (USACE, 2002). Great Salt Lake is fetch-limited. Where fetch is short, such as for Great Salt Lake, the wave-generating surface area is limited, and differences in wind strength greatly affect transfer of energy into the lake surface. Stronger winds increase the height of individual wind waves resulting in higher wave runup and higher shoreline superelevation. Shores facing into the direction of strongest winds have high shoreline superelevation relative to shores facing into moderate winds. In contrast, where fetch is long, such as for high levels of Lake Bonneville or for Lake Michigan, differences in wind strength make proportionately less difference to significant wave height because the lake surface approaches being a fully arisen sea of energetic waves

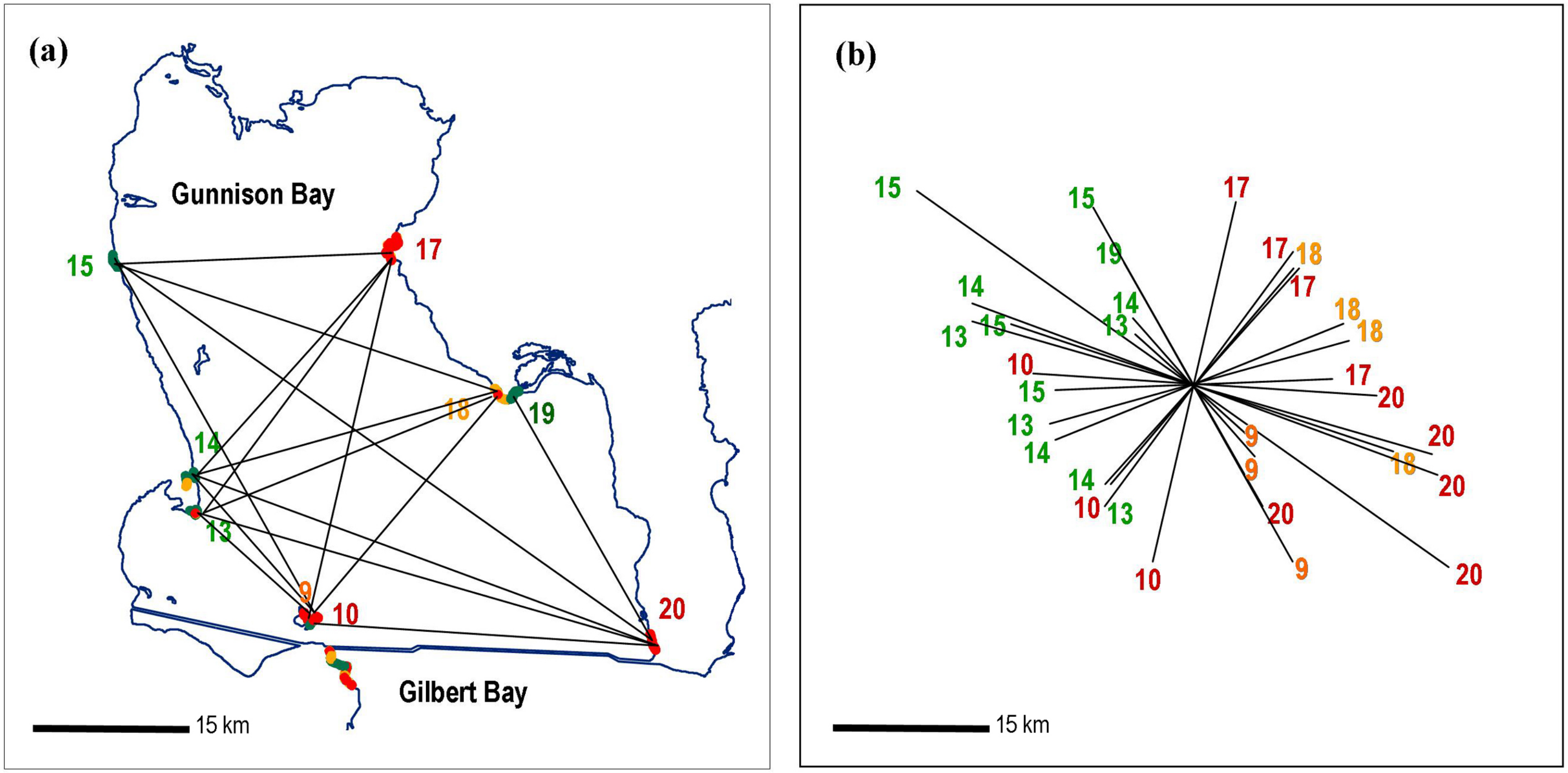


Figure 5.8. Pairings of equal fetch.
Map (a) displays pairings of surveyed shores around Gunnison Bay. Numbers represent places on map of Figure 5.2. Color indicates generalized superelevation of the surveyed shores. Lines drawn digitally between pairs of locations, were copied and pasted onto the diagram at right as fetch vectors. The length of each line represents length and direction of fetch between facing shores. If fetch alone accounts for shoreline superelevation, the pattern of superelevation of diagram (b) would resemble concentric circles with low superelevation closer to the center and high superelevation distant from the center. However, the pattern of diagram (b) indicates generally lower shoreline superelevation for locations on upwind locations and higher shoreline superelevation for locations facing into strong storm winds, evidence that wind strength contributes to shoreline superelevation.

that are physically unstable and approach the same height. Winds other than from the direction of strongest winds achieve fully arisen seas with wave height similar to those caused by strongest winds. Relative shoreline superelevation for fetch-dominated, large lakes is evidence of relative wave energy, but not necessarily evidence of relative wind strength or direction of strong winds.

Shorezone Slope and Coastal Landforms

Field investigations around Great Salt Lake generally corroborate findings of Antelope Island research with respect to shorezone slope and coastal landforms. Findings of associations of shorezone materials and shoreline superelevation of Antelope Island research were beyond the scope of the field investigations around Great Salt Lake because they entailed detailed mapping of shore characteristics.

With respect to shorezone slope, a ranking of the 20 contrasting surveyed shores of Great Salt Lake from steep to gentle upper-shorezone slope indicates that, as with Antelope Island, gentle shorezone slope is associated with low shoreline superelevation and steeper shorezone slope is associated with high shoreline superelevation (Figure 5.9). The 2 shores with steepest shorezones, Strongs Knob north (#10) and Black Mountain north (#16), have upper-shorezone slope steeper than 9° and have generally high shoreline superelevation. All 6 surveyed shores with upper-shorezone slope less than 0.5° have low shoreline superelevation (#5, 11, 12, 13, 15, and 19). The Antelope Island data set suggests a cutoff of 2° for low shoreline superelevation. The Great Salt Lake shore elevation survey suggests a more gentle, 1° slope as the cutoff. Associations of shorezone slope and superelevation appear more consistent for shores of Great Salt Lake than for Antelope Island and suggest that shorezone slope has promise as an indicator of relative wave-energy environments. Extensive shallow water is associated with low shoreline superelevation on Antelope Island and surveyed shores of Great

	Location	Generalized superelevation	Slope in degrees	GSL observed	Based on AI
10	Strongs Knob NE	High	9.88		
16	Black Mountain N	High	9.11		
18	Rozel Point W	Intermediate	8.67		
3	Stansbury Island NE	High	5.80		
2	Stansbury Island Shanty Springs	High	4.98		
20	Promontory - Little Valley	High	4.65		
17	Black Mountain S	High	3.87		
6	Lakeside harbor E	Intermediate	3.49		
7	Lakeside harbor bay	Low	2.33		
8	Strongs Knob SE	Low	2.00		
14	Finger joint E	Low	1.66		
1	Stansbury Island SD	Intermediate	1.59		
9	Strongs Knob N bay	Intermediate	1.16		
4	Stansbury Island NW	Intermediate	1.16		
19	Rozel Point E	Low	0.44		
13	Finger tip SE	Low	0.35		
12	Finger tip SW	Low	0.17		
15	Crocodile south	Low	0.06		
5	Lakeside Mountains E	Low	0.05		
11	Finger joint W	Low	0.03		

Figure 5.9. Shorezone slope and Great Salt Lake surveyed shores.
Shores are sorted based on decreasing steepness of upper-shorezone slope. Associations around Great Salt Lake generally support findings of Antelope Island research that steep shorezones generally have high shoreline superelevation, and that very low-gradient shorezones generally have low shoreline superelevation. The cutoff for gentle slope and low shoreline superelevation for Antelope Island was estimated as 2°. Field investigations around Great Salt Lake indicate a 1° cutoff.

Salt Lake. Specifically, lakebed elevations higher than 4205 ft (1281.7 m) a.s.l. are consistently associated with low superelevation for Great Salt Lake surveyed shores (Figure 5.10). In contrast, shores with offshore water depths greater than 14 ft (4.3 m), where the lakebed surface is lower than 4198 ft (1279.6 m) a.s.l., all have intermediate-to-high shoreline superelevation. This association is consistent with literature concerning wind wave generation, growth, and energy dispersion (USACE, 2002)

Shores of the field investigations around Great Salt Lake were classified as accretional (based on coastal landforms, such as spits, multiple lagoons, and shore sediments building into the lake) or erosional (based on steep headlands and extent of exposed bedrock). Shores were classified as mixed where beaches and headlands alternate. As with Antelope Island, erosional coastal shores have generally high shoreline superelevation and accretional shores have generally low shoreline superelevation (Figure 5.11). Exposed bedrock is associated with high shoreline superelevation for surveyed shores around Great Salt Lake (Figure 5.12). No surveyed shore that lacked exposed bedrock in the shorezone had high shoreline superelevation. All shores with some exposed bedrock had generally high and intermediate shoreline superelevation. Absence of exposed bedrock along shores is a reliable indication of low shoreline superelevation. Nine of the 9 shores with no exposed bedrock have generally low shoreline superelevation. Exposed bedrock tends to indicate higher-energy wave environments, although it is not a consistent indicator. Of 11 contrasting surveyed shores with exposed bedrock, 6 have high shoreline superelevation, 5 have intermediate, and none has low superelevation. Offshore shallow water and mudflats are consistently associated with low shoreline superelevation for Great Salt Lake surveyed shores (Figure 5.10). Of 5 contrasting surveyed shores with lakebed > 4200 ft (> 1280.16 m) a.s.l., all have low shoreline superelevation. These observations corroborate the general patterns observed on Antelope Island, although percentage

	Location	Generalized Superelevation	Elevation of lakebed in ft a.s.l.	Elevation of lakebed in m a.s.l.	Lakebed >4200 ft > 1280.16 m a.s.l.	GSL observed	Based on AI
3	Stansbury Island NE	High	4193	1278.0	No		
18	Rozel Point W	Intermediate	4193	1278.0	No		
1	Stansbury Island SE	Intermediate	4195	1278.6	No		
2	Stansbury Island Shanty Springs	High	4195	1278.6	No		
6	Lakeside harbor E	Intermediate	4196	1278.9	No		
16	Black Mountain N	High	4197	1279.2	No		
17	Black Mountain S	High	4197	1279.2	No		
9	Strongs Knob N bay	Intermediate	4198	1279.6	No		
10	Strongs Knob NE	High	4198	1279.6	No		
7	Lakeside harbor bay	Low	4199	1279.9	No		
8	Strongs Knob SE	Low	4199	1279.9	No		
13	Finger tip SE	Low	4199	1279.9	No		
14	Finger joint E	Low	4199	1279.9	No		
20	Promontory - Little Valley	High	4199	1279.9	No		
4	Stansbury Island NW	Intermediate	4200	1280.2	No		
12	Finger tip SW	Low	4205	1281.7	Yes		
19	Rozel Point E	Low	4205	1281.7	Yes		
15	Crocodile south	Low	4206	1282.0	Yes		
5	Lakeside Mountains E	Low	4207	1282.3	Yes		
11	Finger joint W	Low	4207	1282.3	Yes		

Figure 5.10. Offshore water depth and Great Salt Lake surveyed shores.
Shores are sorted based on elevation of near- and offshore nearly horizontal mudflats or lakebed. Associations on Antelope Island and around Great Salt Lake indicate that extensive shallow water offshore is associated with low shoreline superelevation.

	Location	Generalized superelevation	Accretion vs.erosion	GSL observed	Based on AI
10	Strongs Knob NE	High	Erosional		
16	Black Mountain N	High	Erosional		
17	Black Mountain S	High	Erosional		
20	Promontory - Little Valley	High	Erosional		
3	Stansbury Island NE	High	Erosional		
18	Rozel Point W	Intermediate	Erosional		
2	Stansbury Island Shanty Springs	High	Mixed		
9	Strongs Knob N bay	Intermediate	Mixed		
6	Lakeside harbor E	Intermediate	Mixed		
1	Stansbury Island SE	Intermediate	Mixed		
4	Stansbury Island NW	Intermediate	Mixed		
5	Lakeside Mountains E	Low	Mixed		
7	Lakeside harbor bay	Low	Accretional		
8	Strongs Knob SE	Low	Accretional		
11	Finger joint W	Low	Accretional		
12	Finger tip SW	Low	Accretional		
13	Finger tip SE	Low	Accretional		
14	Finger joint E	Low	Accretional		
15	Crocodile south	Low	Accretional		
19	Rozel Point E	Low	Accretional		

Figure 5.11. Coastal landforms and Great Salt Lake surveyed shores.
Shores are sorted based on associations of shoreline superelevation with coastal landforms observed on Antelope Island. Associations around Great Salt Lake generally support Antelope Island findings that accretional coastal landforms, such as spits, barrier beach complexes, and lagoons, are generally associated with low superelevation and erosional coastal landforms, such as sea cliffs and bedrock headlands, are generally associated with high superelevation.

	Location	Generalized superelevation	Bedrock %	Bedrock	GSL observed	Based on AI
18	Rozel Point W	Intermediate	60%	Yes		
10	Strongs Knob NE	High	40%	Yes		
3	Stansbury Island NE	High	40%	Yes		
20	Promontory-Little Valley	High	30%	Yes		
2	Stansbury Island Shanty Springs	High	20%	Yes		
4	Stansbury Island NW	Intermediate	15%	Yes		
16	Black Mountain N	High	10%	Yes		
17	Black Mountain S	High	10%	Yes		
9	Strongs Knob N bay	Intermediate	5%	Yes		
6	Lakeside harbor E	Intermediate	3%	Yes		
1	Stansbury Island SE	Intermediate	3%	Yes		
8	Strongs Knob SE	Low	0%	No		
7	Lakeside harbor bay	Low	0%	No		
14	Finger joint E	Low	0%	No		
19	Rozel Point E	Low	0%	No		
13	Finger tip SE	Low	0%	No		
12	Finger tip SW	Low	0%	No		
15	Crocodile south	Low	0%	No		
5	Lakeside Mountains E	Low	0%	No		
11	Finger joint W	Low	0%	No		

Figure 5.12. Exposed bedrock and Great Salt Lake surveyed shores.
Shores are sorted by decreasing exposed bedrock in the shorezone. Antelope Island research found that bedrock headlands are generally associated with high shoreline superelevation although some bays with bedrock have low superelevation. For Great Salt Lake shores (GSL observed), abundant exposed bedrock (20 percent or more) is associated with high and intermediate superelevation. All Great Salt Lake surveyed shores with no exposed bedrock had low superelevation.

of exposed bedrock was not mapped per se as part of the Antelope Island shoreline surveys.

In spite of strong evidence that corroborates the major findings of the Antelope Island research concerning associations of shorezone slope, coastal landforms and shoreline superelevation, the observations of the field investigations around Great Salt Lake do not rule out the possibility that noncoastal processes determine patterns of shorezone slope and beachzone materials around Great Salt Lake. If, for example, shorezone slope results from tectonic activity and not from coastal processes, then the initial finding of the field investigations around Great Salt Lake that coastal landform patterns are causally associated with shoreline superelevation would be invalid. An additional complexity is that landforms and shorezone slope affect wave energy and also are affected by wave action. Field investigations around Great Salt Lake did not address these complexities.

Future Research: Remaining Evidence of 1986/87 Flooding

Shoreline evidence of 1986/87 was unexpectedly abundant for some shore stretches around Gunnison Bay, on the west shore of Gilbert Bay, and on islands of the lake even after 16 years of exposure to natural processes, such as fire and human activities, including livestock grazing and disruption by motorized vehicles. Even so, field investigations around Great Salt Lake substantiate concerns that shorelines of the Bonneville basin are precious archives of earth systems history endangered by natural processes and human development (Chan and others, 2003b). The sooner and more thoroughly that shoreline evidence of highstands of Great Salt Lake and other shallow closed-basin lakes is documented, the more complete a story it can tell. Documentation of evidence of the 1860s-70s highstand and pre-1980s highstand conditions is surprisingly scarce considering the number of ranchers, sailors, and geomorphologists who worked and walked along shores of Great Salt Lake during the intervening century. Few photographs document pre-1980s conditions, making change analysis associated with processes of the 1980s highstand almost impossible. With improved precision of vertical control associated with GPS technology and with remote sensing techniques, such as LIDAR, it may be possible to survey remaining evidence of tires, railroad ties, and driftwood before it is lost in the next decades to fire and human disturbance.

In 2005 it is still possible to document considerable remaining evidence by walking out the shore, photographing evidence, and referencing geographic location with GPS units. Survey grade, mobile GPS devices could tie survey stations of the 20 contrasting surveyed shores to a common vertical control, tie them to Antelope Island survey control, and tie to USGS lake gage control. This would test comparative field survey techniques and provide insight to the accuracy of benchmarks in the vicinity of Great Salt Lake. Benchmark datums have been of considerable concern for lake-level monitoring of Gunnison and Gilbert Bays (Loving, 2002) as well as of scientific interest as evidence of isostatic and tectonic movement. If geomorphic surveys with vertical and horizontal control are made along the shores of Great Salt Lake, they will be the basis for examining the geomorphic work of the next record highstand when Great Salt Lake rises above its 1986/87 level.

CHAPTER 6

CONCLUSIONS

Shoreline expressions of the 1986/87 highstand fluctuation of Great Salt Lake provide extraordinary evidence of coastal lacustrine processes of shallow, closed-basin lakes. The shoreline evidence is unusual because its age is narrowly constrained and its materials are relatively undisturbed. Evidence of the lake's highstand includes not only the physical expressions of landforms and shore materials but also photographs of shore conditions taken during and after the highstand, regional weather records, lake-level monitoring, and personal accounts of storm-wave conditions. This array of evidence allows for connections to be made between coastal processes and geomorphic evidence that typically are not possible for paleoconditions.

The well-exposed, nearly continuous expressions of the 1986/87 shoreline on Antelope Island provide sufficient evidence to describe, quantify, and analyze the magnitude and patterns of shoreline superelevation. Patterns observed on Antelope Island were tested at specific sites around Great Salt Lake. Shoreline superelevation is evidence of wave-energy environments, and, therefore, shoreline expressions of 1986/87 provide opportunities to explore relationships among wave-energy environments, coastal processes, and landform expressions. Research conclusions summarized in Table 6.1 are based on evidence of shoreline superelevation on Antelope Island and around Great Salt Lake. Geomorphologists including Gilbert (1890) and Currey (1980) who have studied lacustrine coastal environments have noted similarities among shallow, closed-basin lakes at different geographic locations. Thus, it is

Table 6.1. Summary of research conclusions.

Issue explored	Evidence supports
Pattern and magnitude of shoreline superelevation.	
• Shoreline expressions document still-water lake elevation precisely.	No
• Shoreline expressions describe a horizontal plane.	No
• Shoreline superelevation is random and inconsequential.	No
Shore processes.	
• Changes in lake surface due to wind set-up resemble lake seiche.	No
• Wave runup explains shoreline superelevation.	Yes
• Shoreline superelevation represents wave energy.	Yes
Coastal conditions.	
• Strong storm winds result in shoreline superelevation.	Yes
• Long fetch alone explains high shoreline superelevation.	No
• Steep shorezone slope is associated with high shoreline superelevation.	Yes
• Shallow offshore slope is associated with low shoreline superelevation.	Yes
• Coarse beachzone materials indicate high-energy wave environments.	No
Applicability.	
• Antelope Island shores represent shores of Great Salt Lake.	Yes

expected that conclusions of Antelope Island and Great Salt Lake coastal research will apply to other shallow, closed-basin, fetch-limited lakes and paleolakes. Applications of these findings to other basins, however, should be made with caution. Relative shoreline superelevation is evidence of relative shorezone wave environments only where other processes, such as fault displacement, deltaic sedimentation, or processes associated with ice do not overwhelm effects of waves.

Evidence from Antelope Island and Great Salt Lake argues for a conceptual change away from assumptions that lacustrine shoreline evidence forms essentially at still-water lake level. Surveyed shoreline expressions on Antelope Island and around Great Salt Lake provide overwhelming evidence that shoreline superelevation is a lake-wide phenomenon with spatial patterns caused by lacustrine coastal processes. Except where debris was caught in wetland vegetation, all shoreline expressions on Antelope Island were deposited above still-water lake elevation. One-third of the surveyed shoreline expressions are more than 3.4 ft (1 m) above still-water lake elevation and some were deposited almost 12 ft (3.7 m) above still-water lake elevation. Shoreline superelevation, far from being unusual, should be expected along lake shores.

The plane the shoreline expressions describe is not horizontal and has potential to be mistaken for postdepositional displacement. Elevations of the 1986/87 shoreline expressions are, on average, 1.7 ft (0.5 m) higher on the west side of the island than on the east side. The magnitude of shoreline superelevation is small, on the order of 1-12 ft (0.3-3.7 m), compared to some postdepositional displacements that are over 10 times as large, such as tectonic displacement of shorelines by faulting along the Wasatch Front (Hecker, 1993) or isostatic rebound of Bonneville-level shorelines (Gilbert, 1890; Crittenden, 1963; Bills and others, 2002). However, a meter of elevation difference is the order of magnitude of isostatic displacement at the margin of some basins (Lillquist, 1994) and of some fault displacements (McCalpin and others, 1992).

Some calculations of highstand recurrence and associated flooding rely on accurate identification of paleoshoreline evidence (Atwood, 1994). Where shoreline evidence is continuous and where evidence of individual paleohighstands can be walked out, differences in paleoshoreline elevations on the order of 1 ft (0.3 m) can be identified and those elevation differences can be used to calculate recurrence of lake highstand fluctuations (Lillquist, 1994). However, where paleoshoreline evidence is not continuous, correlations of paleolake highstand evidence based on elevation alone, without consideration of superelevation, may lead to inaccurate interpretations of the frequency and magnitude of lake-level fluctuations and associated flooding hazards.

Although coastal processes of Great Salt Lake generally resemble those of marine and large-lake environments, there are important differences. Marine storm surge is complex, involving tides, currents, and atmospheric pressure differences. Because Great Salt Lake is a smaller and, presumably, simpler system, effects of components of storm processes can be more easily isolated and analyzed than along marine shores. This Great Salt Lake research determined that wave runup of individual wind waves is the dominant process that determines magnitude and variability of shoreline superelevation around the lake. Thus, shorezone characteristics of Great Salt Lake and, by inference, other fetch-limited lakes result from cumulative effects of individual wind waves and not from wave trains or swell from distant storms. This research concluded that lake set-up is sufficiently small in comparison to wave runup, or sufficiently complex, not to be identifiable as a component of shoreline superelevation.

This research clarifies that shoreline expressions of Great Salt Lake result from wave-action due to storms and that wave energy of the shorezone is the net result of transfer of wind energy into the lake surface and dissipation of wave energy. The spatial patterns of the magnitude of superelevation of the 1986/87 expressions of shorelines of Great Salt Lake are explained by variations in wind strength and direction, wave-generating area, and shore environments. The west side, high-superelevation side, of Antelope Island faces into the direction of strong storm winds that traverse comparatively large areas of open water of Gilbert Bay. In contrast, the island's eastern shore is in the lee of the island, exposed to weaker, easterly winds that traverse shorter expanses of the open water of Farmington Bay, and has low shoreline superelevation. Evidence from sites around Great Salt Lake further clarifies the relative importance of fetch and wind strength to shoreline superelevation indicating that, for lake levels of 1986/87, direction of strong winds was more important than fetch in determining shoreline superelevation. Shores facing into storm winds have higher shoreline superelevation than those in the lee of mountains, islands, and headlands regardless of fetch. For example, shoreline expressions along the northwest shore of Gunnison Bay have low superelevation compared to southeast shores of the bay that face into strong storm winds from the northwest.

This research postulates that Great Salt Lake's fetch-limited size explains the unmistakable contribution of wind strength to shoreline superelevation. Great Salt Lake is fetch-limited, on the order of 60 km in contrast to fetch of hundreds of kilometers for fetch-dominated marine coasts and large lakes, such as Lake Michigan or Lake Bonneville. Storm winds do not transform the surface of Great Salt Lake into wave trains of a fully arisen sea and waves of Great Salt Lake do not become energy-saturated. Therefore, for fetch-limited lakes, increased wind strength increases wave height and wave energy in the shorezone.

This research also concludes that coastal landforms and shorezone slope are, in part, due to relative wave energy in the shorezone and, therefore, that they are geomorphic evidence of the relative wave-energy environments that cause them. Although shorezone slope is generally indicative of wave energy, the relationship can be complicated by underlying geology and by other shorezone characteristics, such as shorezone roughness.

For fetch-limited, shallow, closed-basin lakes, such as Great Salt Lake, coastal characteristics that are closely associated with shoreline superelevation are evidence of relative wave energy and, because the lake is fetch-limited, evidence of the direction and relative strength of storm winds. For example, steep bedrock headlands are associated with high shoreline superelevation. The relationship of high-energy wave environments and steep shorezones are interrelated for shorezones facing into strong winds: alongshore and offshore currents transport fine material away from shore and steepen shorezone slope; and, because the shorezone is steep, waves do not lose energy until they arrive onshore. Long, gently sloped shorezones of shallow water and extensive mudflats are associated with low shoreline superelevation. Waves cannot grow where they are limited by shallow water. Gently sloped shorezones dissipate energy of waves arriving onshore as the waves touch bottom and break. Upwelling onshore currents due to offshore winds tend to accrete, rather than erode, shorezones in the lee of land masses. This research concludes that contrasting patterns of erosional landforms, such as bedrock headlands, versus patterns of accretional landforms, such as multiple barrier beaches, are evidence of contrasting wave-energy environments. Where bedrock headlands are on one side of an island or a peninsula and multiple lagoons and accreting barrier beaches are on the opposite side, the bedrock headland faces into storm winds and the accreting shore is in the lee of the landform. Therefore, contrasting patterns of coastal landforms of fetch-limited paleolakes should be considered as a line of evidence for determining direction of strong paleowinds.

This research found that shorezone materials and shoreline superelevation are, unexpectedly, poorly associated for shores of Antelope Island. For example, cobbles and gravel were not consistently associated with high-energy wave environments.

The inconsistent associations can be explained by noncoastal-process provenance of materials of the beach zone. Proximity to bedrock and beach nourishment by debris-flow deposits affect size of materials of the beach zone. Beach material size should be used with considerable caution to infer wave-energy environments for environments similar to Great Salt Lake where shorezones have materials that are not exclusively the product of wave action.

Future Work

Four general research areas can build on and refine findings of this research. First, real-time monitoring of lake-surface elevation changes and storm conditions could greatly clarify evolution, magnitude, and mechanisms of lake set-up; initiation of seiching; and effects on lake circulation. Although this Antelope Island – Great Salt Lake research does not validate a simple-tilt model of lake set-up, it does not dismiss the possibility that lake set-up is a complex and important lake process. The present configuration of a single lake gage in Gunnison and in Gilbert Bays and the historical configuration of two gages in Gilbert Bay have successfully documented daily, seasonal, and cyclic fluctuation of lake level. However, this configuration of gages has been insufficient to document evolution of lake set-up. A better understanding of the magnitude and patterns of changes of lake-surface elevation during storms could lead to a better understanding of storm-related lake circulation patterns including flow paths of nutrients and pollutants. Advances in remote sensing techniques for real-time monitoring of water surface elevation has potential to document the magnitude and distribution of storm-related lake-surface changes.

Second, bay-specific investigations can further test island-scale and lake-scale findings of this research and develop location-specific definitions of storm-related inundation hazards. Bay-scale processes, such as effects of wetland vegetation, were not studied at a detailed scale as part of superelevation research. However, all surveyed locations of Antelope Island shoreline expressions that were at or below still-water lake elevation were associated with coastal wetlands that dissipated wave energy and trapped debris as it came onshore. If shoreline superelevation and the inundation hazards it represents can be diminished by local modifications, such as by wetland vegetation or change of shorezone slope, local shorezone modifications have potential to lessen damage for some areas vulnerable to wave action and storm inundation.

Third, based on Great Salt Lake research, coastal features of small, fetch-limited paleolakes have potential to indicate not only relative wave energy but also the dominant direction of strong winds. Fetch-limited paleolakes have a suite of evidence of relative wind strength that differs from and complements that of fetch-dominated paleolakes.

Fourth, and most urgent, the remaining evidence of the 1986/87 shoreline of Great Salt Lake should be documented for posterity. Evidence collected on Antelope Island and the shores of Great Salt Lake provided the evidence critical for definition of shoreline superelevation, a phenomenon that was previously recognized, but whose magnitude was underestimated and whose patterns were dismissed as inconsequential. Not all of the 1986/87 shoreline expressions around Great Salt Lake have been investigated even at a reconnaissance level. Shoreline evidence around Great Salt Lake will be baseline data for shorezone change analysis following the next record highstand of Great Salt Lake. If evidence of the 1860s-70s highstand had been recorded, policy makers would have had the benefit of evidence of inundation in deliberations of hazards associated with the wet cycle of the 1980s.

With more development on the lake's historic floodplain, vulnerability to lake fluctuation increases, and understanding of coastal processes of Great Salt Lake is increasingly timely. Public policies impact shorezones. Discussions include weighing the impacts of transportation corridors through lake-shore wetlands on the east shore of Farmington Bay; low- to moderate-cost housing developments in northwestern Salt Lake City across the lake's floodplain; and life-cycle costs of critical facilities, such as Salt Lake International Airport and municipal sewage facilities, constructed on shores known to be damaged by storm processes of 1986/87. These discussions can benefit not only from more precise and accurate delineation of the inundation hazard zone but also from understanding the natural processes that govern high-, intermediate-, and low-energy wave environments.

APPENDIX A

SURVEYED ELEVATIONS ON ANTELOPE ISLAND

Elevations of shoreline expressions of the 1986/87 highstand of Great Salt Lake were surveyed at 1228 locations on Antelope Island. Surveyed elevations are listed below in two columns:

Location (m) = location along the linearly referenced shore-route measured clockwise in meters from Ladyfinger Point.

Easting (UTM e) = UTM geographic coordinates, zone 12, NAD27

Northing (UTM n) = UTM geographic coordinate NAD27

Z = elevation of surveyed location above the vertical datum 4200 ft (4280.16 m) a.s.l.

m	UTM e	UTM n	Z
13	394784	4545953	13.8
23	394796	4545950	14.7
46	394816	4545957	14.0
93	394848	4545946	14.7
112	394865	4545939	15.8
138	394884	4545910	15.2
173	394907	4545884	13.5
182	394910	4545875	13.2
182	394914	4545879	13.4
221	394939	4545848	14.0
227	394947	4545850	15.3
262	394981	4545836	13.5
262	394982	4545835	15.0
264	394984	4545838	13.4
283	395003	4545836	13.3
284	395003	4545839	13.5
304	395024	4545839	13.7
305	395024	4545837	13.7
321	395041	4545835	14.0
321	395041	4545837	14.0
333	395053	4545848	13.9
334	395054	4545847	14.3
373	395089	4545842	13.1
374	395090	4545841	13.5
389	395104	4545837	14.3
411	395128	4545841	16.7
414	395129	4545846	14.2
435	395148	4545856	15.3
448	395162	4545854	14.7
465	395181	4545851	13.6
465	395181	4545849	14.3
506	395222	4545856	14.0
515	395230	4545863	13.9
518	395232	4545862	14.0
565	395277	4545877	13.9
582	395295	4545886	13.8
616	395329	4545895	13.6
617	395330	4545891	15.3
627	395341	4545899	13.3
674	395388	4545903	13.6
677	395390	4545899	14.1
690	395404	4545907	13.5
717	395431	4545911	14.0
719	395433	4545911	14.2
734	395448	4545922	14.1

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
736	395450	4545921	14.8	2523	396409	4544737	13.4
740	395455	4545927	15.0	2525	396410	4544735	13.6
744	395458	4545912	12.5	2587	396437	4544679	13.4
744	395459	4545932	13.1	2648	396463	4544624	13.3
745	395460	4545931	14.0	2648	396462	4544623	13.6
758	395469	4545868	12.7	2685	396483	4544592	13.3
763	395472	4545880	12.8	2685	396482	4544592	13.4
786	395498	4545872	13.4	2752	396516	4544535	13.4
787	395498	4545875	12.9	2754	396517	4544533	13.4
793	395504	4545878	13.6	2780	396533	4544512	13.4
835	395543	4545892	13.2	2780	396532	4544512	13.6
1239	395937	4545865	13.0	2839	396572	4544468	13.8
1358	396048	4545824	14.5	2900	396616	4544427	13.8
1400	396075	4545788	16.3	2901	396617	4544428	13.2
1483	396129	4545731	13.3	2953	396660	4544398	13.9
1521	396150	4545698	13.8	2954	396663	4544400	13.7
1530	396156	4545691	13.7	3002	396704	4544377	14.2
1590	396176	4545636	13.5	3004	396706	4544378	13.7
1642	396192	4545586	13.6	3066	396763	4544353	13.9
1642	396192	4545586	13.8	3067	396765	4544355	13.7
1643	396194	4545586	12.7	3127	396823	4544338	14.2
1673	396194	4545555	13.6	3129	396825	4544340	14.0
1765	396219	4545466	14.0	3177	396872	4544333	14.3
1860	396234	4545373	13.6	3177	396873	4544337	14.3
1936	396243	4545297	13.4	3191	396886	4544334	13.7
2006	396252	4545228	13.6	3191	396886	4544333	14.0
2065	396261	4545169	13.3	3243	396939	4544334	14.1
2120	396271	4545115	13.2	3244	396939	4544332	14.4
2122	396271	4545113	13.6	3275	396970	4544323	13.8
2188	396287	4545049	12.6	3294	396987	4544314	13.9
2188	396286	4545048	13.2	3295	396987	4544313	14.1
2281	396315	4544960	13.2	3338	397028	4544302	13.3
2281	396314	4544960	13.3	3340	397030	4544299	13.6
2318	396328	4544925	13.3	3385	397074	4544291	13.8
2318	396329	4544925	13.3	3424	397113	4544287	13.9
2382	396354	4544866	13.3	3493	397181	4544279	13.4
2460	396382	4544793	13.5	3555	397243	4544271	13.8

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
3574	397262	4544270	13.5	4971	398585	4543913	14.0
3628	397316	4544265	13.5	5022	398634	4543901	13.9
3657	397350	4544257	13.7	5027	398639	4543900	13.9
3658	397353	4544258	13.4	5027	398640	4543901	14.5
3681	397380	4544251	13.1	5051	398663	4543895	14.2
3683	397380	4544247	13.4	5119	398725	4543869	13.8
3685	397382	4544247	14.0	5164	398766	4543849	14.3
3685	397379	4544244	14.1	5231	398830	4543825	13.6
3756	397428	4544211	13.5	5256	398854	4543817	14.3
3759	397432	4544210	13.2	5293	398889	4543805	14.1
3770	397440	4544203	13.4	5346	398938	4543789	14.7
3771	397442	4544204	13.3	5358	398951	4543790	14.9
3816	397481	4544181	12.9	5369	398964	4543794	14.3
3872	397531	4544154	13.4	5397	398980	4543781	13.3
3940	397590	4544124	14.5	5431	399003	4543755	13.8
3971	397618	4544109	14.9	5465	399026	4543729	14.4
4027	397670	4544089	14.4	5522	399046	4543681	14.1
4097	397737	4544067	14.6	5600	399073	4543609	12.8
4098	397739	4544069	14.0	5692	399110	4543522	14.0
4179	397810	4544031	14.4	5718	399124	4543498	13.9
4247	397874	4544006	14.6	5798	399170	4543433	14.2
4263	397889	4544001	15.0	6009	399280	4543247	13.3
4399	398022	4543982	15.0	6033	399280	4543223	13.2
4409	398032	4543979	15.3	6035	399281	4543221	13.1
4479	398100	4543967	14.8	6037	399259	4543218	13.5
4484	398105	4543974	14.8	6047	399278	4543209	13.3
4492	398112	4543966	14.4	6553	399405	4542754	14.3
4493	398114	4543967	13.9	6593	399432	4542728	13.5
4566	398187	4543965	14.2	6613	399443	4542708	13.3
4569	398190	4543963	14.1	6696	399480	4542635	13.9
4638	398258	4543953	14.1	6720	399503	4542627	14.1
4692	398311	4543947	14.2	6746	399523	4542610	14.0
4739	398358	4543938	14.6	6751	399525	4542604	14.0
4821	398439	4543928	14.7	6786	399551	4542579	13.2
4869	398488	4543923	14.2	6786	399553	4542583	13.7
4873	398491	4543929	13.8	6812	399577	4542573	13.8
4935	398551	4543922	14.4	6824	399587	4542567	13.7

m	UTM e	UTM n	Z
6848	399578	4542518	12.6
6851	399608	4542550	13.8
6857	399615	4542548	13.9
6863	399618	4542542	13.3
6870	399609	4542512	12.8
6886	399639	4542532	13.2
6887	399594	4542446	12.9
6897	399649	4542527	13.6
6900	399652	4542526	13.4
6901	399652	4542525	13.4
6902	399620	4542463	12.9
6903	399645	4542507	12.9
6966	399679	4542471	12.5
6971	399696	4542475	12.7
6998	399716	4542456	12.6
7000	399706	4542448	12.1
7013	399715	4542438	12.7
7030	399730	4542420	13.2
7039	399719	4542415	13.1
7055	399683	4542416	13.0
7068	399719	4542383	12.7
7069	399723	4542381	13.6
7071	399674	4542402	12.7
7080	399700	4542379	13.6
7100	399657	4542377	12.7
7122	399681	4542342	13.3
7125	399676	4542341	12.5
7152	399631	4542332	12.6
7156	399666	4542311	13.4
7185	399620	4542300	12.4
7216	399642	4542256	13.2
7243	399602	4542245	12.6
7281	399625	4542198	13.3
7352	399623	4542126	13.2
7354	399613	4542124	12.1
7423	399640	4542065	12.7
7423	399645	4542069	13.4
7447	399659	4542049	13.5
7450	399652	4542040	12.8
7522	399708	4541994	12.9
7522	399711	4541998	13.7
7606	399781	4541951	13.6
7607	399779	4541948	13.1
7681	399849	4541919	13.6
7681	399849	4541917	13.7
7754	399918	4541895	13.8
7755	399919	4541897	13.7
7805	399968	4541881	14.0
7805	399969	4541883	14.1
7867	400029	4541871	13.7
7867	400029	4541868	14.1
7963	400115	4541837	13.0
7963	400115	4541835	13.1
8003	400133	4541806	12.9
8076	400168	4541743	12.5
8076	400166	4541742	13.0
8151	400211	4541679	12.9
8190	400247	4541658	13.6
8198	400243	4541649	13.2
8241	400280	4541614	12.5
8241	400280	4541614	12.6
8241	400280	4541614	12.7
8241	400280	4541614	12.7
8248	400262	4541589	13.4
8314	400201	4541559	13.0
8371	400161	4541519	13.1
8375	400180	4541494	13.3
8427	400142	4541459	13.6
8443	400112	4541466	13.1
8490	400079	4541432	13.2
8504	400085	4541406	13.8
8562	400042	4541367	13.7
8574	400019	4541373	13.3
8623	399985	4541338	13.1

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
8628	399995	4541322	14.1	9635	399922	4540553	13.7
8672	399963	4541292	14.2	9636	399923	4540552	13.4
8687	399940	4541294	13.1	9638	399929	4540551	13.9
8758	399890	4541243	12.9	9639	399930	4540550	13.4
8764	399900	4541226	14.0	9681	399927	4540508	13.5
8812	399868	4541190	13.7	9732	399927	4540457	13.3
8824	399860	4541180	13.7	9733	399926	4540457	13.4
8828	399852	4541183	13.5	9748	399930	4540436	13.8
8829	399843	4541190	13.1	9755	399923	4540435	14.6
8926	399794	4541109	13.9	9775	399906	4540424	14.4
8957	399775	4541083	13.7	9806	399878	4540410	13.9
8958	399784	4541077	13.3	9807	399875	4540413	13.7
9003	399761	4541038	13.5	9811	399868	4540419	13.7
9016	399748	4541036	13.5	9842	399861	4540380	14.4
9085	399723	4540971	13.1	9846	399849	4540388	13.9
9097	399730	4540957	13.5	9883	399832	4540352	14.3
9139	399726	4540920	13.4	9887	399821	4540358	13.8
9183	399735	4540877	13.1	9960	399773	4540307	13.9
9247	399765	4540822	12.9	9961	399781	4540300	14.0
9302	399808	4540787	13.7	10054	399711	4540235	13.9
9319	399824	4540785	11.9	10054	399714	4540233	14.0
9370	399874	4540776	12.9	10133	399660	4540174	13.9
9370	399875	4540774	13.3	10133	399658	4540176	14.0
9416	399917	4540756	12.9	10175	399633	4540143	13.8
9416	399916	4540754	13.6	10175	399630	4540145	14.3
9449	399943	4540738	13.4	10222	399600	4540108	13.8
9450	399942	4540737	13.7	10223	399598	4540109	14.3
9461	399953	4540727	12.9	10289	399558	4540056	13.5
9461	399952	4540727	13.5	10290	399554	4540058	13.9
9487	399951	4540700	12.8	10352	399513	4540012	13.7
9487	399949	4540700	13.5	10416	399474	4539966	13.7
9491	399946	4540696	13.7	10426	399461	4539961	13.5
9491	399945	4540696	14.0	10477	399445	4539914	13.4
9503	399948	4540681	13.2	10477	399440	4539914	13.5
9504	399946	4540680	13.8	10537	399437	4539854	14.7
9559	399931	4540630	14.0	10572	399430	4539820	14.4
9560	399933	4540630	13.6	10574	399428	4539819	15.8

m	UTM e	UTM n	Z
10632	399414	4539763	15.1
10676	399402	4539721	15.5
11979	399545	4538494	14.0
12041	399567	4538435	13.6
12099	399597	4538384	13.8
12240	399650	4538258	12.0
12450	399753	4538074	14.0
12450	399751	4538074	14.5
13840	400441	4536933	14.5
13865	400461	4536918	13.2
14113	400580	4536701	13.1
14114	400582	4536701	13.1
14190	400587	4536625	13.5
14284	400615	4536536	13.6
14371	400653	4536457	13.5
14423	400688	4536411	13.4
14502	400710	4536341	13.1
14772	400792	4536094	13.2
14844	400820	4536025	13.3
15044	400952	4535882	13.5
15122	400987	4535814	13.3
15136	400985	4535799	14.3
15174	400992	4535762	15.1
15382	401032	4535558	13.9
15891	401181	4535087	14.6
15954	401210	4535031	14.3
16029	401234	4534963	13.9
16432	401484	4534660	12.9
16445	401493	4534651	14.5
16495	401520	4534611	13.7
16554	401551	4534561	14.1
17090	401946	4534221	13.4
17291	402113	4534108	12.1
17398	402211	4534064	12.3
17519	402324	4534023	11.6
17589	402386	4533991	12.1
17892	402487	4533714	13.8

m	UTM e	UTM n	Z
17893	402493	4533701	13.4
17894	402525	4533655	13.5
17895	402575	4533613	12.5
17896	402632	4533571	12.8
17897	402673	4533520	12.1
17898	402683	4533496	12.2
17905	402666	4533493	11.1
17945	402620	4533512	11.6
17975	402547	4533508	12.3
17992	402408	4533653	12.2
18022	402477	4533493	12.6
18034	402458	4533483	12.6
18070	402417	4533469	12.8
18132	402357	4533449	13.1
18203	402271	4533494	11.2
18213	402313	4533431	12.9
18220	402308	4533427	12.9
18226	402302	4533424	13.0
18292	402251	4533399	13.1
18353	402196	4533366	13.1
18376	402156	4533371	13.1
18421	402134	4533326	13.3
18480	402084	4533291	13.3
18529	402021	4533287	12.5
18537	402015	4533282	12.7
18607	401985	4533213	13.1
18645	401948	4533198	12.6
18660	401928	4533196	12.7
18674	401936	4533168	13.3
18746	401894	4533126	12.9
18803	401841	4533089	13.1
18808	401849	4533076	13.0
18861	401815	4533036	13.1
18910	401774	4533005	12.5
18916	401780	4532993	13.4
19005	401737	4532926	12.8
19025	401727	4532908	12.9

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
19043	401706	4532896	12.4	25366	401587	4526818	13.7
19090	401702	4532849	12.7	25367	401590	4526818	13.4
19127	401692	4532814	12.4	25413	401612	4526777	14.0
21319	401906	4530692	13.1	25482	401638	4526713	13.6
21373	401873	4530649	12.6	25484	401634	4526709	13.7
21441	401839	4530590	12.9	25522	401630	4526672	14.1
21445	401798	4530609	11.7	25568	401626	4526626	13.6
21518	401810	4530524	13.0	25633	401604	4526564	14.1
21565	401790	4530480	13.4	25636	401618	4526558	13.2
21608	401781	4530438	13.1	25734	401587	4526464	13.5
21610	401771	4530439	12.7	25791	401558	4526415	12.5
21773	401729	4530282	13.4	25798	401595	4526386	13.7
21789	401724	4530266	13.4	25813	401573	4526379	13.2
21810	401715	4530247	13.1	25874	401576	4526303	13.2
22026	401642	4530044	11.8	25965	401531	4526259	13.7
22237	401618	4529833	13.5	25976	401561	4526246	13.6
22449	401612	4529619	13.3	26048	401525	4526187	13.6
22617	401614	4529463	13.7	26049	401542	4526187	13.3
22653	401620	4529427	13.5	26053	401521	4526181	14.2
22779	401579	4529306	14.6	26113	401502	4526118	13.6
22780	401592	4529300	13.6	26119	401518	4526114	12.6
22946	401560	4529137	14.1	26213	401486	4526016	12.6
23253	401555	4528847	14.0	26429	401513	4525809	15.0
24557	401336	4527572	12.5	26516	401483	4525709	14.2
24753	401379	4527383	13.3	26662	401504	4525583	14.2
24818	401404	4527323	13.8	26727	401523	4525499	12.8
24820	401414	4527328	12.8	26746	401483	4525501	12.1
24878	401436	4527272	13.2	26749	401506	4525483	12.8
24959	401491	4527213	13.5	28053	401182	4524285	14.5
24960	401482	4527208	13.4	28122	401222	4524230	13.9
25031	401500	4527143	13.8	28123	401218	4524227	14.0
25095	401526	4527083	13.5	28147	401240	4524210	14.3
25098	401521	4527078	13.6	28175	401189	4524157	13.4
25172	401545	4527007	14.1	28262	401252	4524106	12.9
25235	401566	4526949	13.3	28290	401232	4524087	13.4
25269	401561	4526912	13.3	28316	401215	4524066	12.9
25277	401579	4526909	13.5	28333	401173	4524071	13.2

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
28350	401173	4524052	14.0	29929	401213	4522618	14.0
28468	401146	4523934	14.3	29962	401223	4522582	13.3
28505	401146	4523895	13.5	29999	401281	4522593	14.0
28580	401139	4523825	13.3	30037	401315	4522575	13.8
28668	401157	4523738	13.7	30045	401250	4522491	13.5
28732	401164	4523675	13.8	30076	401350	4522554	13.2
28762	401168	4523644	14.1	30090	401283	4522473	13.9
28823	401170	4523581	13.9	30098	401372	4522551	13.9
28946	401174	4523471	13.9	30109	401380	4522542	13.6
29008	401162	4523405	13.5	30130	401402	4522541	14.1
29067	401158	4523345	13.1	30153	401423	4522529	13.9
29138	401167	4523275	13.3	30165	401318	4522450	13.3
29185	401171	4523228	13.9	30175	401457	4522521	13.6
29201	401174	4523211	14.3	30185	401458	4522517	12.8
29202	401177	4523210	14.7	30248	401412	4522485	12.9
29220	401166	4523193	13.3	30310	401355	4522459	12.2
29248	401149	4523171	13.8	30353	401316	4522441	13.6
29285	401128	4523141	13.7	30403	401268	4522425	13.9
29350	401094	4523085	12.8	30404	401267	4522427	13.8
29394	401073	4523047	11.9	30451	401222	4522413	13.8
29454	401042	4522996	13.0	30451	401222	4522411	13.8
29494	401035	4522956	12.9	30499	401175	4522402	13.7
29541	401015	4522917	13.1	30502	401176	4522392	14.1
29578	401002	4522880	13.7	30540	401135	4522394	13.8
29630	401017	4522830	13.5	30543	401134	4522389	14.0
29652	401010	4522804	12.9	30585	401091	4522381	14.1
29672	400998	4522766	13.0	30590	401088	4522376	13.8
29684	401039	4522782	13.5	30642	401037	4522365	14.4
29707	401022	4522735	13.1	30643	401037	4522360	13.9
29745	401079	4522735	13.7	30682	400999	4522351	13.4
29753	401055	4522704	13.3	30708	400981	4522329	13.6
29792	401084	4522673	13.5	30732	400963	4522312	15.2
29809	401126	4522693	14.1	30733	400962	4522312	15.3
29833	401124	4522644	13.8	30734	400964	4522309	13.8
29873	401161	4522626	13.4	30810	400926	4522336	15.5
29874	401178	4522653	13.8	30811	400927	4522337	16.0
29902	401198	4522628	13.8	30835	400910	4522353	17.7

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
30837	400908	4522353	15.1	32287	399974	4523181	16.3
30837	400908	4522354	15.4	32374	399927	4523254	17.8
30837	400908	4522354	15.5	32445	399888	4523312	15.4
30838	400909	4522356	16.3	32447	399889	4523315	16.5
30860	400887	4522364	14.9	32487	399867	4523349	16.5
30860	400888	4522365	16.1	32535	399841	4523390	16.1
30934	400826	4522403	15.5	32609	399805	4523446	15.2
30987	400776	4522421	14.6	32611	399805	4523448	16.1
31019	400747	4522433	14.7	32672	399792	4523508	16.8
31071	400696	4522445	14.1	32689	399791	4523525	17.2
31086	400683	4522455	15.7	32763	399772	4523597	16.7
31110	400658	4522452	14.0	32840	399739	4523668	16.3
31150	400623	4522474	14.8	32841	399741	4523670	16.8
31154	400615	4522465	12.8	32924	399697	4523740	15.9
31228	400549	4522500	14.1	32983	399668	4523791	16.3
31359	400419	4522525	14.5	33036	399648	4523840	16.0
31416	400381	4522505	14.9	33132	399599	4523923	16.5
31456	400338	4522493	14.5	33180	399573	4523964	13.6
31476	400319	4522496	14.5	33182	399577	4523968	16.6
31515	400293	4522514	11.9	33242	399548	4524022	16.3
31515	400295	4522515	15.8	33341	399489	4524092	14.9
31592	400233	4522563	13.4	33359	399474	4524102	15.7
31664	400176	4522606	15.0	33432	399418	4524147	14.2
31723	400135	4522647	15.5	33582	399332	4524270	14.6
31724	400137	4522649	18.2	33591	399324	4524275	15.0
31750	400125	4522672	16.2	33660	399272	4524321	15.5
31753	400122	4522675	13.8	33714	399228	4524354	14.4
31834	400113	4522756	17.8	33796	399162	4524398	14.6
31835	400111	4522757	16.3	33800	399159	4524402	14.3
31912	400108	4522833	16.2	33801	399157	4524400	14.4
31966	400104	4522887	16.8	33820	399140	4524409	14.7
31992	400095	4522913	16.8	33822	399138	4524408	14.4
32063	400072	4522980	16.1	33823	399136	4524408	14.0
32067	400074	4522985	15.3	33887	399075	4524424	14.6
32137	400049	4523050	15.5	33954	399010	4524426	14.8
32138	400045	4523049	15.8	33957	399007	4524425	14.3
32220	400009	4523123	16.8	34008	398956	4524433	14.2

m	UTM e	UTM n	Z
34009	398954	4524431	14.1
34029	398935	4524431	13.9
34047	398917	4524433	14.3
34048	398915	4524432	13.0
34071	398903	4524445	14.7
34071	398904	4524446	14.9
34103	398884	4524471	15.9
34104	398882	4524471	14.9
34116	398877	4524482	15.5
34117	398875	4524481	15.2
34172	398843	4524526	15.2
34172	398843	4524527	15.4
34228	398809	4524572	15.4
34229	398807	4524571	15.1
34305	398754	4524626	15.1
34305	398756	4524627	15.3
34360	398715	4524663	15.7
34360	398716	4524663	16.3
34419	398669	4524700	16.2
34419	398670	4524701	17.4
34431	398658	4524705	14.9
34431	398659	4524706	15.7
34485	398612	4524733	14.8
34485	398613	4524734	15.3
34558	398544	4524760	14.6
34558	398545	4524762	15.3
34620	398487	4524783	14.4
34679	398430	4524798	14.9
34728	398382	4524809	14.2
34780	398331	4524827	15.0
34975	398245	4524995	17.0
34991	398246	4525011	16.0
35025	398245	4525045	16.3
35068	398244	4525087	16.3
35089	398246	4525108	16.4
35167	398250	4525186	16.2
35168	398254	4525187	16.9
35168	398252	4525187	17.0
35233	398252	4525252	15.1
35234	398254	4525253	15.9
35298	398255	4525318	15.8
35299	398253	4525318	14.3
35359	398249	4525379	16.1
35360	398246	4525380	15.9
35425	398240	4525442	15.5
35426	398242	4525443	16.0
35478	398216	4525491	14.5
35480	398217	4525495	14.9
35593	398171	4525591	15.7
35594	398169	4525590	15.6
35635	398152	4525627	15.4
35636	398155	4525628	15.7
35668	398142	4525658	15.5
35669	398140	4525658	15.3
35669	398144	4525659	15.8
35784	398082	4525753	15.1
35784	398081	4525751	15.1
35856	398020	4525792	14.8
35856	398021	4525792	15.4
35930	397957	4525819	15.4
36001	397874	4525829	14.7
36003	397861	4525825	17.2
36007	397856	4525825	13.9
36013	397864	4525832	17.4
36015	397862	4525834	15.8
36044	397865	4525869	14.2
36044	397869	4525867	16.8
36080	397870	4525904	16.3
36120	397879	4525943	16.2
36155	397884	4525976	16.5
36158	397883	4525979	13.7
36202	397896	4526022	17.9
36253	397905	4526073	17.4
36293	397904	4526112	14.4

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
36294	397907	4526113	16.5	38181	397414	4527623	17.3
36351	397902	4526171	16.6	38454	397269	4527832	14.7
36351	397903	4526171	17.6	38461	397259	4527833	14.1
36412	397888	4526225	16.3	38645	397167	4527992	15.7
36478	397860	4526284	17.6	38666	397146	4528004	11.2
36726	397704	4526471	13.4	38748	397080	4528052	11.3
36943	397511	4526532	14.4	39414	396861	4528610	15.7
36979	397478	4526529	14.1	39422	396864	4528617	15.5
37114	397432	4526616	18.5	39423	396867	4528615	16.1
37139	397445	4526635	17.8	39476	396884	4528662	15.8
37140	397445	4526637	16.6	39476	396886	4528661	16.4
37311	397489	4526794	17.1	39528	396894	4528707	17.1
37364	397501	4526846	17.4	39539	396897	4528718	16.1
37439	397516	4526920	17.1	39619	396877	4528790	16.1
37441	397514	4526922	16.8	39622	396875	4528792	14.2
37454	397516	4526935	16.8	39633	396869	4528804	14.0
37458	397518	4526938	16.9	39633	396872	4528805	16.8
37549	397522	4527026	16.2	39654	396880	4528830	16.3
37551	397524	4527028	16.7	39665	396882	4528841	17.0
37610	397527	4527087	16.0	39693	396896	4528866	16.2
37660	397531	4527137	15.6	39693	396897	4528865	17.7
37696	397529	4527173	14.5	39759	396912	4528927	17.6
37696	397530	4527173	14.8	39816	396920	4528984	15.9
37699	397514	4527172	14.7	39817	396924	4528985	16.0
37763	397507	4527237	15.6	39894	396919	4529063	14.2
37767	397504	4527240	15.6	39896	396926	4529064	14.6
37827	397481	4527292	15.4	39987	396910	4529150	14.4
37827	397480	4527291	15.6	39987	396907	4529149	15.2
37872	397448	4527324	15.3	40091	396916	4529254	16.1
37875	397443	4527323	14.6	40221	396922	4529383	16.8
37900	397436	4527349	15.4	40297	396900	4529456	15.2
37901	397435	4527349	15.1	40367	396882	4529523	16.7
37978	397441	4527426	17.1	40412	396867	4529566	15.0
37979	397437	4527427	14.9	40536	396804	4529669	18.0
38001	397441	4527449	17.2	40573	396794	4529697	17.1
38045	397437	4527497	17.5	40740	396709	4529840	13.1
38119	397414	4527567	17.2	40779	396676	4529863	17.6

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
40798	396671	4529875	17.6	42232	396253	4531081	15.1
40806	396677	4529881	17.6	42232	396253	4531082	15.3
40810	396677	4529886	17.6	42278	396245	4531128	16.6
40829	396691	4529900	16.1	42312	396240	4531158	15.5
40830	396693	4529899	19.6	42312	396238	4531158	15.8
40873	396707	4529941	16.6	42367	396221	4531206	14.4
40873	396709	4529940	19.2	42368	396218	4531205	14.7
40916	396721	4529982	17.9	42411	396193	4531240	13.4
40967	396732	4530032	17.3	42411	396194	4531241	15.4
40973	396733	4530034	17.9	42470	396153	4531282	15.9
41047	396739	4530104	15.9	42531	396120	4531334	16.6
41050	396742	4530106	16.3	42758	395967	4531495	14.4
41118	396742	4530178	16.1	42784	395944	4531509	14.1
41198	396732	4530244	15.8	42785	395942	4531508	14.3
41275	396706	4530319	15.8	42807	395930	4531518	15.2
41275	396710	4530321	16.1	42874	395892	4531576	16.4
41348	396669	4530382	15.4	42910	395900	4531605	16.3
41349	396670	4530384	15.4	42954	395906	4531649	16.5
41413	396619	4530432	14.9	42984	395899	4531680	15.7
41471	396565	4530455	14.0	43043	395874	4531733	15.1
41488	396551	4530464	14.5	43043	395872	4531732	15.1
41525	396516	4530480	15.1	43102	395835	4531777	15.1
41561	396484	4530497	14.3	43104	395833	4531777	15.0
41591	396455	4530506	14.4	43178	395778	4531822	15.1
41637	396414	4530524	14.7	43243	395725	4531863	14.6
41686	396401	4530572	15.7	43246	395723	4531865	15.2
41687	396403	4530572	16.9	43308	395668	4531897	14.1
41844	396382	4530727	16.1	43309	395668	4531899	14.7
41873	396375	4530755	15.6	43313	395664	4531899	13.9
41875	396379	4530757	15.5	43315	395663	4531901	15.5
41942	396356	4530822	17.5	43318	395659	4531903	14.5
41987	396353	4530867	15.8	43319	395659	4531904	14.7
41987	396355	4530867	16.2	43374	395611	4531932	14.3
42145	396267	4530997	14.3	43374	395611	4531933	14.8
42145	396268	4530997	14.4	43407	395579	4531950	14.9
42200	396259	4531051	15.1	43408	395578	4531948	13.9
42200	396259	4531051	15.8	43451	395538	4531967	14.4

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
43454	395536	4531969	14.7	44441	395106	4532762	14.2
43501	395500	4531987	15.0	44511	395054	4532802	20.4
43520	395482	4531995	14.7	44643	394986	4532916	14.7
43545	395458	4532002	14.6	44672	394975	4532942	15.1
43592	395424	4532021	15.4	44733	394940	4532993	15.2
43621	395400	4532037	15.3	44805	394906	4533056	15.0
43667	395374	4532065	14.0	44940	394834	4533170	17.4
43671	395372	4532068	17.1	44978	394823	4533207	15.0
43795	395316	4532170	17.4	44978	394827	4533209	17.5
43807	395313	4532182	15.2	45000	394825	4533229	16.9
43807	395315	4532183	16.7	45116	394788	4533340	18.0
43849	395317	4532224	16.7	45175	394754	4533392	16.5
43871	395315	4532246	15.6	45205	394732	4533413	16.2
43914	395313	4532289	16.0	45235	394711	4533435	14.3
43914	395311	4532289	16.2	45237	394711	4533438	15.3
43981	395307	4532355	15.5	45298	394661	4533472	14.6
43983	395304	4532355	15.7	45338	394626	4533503	14.4
44028	395292	4532401	15.4	45436	394577	4533538	14.5
44029	395290	4532400	15.5	45507	394550	4533586	16.6
44079	395268	4532445	15.0	45516	394555	4533594	18.2
44079	395265	4532444	15.0	45533	394570	4533604	17.3
44110	395247	4532469	14.9	45537	394573	4533607	17.5
44111	395248	4532470	16.0	45574	394587	4533642	17.4
44160	395219	4532512	14.7	45593	394602	4533657	16.4
44160	395220	4532513	15.4	45644	394629	4533701	16.2
44192	395210	4532543	16.1	45713	394656	4533758	15.9
44258	395188	4532601	14.9	45915	394767	4533931	16.8
44278	395176	4532617	14.6	45915	394768	4533930	17.9
44278	395177	4532618	14.9	45990	394799	4534001	16.6
44308	395159	4532642	16.8	45990	394801	4534000	17.0
44338	395159	4532672	15.6	46082	394831	4534094	15.4
44339	395160	4532672	16.3	46085	394835	4534097	16.2
44389	395141	4532721	14.9	46134	394829	4534153	15.8
44391	395139	4532722	13.9	46226	394768	4534239	17.8
44413	395125	4532740	14.8	46292	394733	4534282	22.3
44413	395126	4532741	15.0	46470	394643	4534423	14.7
44440	395107	4532761	13.9	47670	394788	4535534	16.6

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
47748	394836	4535597	17.9	50380	394938	4537583	14.8
47839	394878	4535668	15.8	50417	394901	4537598	15.0
47914	394912	4535735	18.1	50418	394900	4537596	13.5
47941	394923	4535759	18.9	50461	394857	4537596	14.4
48030	394939	4535810	17.2	50495	394825	4537600	14.9
48033	394937	4535811	14.3	50528	394794	4537584	11.9
48055	394935	4535840	14.0	50528	394794	4537584	12.1
48061	394932	4535845	14.9	50558	394767	4537575	15.0
49409	395025	4536823	15.2	50602	394723	4537567	14.6
49440	395057	4536815	15.3	50682	394653	4537526	18.3
49441	395058	4536818	16.0	50685	394648	4537528	16.4
49472	395093	4536823	15.7	50824	394721	4537637	18.1
49486	395101	4536835	15.8	50860	394738	4537672	17.3
49488	395102	4536835	16.9	50886	394748	4537702	17.8
49552	395127	4536900	16.7	50898	394746	4537714	20.3
49553	395128	4536900	17.1	51217	394878	4537975	18.3
49615	395145	4536960	16.9	51245	394897	4537997	17.0
49696	395163	4537040	16.9	51282	394919	4538027	18.2
49784	395171	4537125	16.6	51290	394923	4538035	17.6
49786	395176	4537127	17.1	51336	394942	4538077	17.4
49806	395173	4537147	15.9	51337	394942	4538078	16.3
49807	395176	4537147	16.4	51470	394985	4538206	20.7
49891	395169	4537232	15.4	51514	394989	4538260	20.0
49892	395173	4537233	15.7	52438	395307	4538779	16.9
49944	395151	4537277	14.2	52457	395325	4538787	14.6
49946	395158	4537281	14.5	52492	395357	4538804	15.9
49987	395138	4537318	16.0	52520	395383	4538806	14.9
50025	395139	4537360	15.8	52567	395429	4538822	14.9
50069	395124	4537404	15.1	52716	395565	4538861	14.0
50074	395121	4537408	15.6	52761	395592	4538897	13.4
50146	395096	4537455	15.7	52763	395598	4538895	14.1
50215	395056	4537512	16.0	52858	395647	4538976	13.9
50278	395016	4537549	14.5	52892	395665	4539006	13.8
50278	395017	4537550	14.8	52970	395696	4539077	13.9
50307	394991	4537565	14.7	53003	395720	4539102	13.7
50328	394990	4537564	13.8	53054	395737	4539150	13.8
50347	394971	4537573	15.1	53121	395778	4539206	14.2

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
53157	395779	4539245	14.8	54638	395917	4540638	15.2
53179	395793	4539263	14.6	54640	395920	4540640	14.9
53243	395818	4539321	14.6	54713	395923	4540713	15.5
53320	395851	4539390	15.2	54715	395927	4540713	15.9
53412	395882	4539477	14.8	54758	395931	4540757	16.1
53486	395909	4539546	15.1	54805	395937	4540804	15.0
53523	395921	4539581	14.4	54824	395947	4540823	15.8
53524	395919	4539582	14.4	54870	395956	4540849	15.4
53587	395942	4539641	15.2	54897	395958	4540883	15.1
53646	395958	4539700	14.3	54900	395962	4540883	15.5
53646	395961	4539699	14.6	54968	395946	4540951	15.8
53706	395972	4539755	14.8	55043	395933	4541025	15.5
53707	395974	4539755	15.6	55120	395914	4541100	15.3
53753	395988	4539802	15.6	55207	395893	4541180	15.3
53755	395987	4539804	14.6	55288	395876	4541259	15.7
53783	395995	4539832	15.3	55346	395858	4541315	15.9
53855	396011	4539898	16.5	55352	395856	4541321	15.7
53866	396011	4539910	14.5	55418	395835	4541383	15.7
53925	396026	4539966	14.3	55568	395786	4541516	15.6
53927	396031	4539967	14.7	55723	395722	4541657	15.1
53992	396039	4540035	14.4	55770	395703	4541701	14.4
53993	396036	4540036	14.5	55889	395647	4541800	13.9
54066	396049	4540103	14.1	55937	395625	4541844	15.9
54067	396045	4540105	14.4	56053	395556	4541938	14.8
54111	396044	4540151	14.4	56148	395496	4542009	15.0
54156	396041	4540198	14.4	56173	395482	4542032	16.3
54185	396026	4540217	14.4	56174	395478	4542029	14.8
54232	396001	4540257	14.5	56295	395396	4542118	16.0
54284	395970	4540298	15.1	56296	395389	4542113	14.0
54343	395953	4540355	13.8	56407	395309	4542181	14.3
54375	395951	4540380	15.0	56412	395307	4542189	14.6
54423	395934	4540427	15.0	56481	395249	4542226	14.2
54473	395931	4540478	15.1	56481	395246	4542221	14.3
54537	395924	4540538	15.3	56549	395187	4542256	14.1
54539	395927	4540540	15.4	56552	395188	4542263	14.0
54576	395919	4540576	14.7	56698	395056	4542327	14.2
54578	395912	4540578	16.2	56700	395052	4542322	13.8

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
56742	395012	4542333	14.0	57811	393971	4542329	13.9
56801	394956	4542352	15.2	57870	393912	4542322	14.3
56802	394955	4542351	13.8	57870	393912	4542319	14.7
56872	394891	4542381	13.6	57871	393911	4542321	14.2
56874	394886	4542374	13.5	57872	393909	4542325	13.4
56941	394821	4542389	13.4	57872	393910	4542319	14.9
56942	394820	4542392	13.8	57915	393867	4542319	15.6
56943	394820	4542394	14.4	57928	393854	4542311	14.4
57046	394715	4542399	13.2	57931	393850	4542321	16.0
57117	394644	4542401	13.8	57951	393832	4542310	13.4
57118	394643	4542399	13.6	57975	393806	4542313	16.3
57198	394563	4542404	14.1	58021	393761	4542307	16.0
57219	394542	4542407	13.8	58022	393762	4542299	14.4
57220	394542	4542409	14.0	58039	393739	4542307	13.1
57323	394457	4542397	13.1	58050	393728	4542309	15.6
57323	394456	4542401	13.9	58054	393723	4542300	14.0
57414	394367	4542380	13.1	58126	393644	4542314	13.8
57414	394367	4542383	14.2	58140	393631	4542319	14.1
57467	394313	4542378	13.4	58144	393638	4542342	13.7
57471	394305	4542401	13.6	58208	393574	4542359	13.5
57489	394293	4542370	13.1	58262	393522	4542374	13.1
57490	394291	4542372	13.1	58333	393455	4542409	13.8
57520	394259	4542375	14.3	58399	393398	4542441	13.0
57521	394258	4542372	13.3	58458	393336	4542463	13.4
57537	394239	4542389	13.4	58487	393308	4542474	14.3
57587	394190	4542379	13.3	58499	393298	4542482	13.3
57604	394175	4542361	13.4	58547	393263	4542514	13.4
57654	394125	4542360	13.0	58560	393242	4542560	13.5
57656	394125	4542351	13.4	58598	393233	4542599	13.9
57659	394122	4542348	14.1	58655	393230	4542657	14.2
57708	394072	4542351	13.9	58713	393233	4542719	15.0
57711	394069	4542349	13.3	58730	393227	4542741	14.1
57712	394069	4542340	13.4	59045	393197	4543023	13.9
57712	394070	4542339	13.4	59131	393170	4543085	14.3
57761	394021	4542331	13.0	59192	393138	4543137	13.9
57761	394021	4542333	13.9	59243	393106	4543177	14.3
57771	394009	4542343	13.5	59316	393067	4543237	13.7

m	UTM e	UTM n	Z	m	UTM e	UTM n	Z
59392	393018	4543296	13.8	61585	394124	4543810	14.5
59453	392981	4543341	13.7	61668	394198	4543849	15.0
59524	392925	4543386	15.0	61767	394276	4543898	15.0
59580	392882	4543422	14.5	61837	394330	4543942	15.1
59704	392791	4543506	13.6	61907	394381	4543989	14.0
59789	392748	4543580	15.7	62032	394474	4544074	15.5
59911	392691	4543703	23.4	62093	394516	4544118	15.1
59947	392707	4543736	15.1	62143	394552	4544153	15.1
59971	392720	4543756	14.4	62219	394606	4544207	15.1
60011	392744	4543790	15.2	62317	394674	4544277	16.3
60093	392784	4543863	14.9	62428	394742	4544357	17.4
60151	392804	4543915	15.4	62500	394793	4544409	17.0
60218	392848	4543959	15.3	62541	394821	4544439	18.5
60250	392878	4543971	15.0	62863	395029	4544685	17.5
60300	392914	4543999	15.4	62961	395085	4544766	17.7
60363	392977	4543989	14.5	63040	395132	4544829	19.7
60413	393025	4543981	14.8	63184	395195	4544950	18.2
60456	393070	4543968	15.6	63309	395241	4545058	15.7
60546	393143	4543941	16.6	63380	395248	4545129	14.6
60598	393191	4543923	15.6	63429	395267	4545177	14.5
60645	393234	4543906	14.1	63579	395220	4545317	14.2
60703	393287	4543881	14.3	63579	395220	4545317	14.2
60766	393346	4543859	16.2	63622	395201	4545356	17.0
60790	393369	4543853	15.1	63692	395192	4545428	14.2
60844	393422	4543842	14.5	63754	395181	4545489	14.4
60915	393493	4543829	14.3	63824	395145	4545552	13.9
60973	393550	4543818	14.6	63893	395102	4545606	13.6
61041	393618	4543810	13.9	63958	395060	4545655	13.2
61113	393677	4543794	14.2	64029	395003	4545697	13.2
61175	393739	4543785	13.6	64083	394956	4545726	13.9
61241	393803	4543774	13.3	64139	394918	4545766	14.2
61321	393874	4543766	13.3	64276	394836	4545871	13.5
61372	393925	4543762	13.2	64309	394806	4545883	15.1
61406	393959	4543762	13.6	64311	394803	4545882	13.7
61423	393976	4543759	14.6	64311	394805	4545885	16.6
61467	394014	4543768	14.0	64355	394772	4545916	14.7
61513	394058	4543782	13.5				

APPENDIX B

SURVEYED ELEVATIONS AROUND GREAT SALT LAKE

Table B.1. List and key to figures, Appendix B.

Area	Map #	Surveyed shore	Generalized superelevation	Figure
Stansbury Island southeast shores		Location map	....	B.1
	1	Stansbury Island SE	Intermediate	B.2
	2	Stansbury Island Shanty Springs	High	B.3
Stansbury Island north shores		Location map	....	B.4
	3	Stansbury Island NE	High	B.5
	4	Stansbury Island NW	Intermediate	B.6
East of Lakeside Mountains		Location map	....	B.7
	5	Lakeside Mountains E	Low	B.8
Lakeside harbor		Location map	....	B.9
	6	Lakeside harbor east	Intermediate	B.10
	7	Lakeside harbor bay	Low	B.11
Strongs Knob		Location map	....	B.12
	8	Strongs Knob SE	Low	B.13
	9	Strongs Knob N bay	Intermediate	B.14
	10	Strongs Knob NE	High	B.15
The Fingerpoint		Location map	....	B.16
	11	Finger joint W	Low	B.17
	12	Finger tip SW	Low	B.18
	13	Finger tip SE	Low	B.19
	14	Finger joint E	Low	B.20
South of Crocodile Mountain		Location map	....	B.21
	15	Crocodile south	Low	B.22
Black Mountain		Location map	....	B.23
	16	Black Mountain N	High	B.24
	17	Black Mountain S	High	B.25
Rozel Point		Location map	....	B.26
	18	Rozel W	Intermediate	B.27
	19	Rozel E	Low	B.28
Promontory Point		Location map	....	B.29
	20	Promontory–Little Valley	High	B.30

Map # refers to numbers of Figure 5.2.
Figure column refers to figures of Appendix B.
Shoreline superelevation classification breaks are those used on Antelope Island.

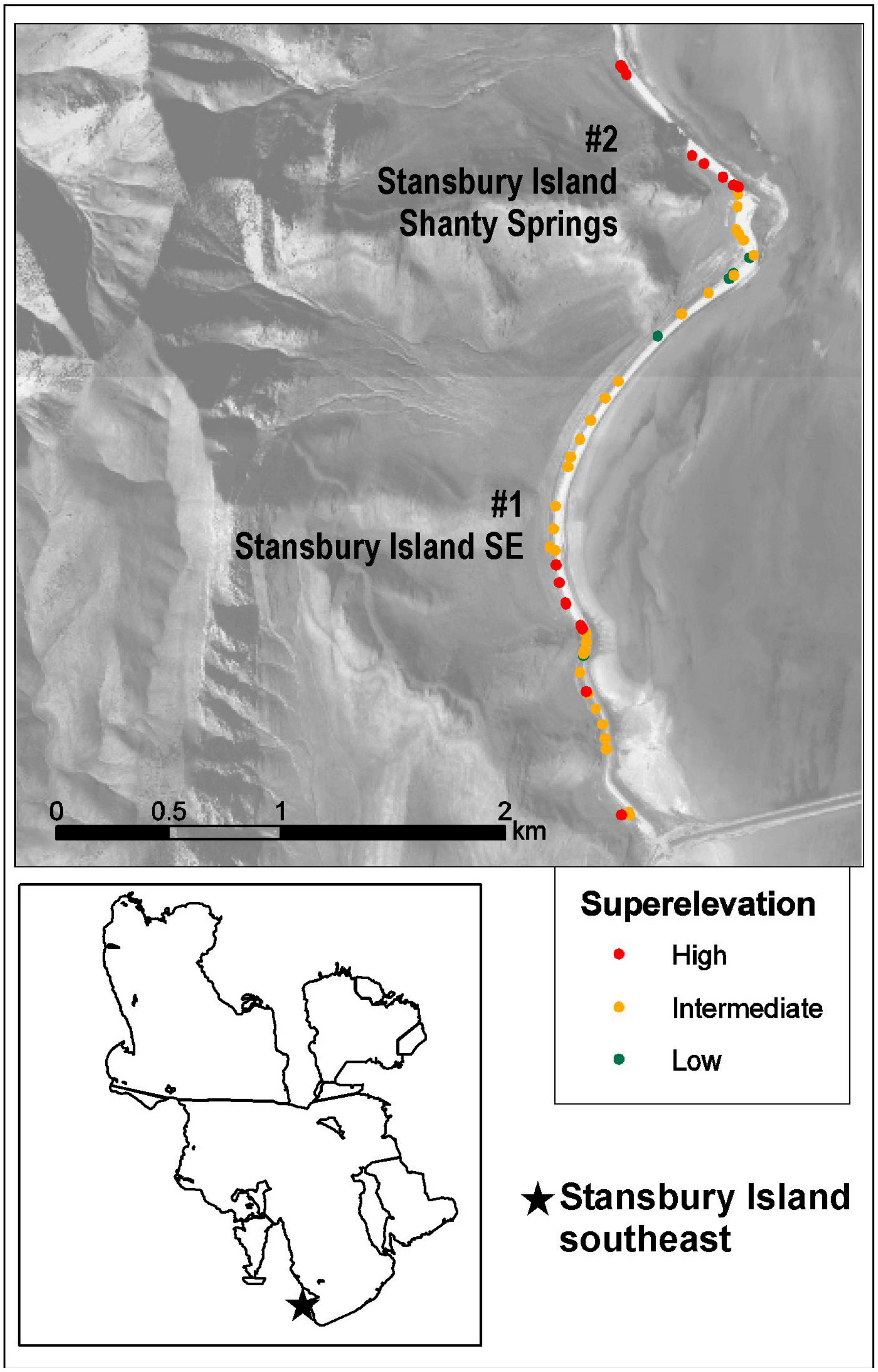
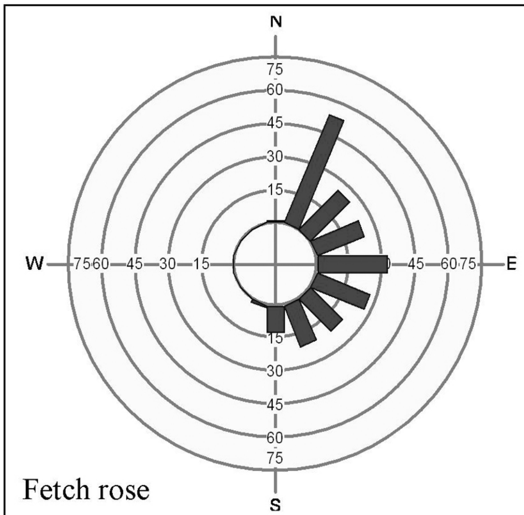


Figure B.1. Surveyed shores of Stansbury Island southeast shore.
Two shore segments are used for analysis of shoreline superelevation, map locations #1 and #2 of Figure 5.2. Stansbury Island SE (#1) is classified as generally intermediate shoreline superelevation. Stansbury Island Shanty Springs (#2) to the north is classified as generally high shoreline superelevation. During 1986-1987 some dikes of salt evaporation ponds, such as those of the lower right of photograph, were above water.

STANSBURY ISLAND SE



Fetch rose

Shoreline superelevation
INTERMEDIATE
Abbreviation: **StIsSE**

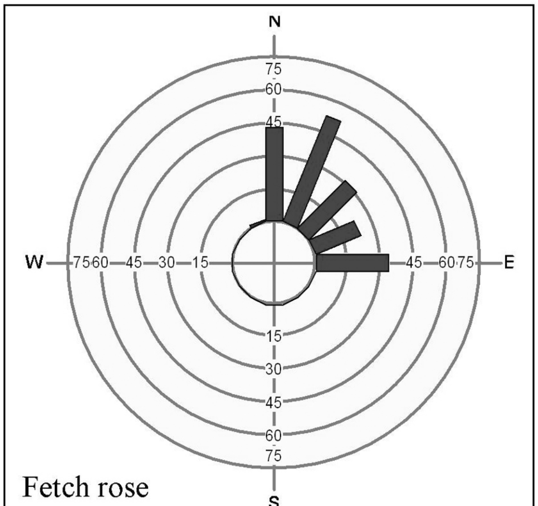
#1 on location maps

Gilbert Bay	
Length of longest fetch	53 km
Direction of longest fetch	NNE
General aspect of the shore	E
Length of fetch N and NW	NA
Location along bay axis	Intermediate
Slope in degrees between 4200 ft and 4220 ft contours	2°
Elevation of near-flat, off-shore lake bed	4195
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Coastline with a series of convex, bedrock points separated by a series of short coves and long, asymmetrically concave bay. Mixed beachface forms including: rocky, rough, bedrock; stepped beaches; and barrier beach and elongate lagoon.
Analogue: Northeast Antelope Island such as along Camera Flats.
Other: Canals, dikes and evaporations ponds of Morton Salt affect coastal hydrodynamics.

Figure B.2. Geomorphic characteristics Stansbury Island SE.

STANSBURY ISLAND Shanty Springs



Fetch rose

Shoreline superelevation
HIGH
Abbreviation: **StIsShSp**
#2 on location maps

Gilbert Bay	
Length of longest fetch	52 km
Direction of longest fetch	NNE
General aspect of the shore	NNE
Length of fetch N and NW	43 km
Location along bay axis	Intermediate
Slope in degrees between 4200 ft and 4220 ft contours	5°
Elevation of near-flat, off-shore lake bed	4195
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Concave coastline interrupted by a bedrock point. Beach face is rugged and rocky along bedrock and consists of a long, relatively straight run-up zone along the south part of the broad bay.
Analogue: southwest Antelope Island from Buffalo Scaffold Bay to Timely Gull.
Other: Well-preserved, 1980s debris. Vegetation associated with springs does not appear to have affected wave run-up.

Figure B.3. Geomorphic characteristics of Stansbury Island Shanty Springs.

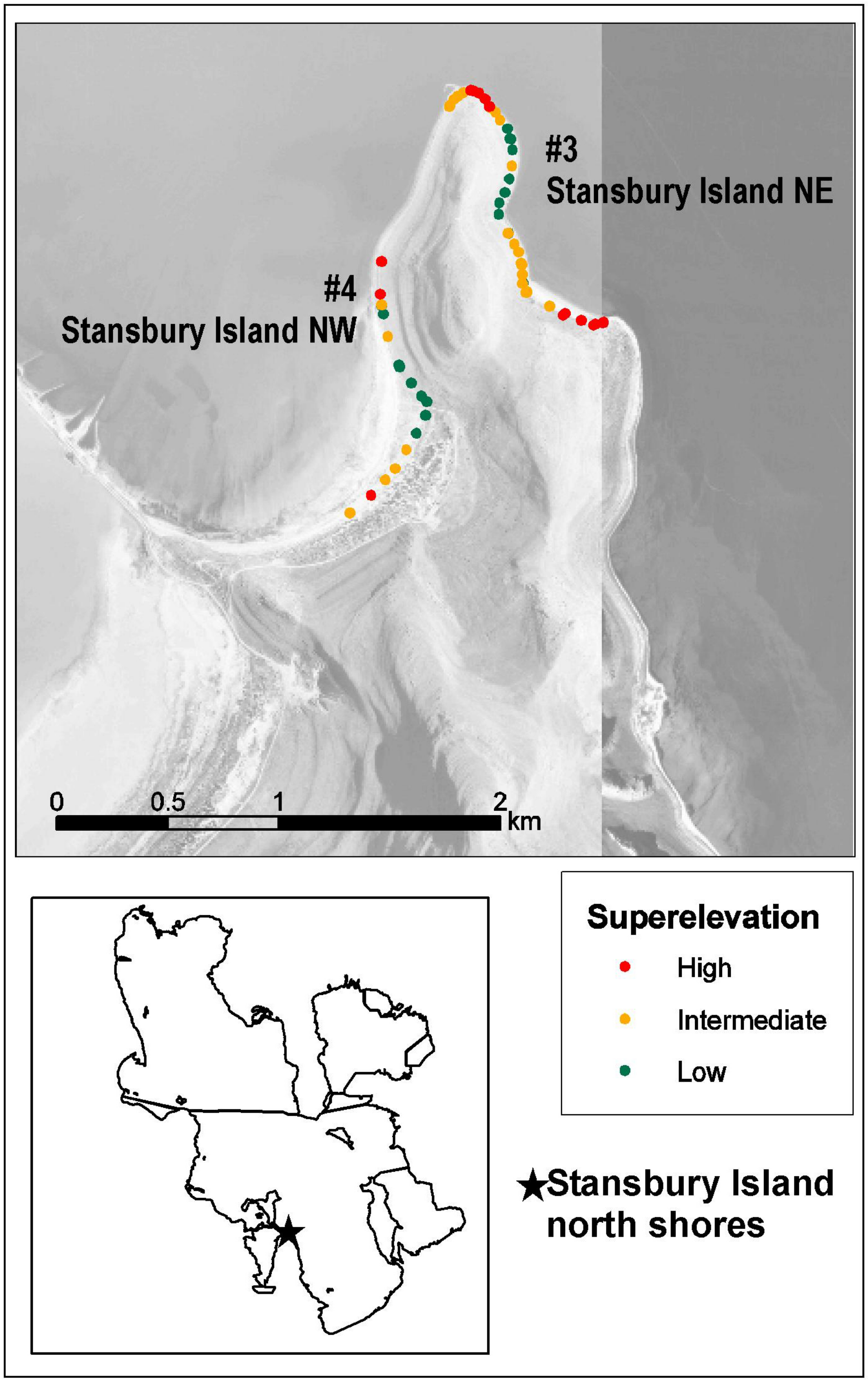
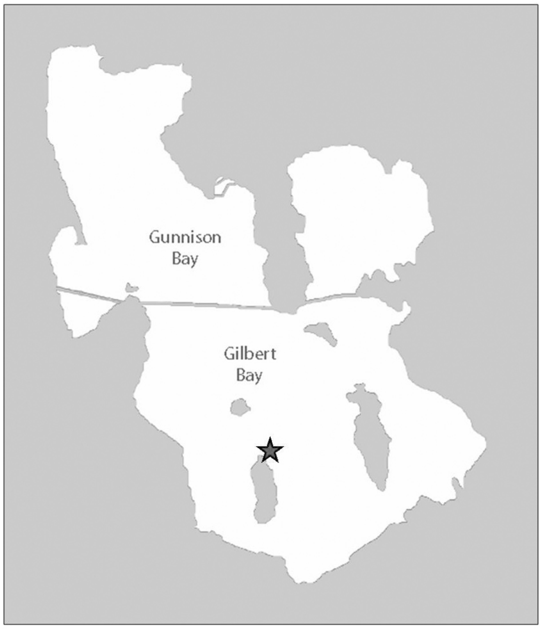
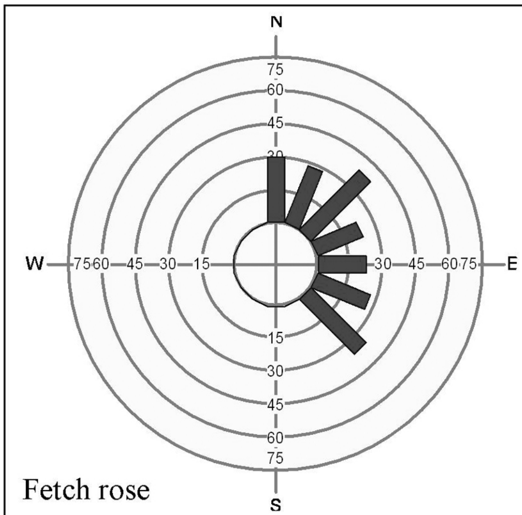


Figure B.4. Surveyed shores of Stansbury Island north shore.
Two shore segments are used for analysis of shoreline superelevation, map locations #3 and #4 of Figure 5.2. Stansbury Island NE is classified as generally high shoreline superelevation. Stansbury Island NW is classified as generally intermediate shoreline superelevation.

STANSBURY ISLAND NE





Fetch rose

Shoreline superelevation
HIGH
Abbreviation: **StIsNE**

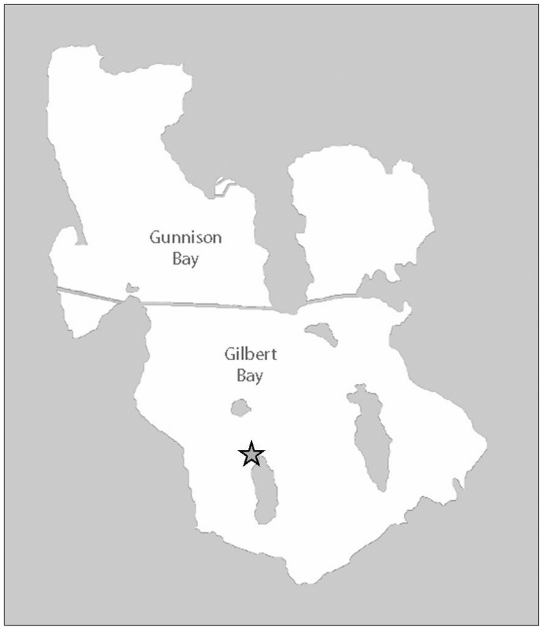
#3 on location maps

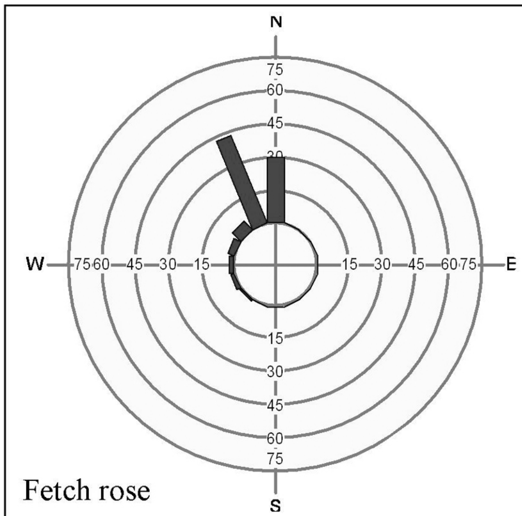
Gilbert Bay	
Length of longest fetch	38 km
Direction of longest fetch	NE
General aspect of the shore	NE
Length of fetch N and NW	30 km
Location along bay axis	Node
Slope in degrees between 4200 ft and 4220 ft contours	6°
Elevation of near-flat, off-shore lake bed	4193
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Convex, rugged, rocky headlands and concave embayments. Beach faces of headlands are steep and bouldery. Beach faces of coves are multiple steps. Beach face of bay is a single barrier beach and associated lagoon.
Analogue: Northernmost Antelope Island, Lady Finger Point, and Buffalo Bay.
Other: Human disturbance includes a marina for brine shrimping boats, collections of shore debris by local cabin owners, and fire.

Figure B.5. Geomorphic characteristics of Stansbury Island NE.

STANSBURY ISLAND NW	
Shoreline superelevation **INTERMEDIATE** Abbreviation: **StIsNW** **#4 on location maps**	
Gilbert Bay	
Length of longest fetch	43 km
Direction of longest fetch	NNW
General aspect of the shore	W
Length of fetch N and NW	43 km
Location along bay axis	Node
Slope in degrees between 4200 ft and 4220 ft contours	1°
Elevation of near-flat, off-shore lake bed	4200
Bedrock between 4200 and 4220 ft a.s.l.	Yes





Fetch rose

Coastal morphology: Convex, rocky headlands and concave, broad bay. Headland includes complex beachfaces: stepped, bouldery, and mixed. Beach face of bay includes a runup zone that cuts into dunes and modifies older beach deposits.
Analogue: Northern Antelope Island, Ladyfinger Point, and Bridger Bay.
Other: Island's restricted access has preserved 1980s shoreline debris. Dike to west has modified fetch from west. Effects of diking and offshore islands are not known.

Figure B.6. Geomorphic characteristics of Stansbury Island NW.

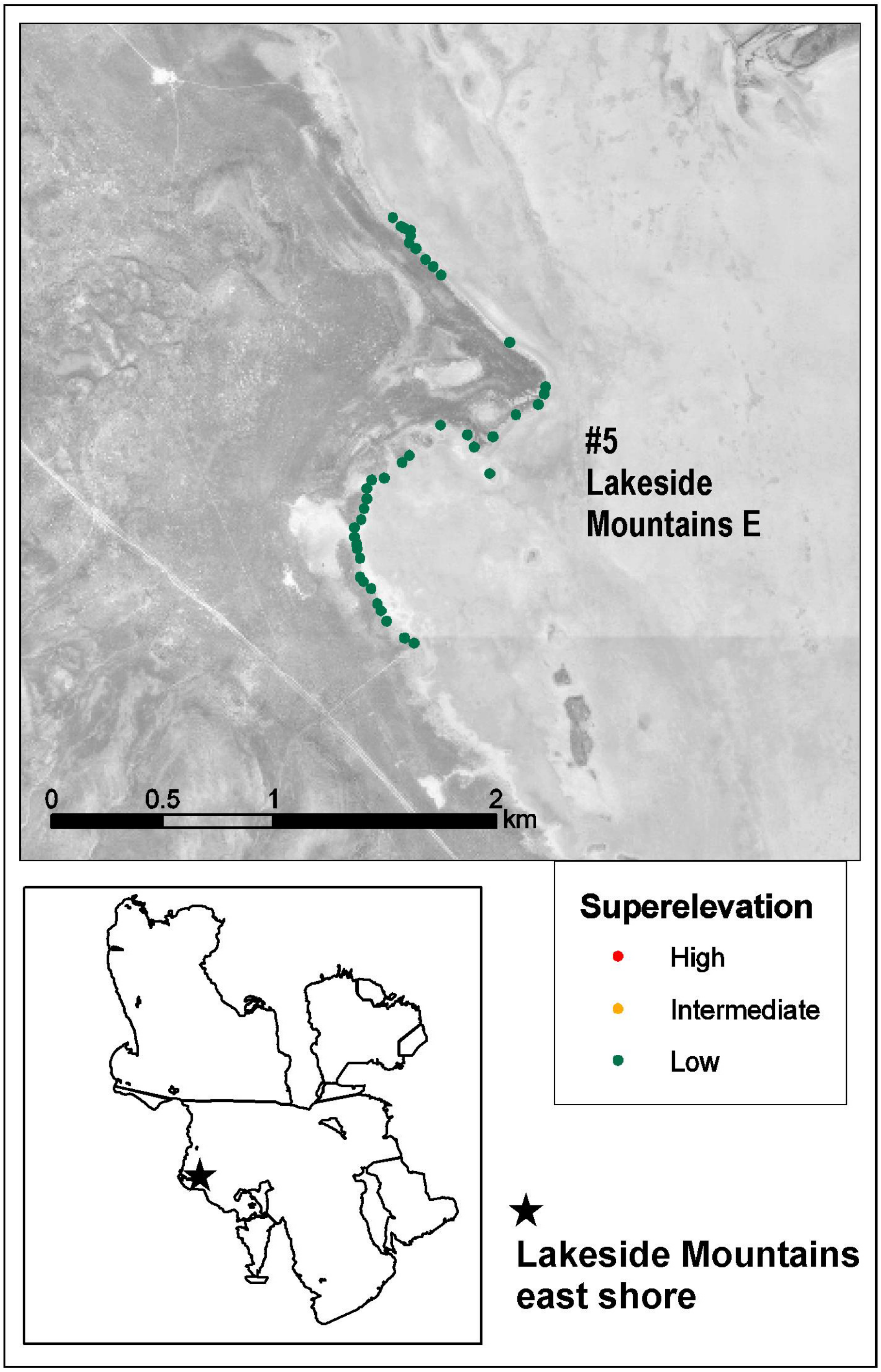
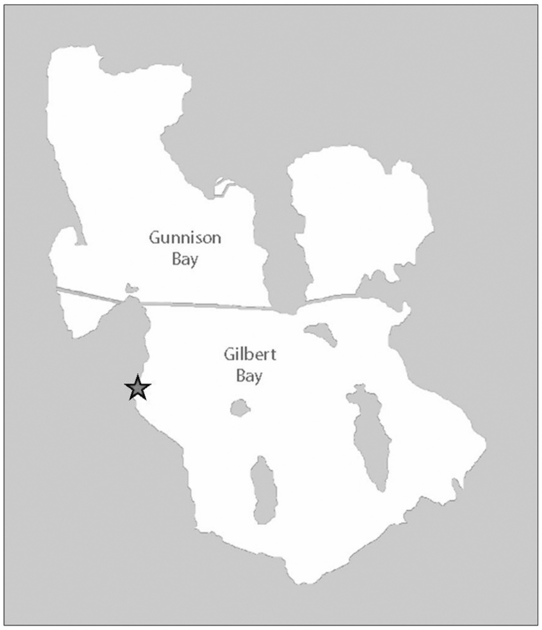
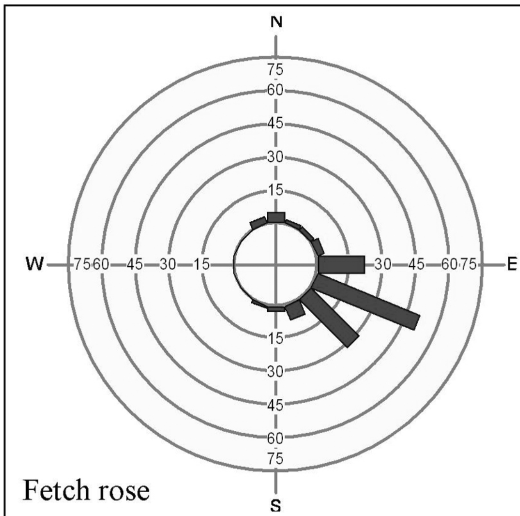


Figure B.7. Surveyed shores along Lakeside Mountains east shore.
One shore segments is used for analysis of shoreline superelevation, map location #5 of Figure 5.2. Lakeside Mountains E is classified as generally low shoreline superelevation.

LAKESIDE MOUNTAINS E





Fetch rose

Shoreline superelevation
Low
Abbreviation: **LksEa**

#5 on location maps

Gilbert Bay	
Length of longest fetch	50 km
Direction of longest fetch	ESE
General aspect of the shore	E
Length of fetch N and NW	NA
Location along bay axis	Intermediate
Slope in degrees between 4200 ft and 4220 ft contours	0.05°
Elevation of near-flat, off-shore lake bed	4207
Bedrock between 4200 and 4220 ft a.s.l.	No

Coastal morphology: Gently curving, concave, low-relief coastline. Complex of cuspate barrier beaches, lagoons, and barrier islands.
Analogue: East-central Antelope Island, such as Sea Gull Point.
Other: No drainages reach the shore. Debris of 1980s is well-preserved. Soil changes demarcate flooded terrain. Human disturbances include off-road vehicle traffic.

Figure B.8. Geomorphic characteristics of Lakeside Mountains E.

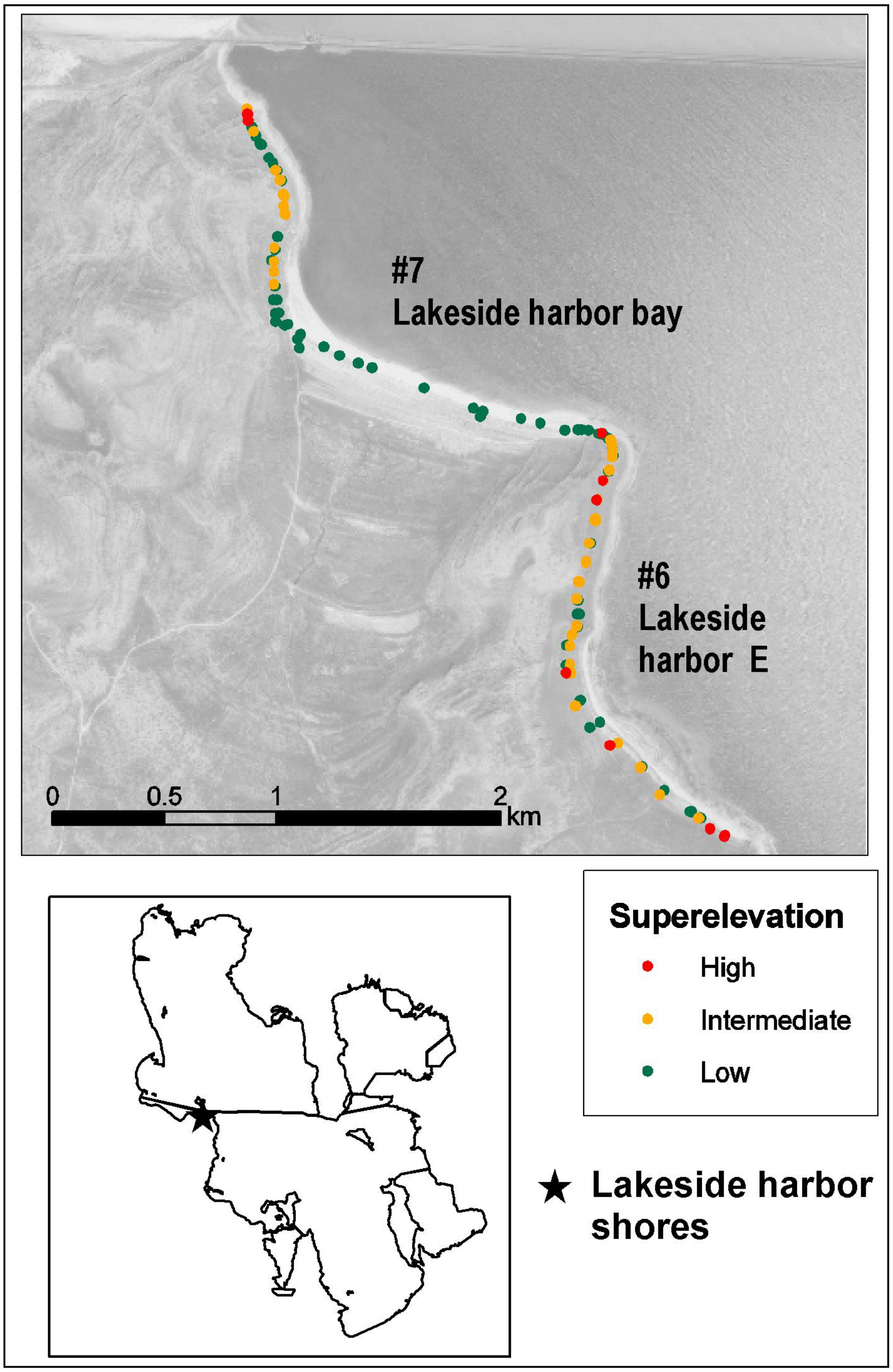
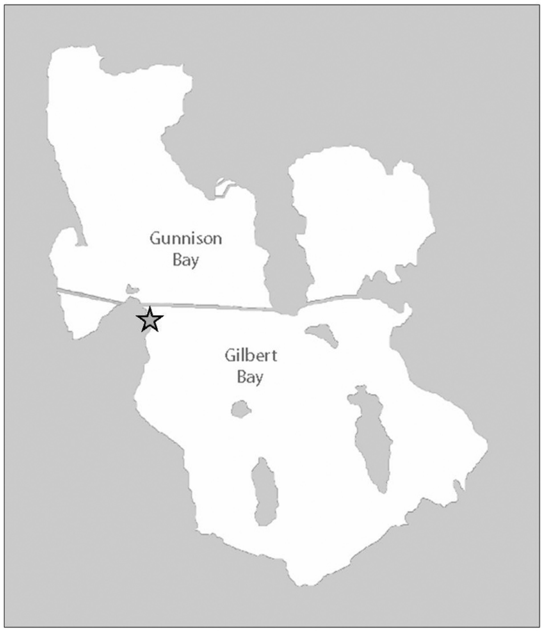
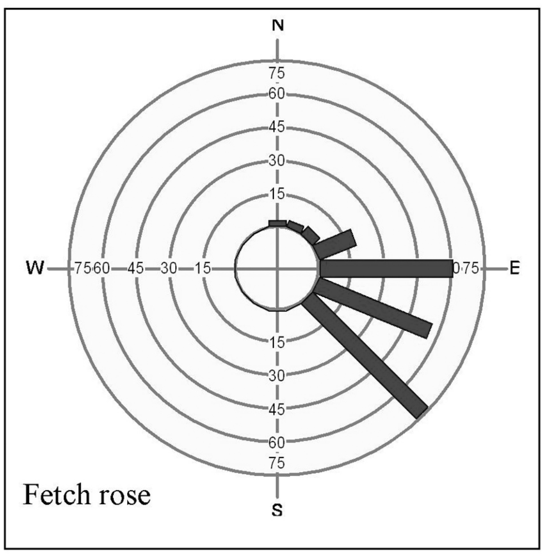


Figure B.9. Surveyed shores of Lakeside harbor area.
Two shore segments are used for analysis of shoreline superelevation, map locations #6 and #7 of Figure 5.2. Lakeside harbor area is south and east of Lakeside and immediately south of the railroad causeway that divides Gunnison and Gilbert Bays. The harbor is used by brine shrimp boats. Lakeside Harbor E is classified as generally intermediate shoreline superelevation. Lakeside harbor bay is classified as generally low shoreline superelevation.

LAKESIDE HARBOR E





Shoreline superelevation
INTERMEDIATE
Abbreviation: **LksHbToE**

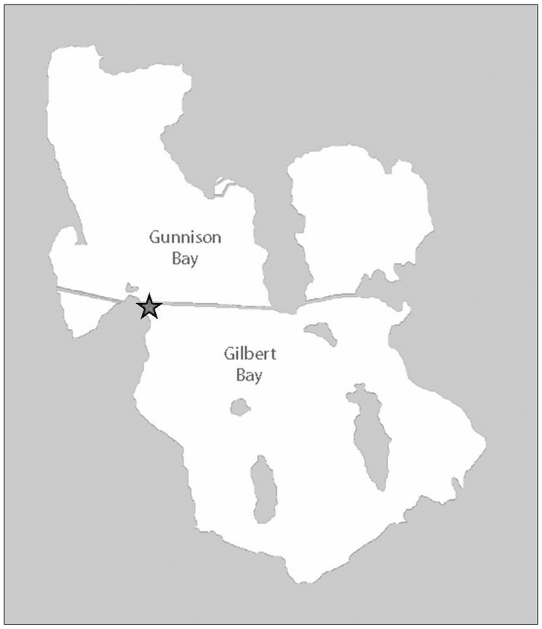
#6 on location maps

Gilbert Bay	
Length of longest fetch	73 km
Direction of longest fetch	SE
General aspect of the shore	E
Length of fetch N and NW	NA
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	3.49°
Elevation of near-flat, off-shore lake bed	4196
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Straight-to-convex coastline along bedrock headland and point. Beach face of concave coastline farthest east consists of multiple steps of sand and gravel.
Analogue: Northeastern Antelope Island, such as south of Buffalo Bay to Camera Flats.
Other: Railroad causeway decreased fetch from north and northeast. Evidence interpreted as 1860s-70s includes elevation of older beaches and changes in their depositional character.

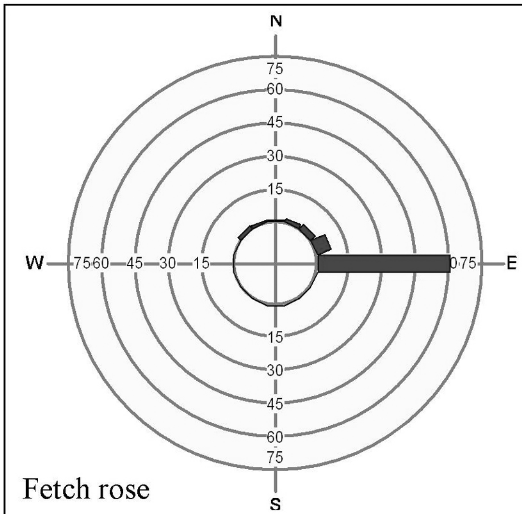
Figure B.10. Geomorphic characteristics of Lakeside harbor E.

LAKESIDE HARBOR BAY



Shoreline superelevation
Low
Abbreviation: **LksHbBay**
#7 on location maps

Gilbert Bay	
Length of longest fetch	60 km
Direction of longest fetch	E
General aspect of the shore	N
Length of fetch N and NW	2 km
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	2.33°
Elevation of near-flat, off-shore lake bed	4199
Bedrock between 4200 and 4220 ft a.s.l.	No



Fetch rose

Coastal morphology: Broad bay. The dominant 1980s beachface consists of a single barrier beach along the sides of the bay and two active barrier beaches along the back bay.
Analogue: Northeast Antelope Island, such as Buffalo Bay or White Rock Bay.
Other: Railroad causeway diminishes fetch to the north. Prominent barrier beach and lagoons 0.5 m above 1980s debris line are interpreted as 1860s-70s shore features.

Figure B.11. Geomorphic characteristics of Lakeside harbor bay.

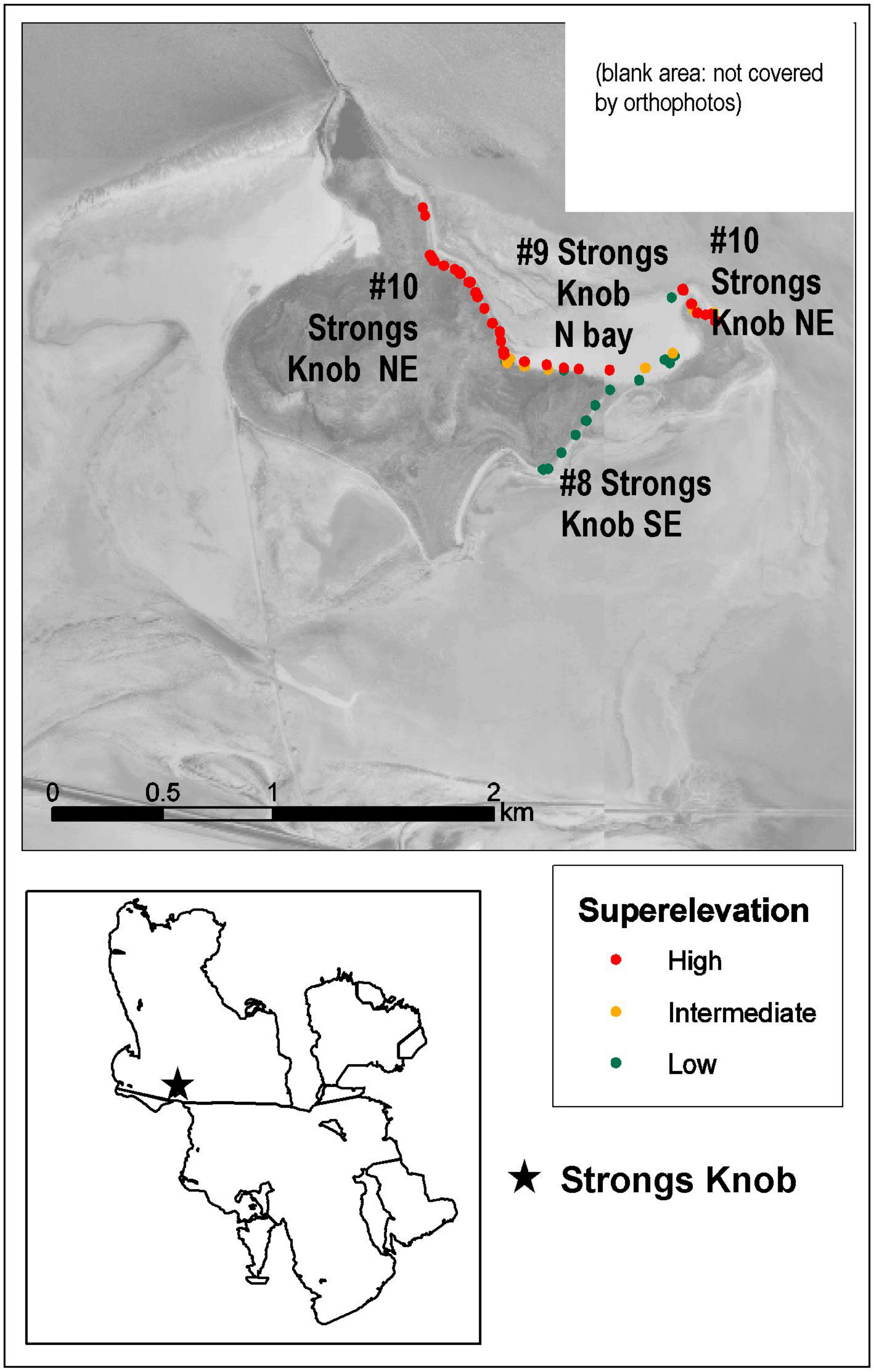
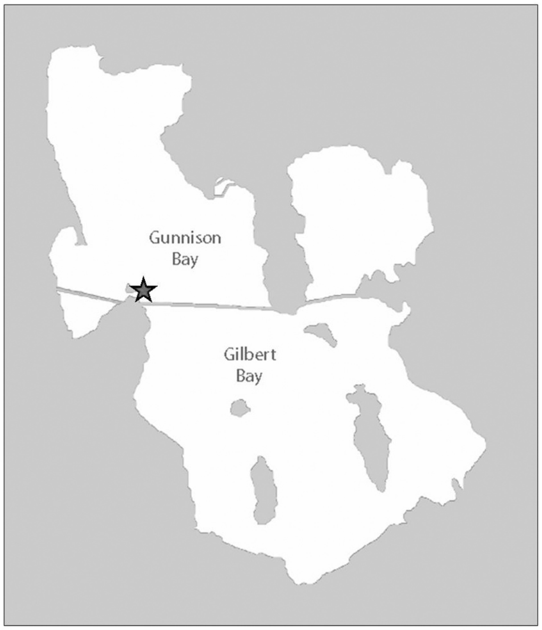
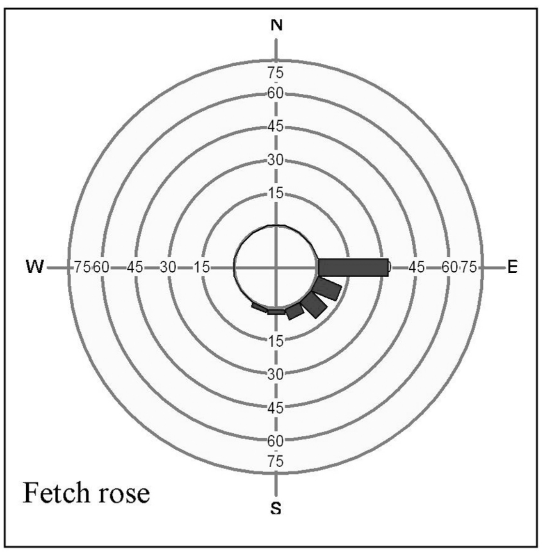


Figure B.12. Surveyed shores of Strongs Knob.
Three shore segments are used for analysis of shoreline superelevation, map locations #8-10 of Figure 5.2. Strongs Knob is in southwestern Gunnison Bay immediately north of the railroad causeway. The northern shore of Strongs Knob is divided into two exposures, Strongs Knob N bay (#9) and Strongs Knob NE (#10). Strongs Knob NE is classified as generally high shoreline superelevation. Strongs Knob N bay is generally intermediate and Strongs Knob SE (#8) is generally low shoreline superelevation.

STRONGS KNOB SE





Shoreline superelevation
Low
Abbreviation: **StrKbSE**

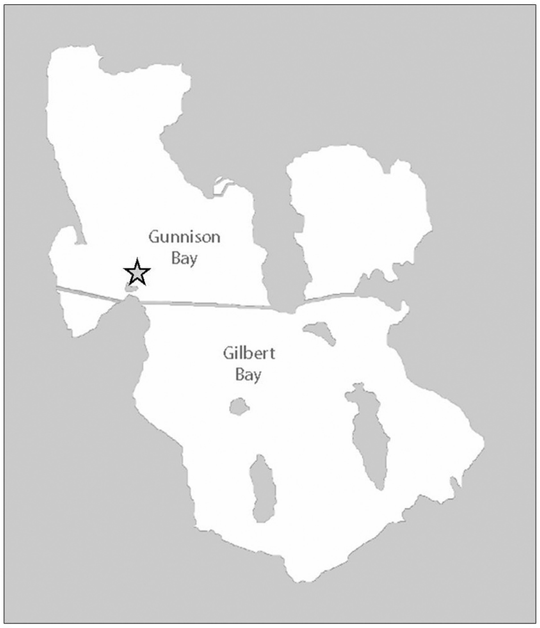
#8 on location maps

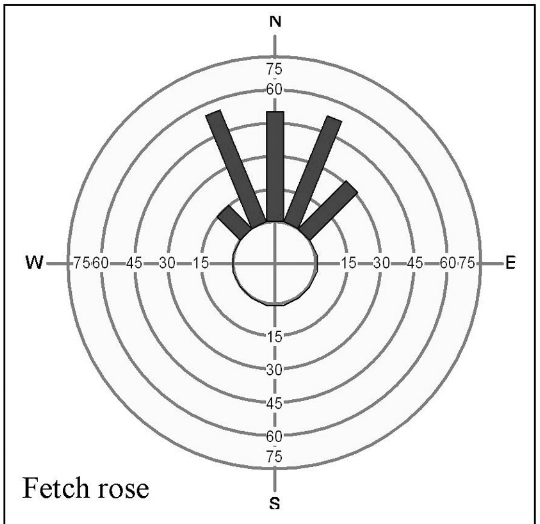
Gunnison Bay	
Length of longest fetch	32 km
Direction of longest fetch	E
General aspect of the shore	SE
Length of fetch N and NW	NA
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	2°
Elevation of near-flat, off-shore lake bed	4199
Bedrock between 4200 and 4220 ft a.s.l.	No

Coastal morphology: Relatively straight coast. Beach face consists of multiple less-than-1-meter steps.
Analogue: Northwestern Antelope Island, north portion of White Rock Bay.
Other: Well preserved debris line and vegetation kill zone. Railroad causeway dramatically reduced fetch to the south. Evidence of 1860s-70s shoreline not identified.

Figure B.13. Geomorphic characteristics of Strongs Knob SE.

STRONGS KNOB N bay





Fetch rose

Shoreline superelevation
INTERMEDIATE
Abbreviation: **StrKbNBay**

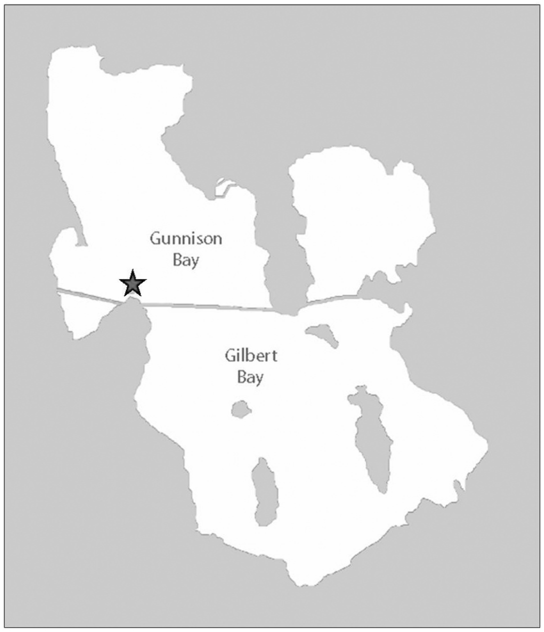
#9 on location maps

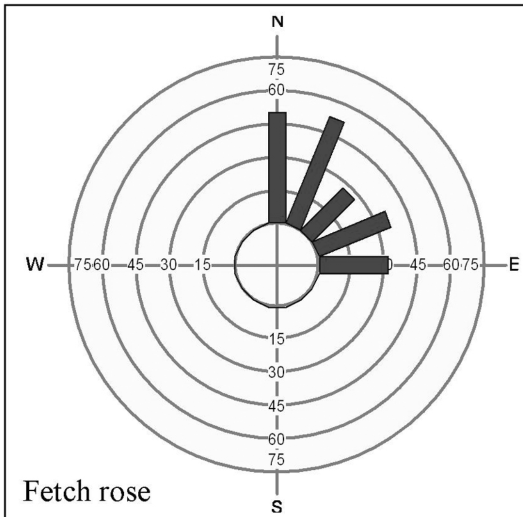
Gunnison Bay	
Length of longest fetch	55 km
Direction of longest fetch	NNW
General aspect of the shore	N
Length of fetch N and NW	55 km
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	1°
Elevation of near-flat, off-shore lake bed	4198
Bedrock between 4200 and 4220 ft a.s.l.	5%

Coastal morphology: Broad bay with dunes. 1980s waves cut into the dunes. 1980s beach face was simple and smooth. Offshore features include multiple, low-gradient barrier beaches and lagoons. Rocky point to east.
Analogue: Northern Antelope Island, Bridger Bay.
Other: Some evidence buried by sand dunes appears to indicate strong winds from the north.

Figure B.14. Geomorphic characteristics of Strongs Knob N bay.

STRONGS KNOB NE





Fetch rose

Shoreline superelevation
HIGH
Abbreviation: **StrKbNE**

#10 on location maps

Gunnison Bay	
Length of longest fetch	52 km
Direction of longest fetch	NNE
General aspect of the shore	NE
Length of fetch N and NW	50 km
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	10°
Elevation of near-flat, off-shore lake bed	4198
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Relatively straight bedrock coastlines interrupted by a cove. Beachface is rough and rocky with a shelf at the 1980s shoreline. The broad bay is another surveyed shore.
Analogue: Northernmost Antelope Island, such as Ladyfinger Point, and bedrock stretches of western Antelope Island, such as Cambria Point.
Other: Well-preserved evidence of the 1980s, undisturbed by fire, tourists, or industry.

Figure B.15. Geomorphic characteristics of Strongs Knob NE.

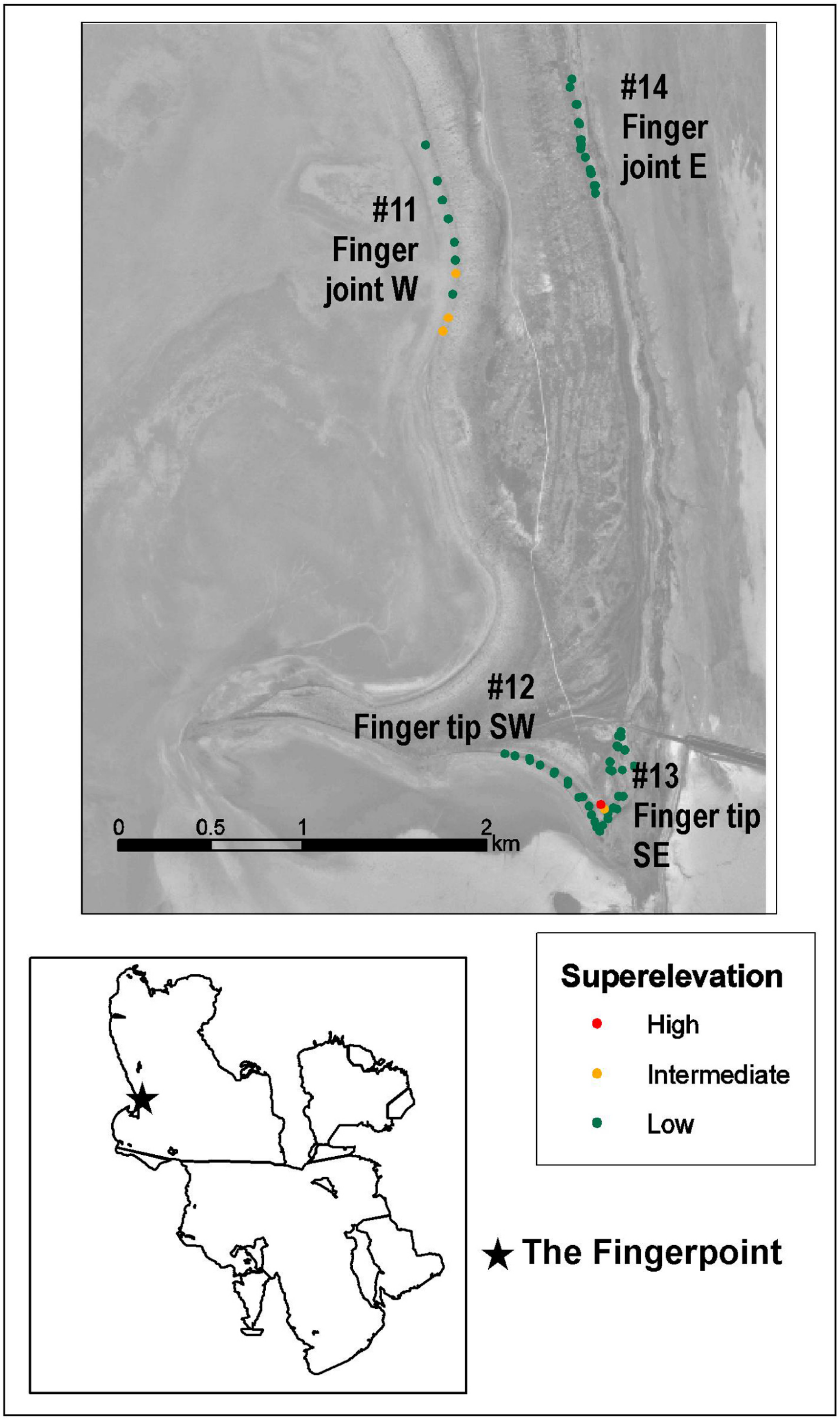
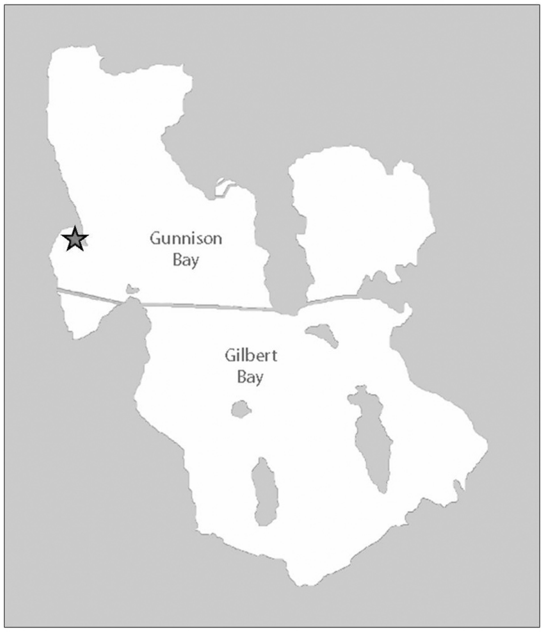
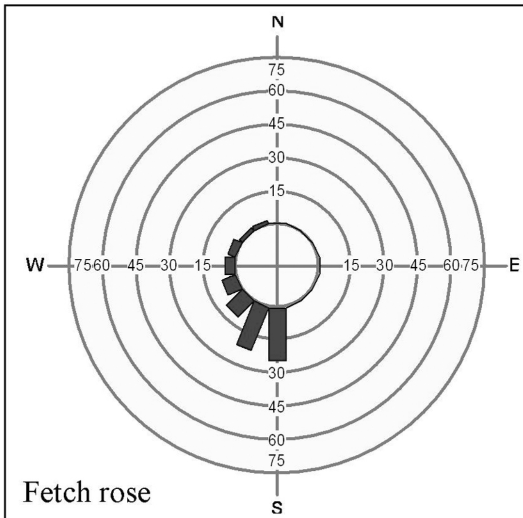


Figure B.16. Surveyed shores along The Fingerpoint.
Four shore segments are used for analysis of shoreline superelevation, map locations #11-14 of Figure 5.2. The Fingerpoint separates Gunnison and Clyman Bays. During 1986-1987 the causeway shown in the lower left of the photograph had not been built. All four surveyed shores are classified as generally low shoreline superelevation.

FINGER JOINT W





Fetch rose

Shoreline superelevation
Low
Abbreviation: **FngJtW**

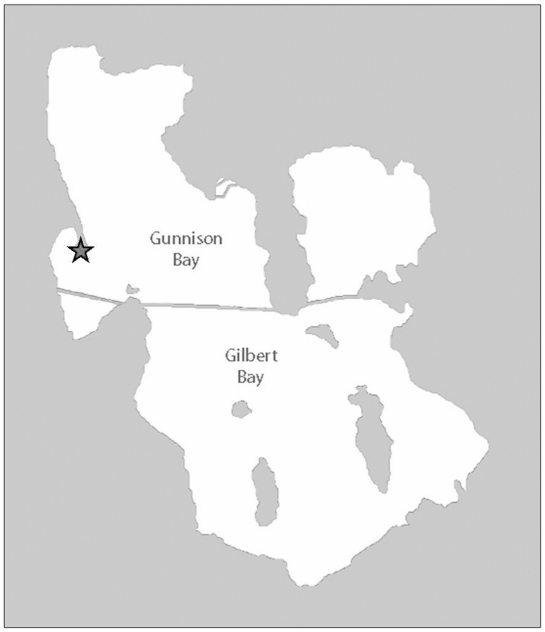
#11 on location maps

Clyman Bay	
Length of longest fetch	24 km
Direction of longest fetch	S
General aspect of the shore	W
Length of fetch N and NW	5 km
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	0.03°
Elevation of near-flat, off-shore lake bed	4207
Bedrock between 4200 and 4220 ft a.s.l.	No

Coastal morphology: Relatively straight coast. Narrow beach face, < 5 m, with a short, straight, runup zone approximately 1 m high.
Analogue: No Antelope Island analogue.
Other: 1980s debris is found in shallow draws eroded by surface runoff. Clyman Bay is very shallow, water depths of < 1 m. Effects of salt evaporation ponds were not evaluated.

Figure B.17. Geomorphic characteristics of Finger joint W.

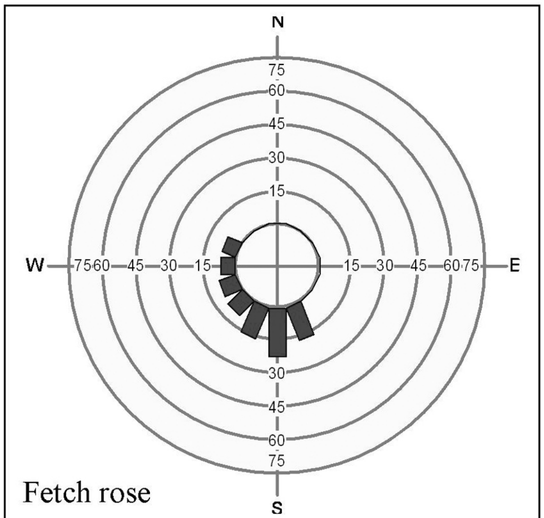
FINGER TIP SW



Shoreline superelevation
Low
Abbreviation: **FngTipSW**

#12 on location maps

Gunnison Bay	
Length of longest fetch	22 km
Direction of longest fetch	S
General aspect of the shore	SW
Length of fetch N and NW	NA
Location along bay axis	Mid-lake
Slope in degrees between 4200 ft and 4220 ft contours	0.17°
Elevation of near-flat, off-shore lake bed	4205
Bedrock between 4200 and 4220 ft a.s.l.	No



Fetch rose

Coastal morphology: Gently curved concave coastline. 1980s beach face consists of a single barrier beach and associated longitudinal lagoon.
Analogue: Southern tip of Antelope Island, east-facing shore of Unicorn Point.
Other: Salt extraction canals, ponds, and dikes may affect lake set-up and transfer of wave energy with unknown consequences to shoreline superelevation.

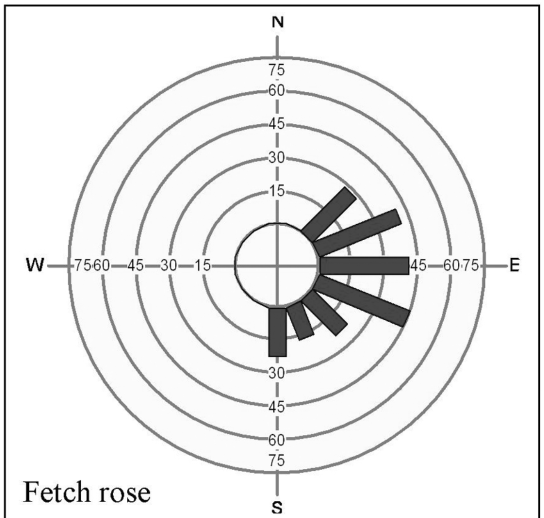
Figure B.18. Geomorphic characteristics of Finger tip SW.

FINGER TIP SE

Shoreline superelevation
Low
Abbreviation: **FngTipE**

#13 on location maps

Gunnison Bay	
Length of longest fetch	44 km
Direction of longest fetch	ESE
General aspect of the shore	ESE
Length of fetch toward NW	NA
Location along bay axis	Intermediate
Slope in degrees between 4200 ft and 4220 ft contours	0.35°
Elevation of near-flat, off-shore lake bed	4199
Bedrock between 4200 and 4220 ft a.s.l.	No

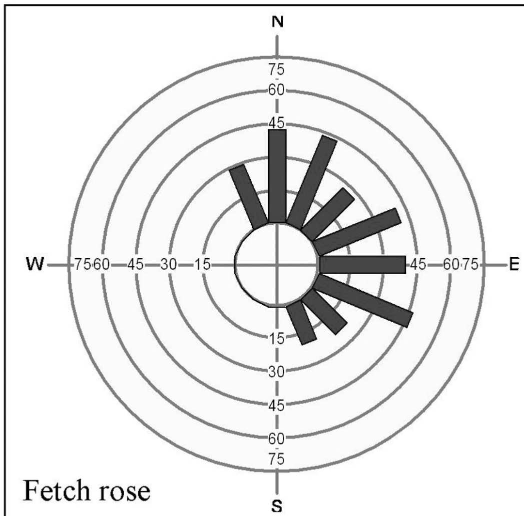


Fetch rose

Coastal morphology: Convex coastline. Complex shorezone with sets of intersecting barrier beaches and lagoons running north-south and southwest-northeast.
Analogue: Southern tip of Antelope Island, Unicorn Point.
Other: 1980s debris is smeared across a broad barrier beach complex. Human disturbances include off-road travel as well as dirt roads plus facilities associated with salt extraction.

Figure B.19. Geomorphic characteristics of Finger tip SE.

FINGER JOINT E



Fetch rose

Shoreline superelevation
Low
Abbreviation: **FngJtE**

#14 on location maps

Gunnison Bay	
Length of longest fetch	47 km
Direction of longest fetch	SE
General aspect of the shore	E
Length of fetch N and NW	43 km
Location along bay axis	Mid-lake
Slope in degrees between 4200 ft and 4220 ft contours	2°
Elevation of near-flat, off-shore lake bed	4199
Bedrock between 4200 and 4220 ft a.s.l.	No

Coastal morphology: Straight coast. Beach face is a relatively simple, relatively straight, relatively smooth runup zone unbroken by steps or barrier beaches.
Analogue: No Antelope Island analogue.
Other: Abundant 1980s debris. Older debris, perhaps of 1860s-70s highstand, is partly buried by sediments of the 1980s.

Figure B.20. Geomorphic characteristics Finger joint E.

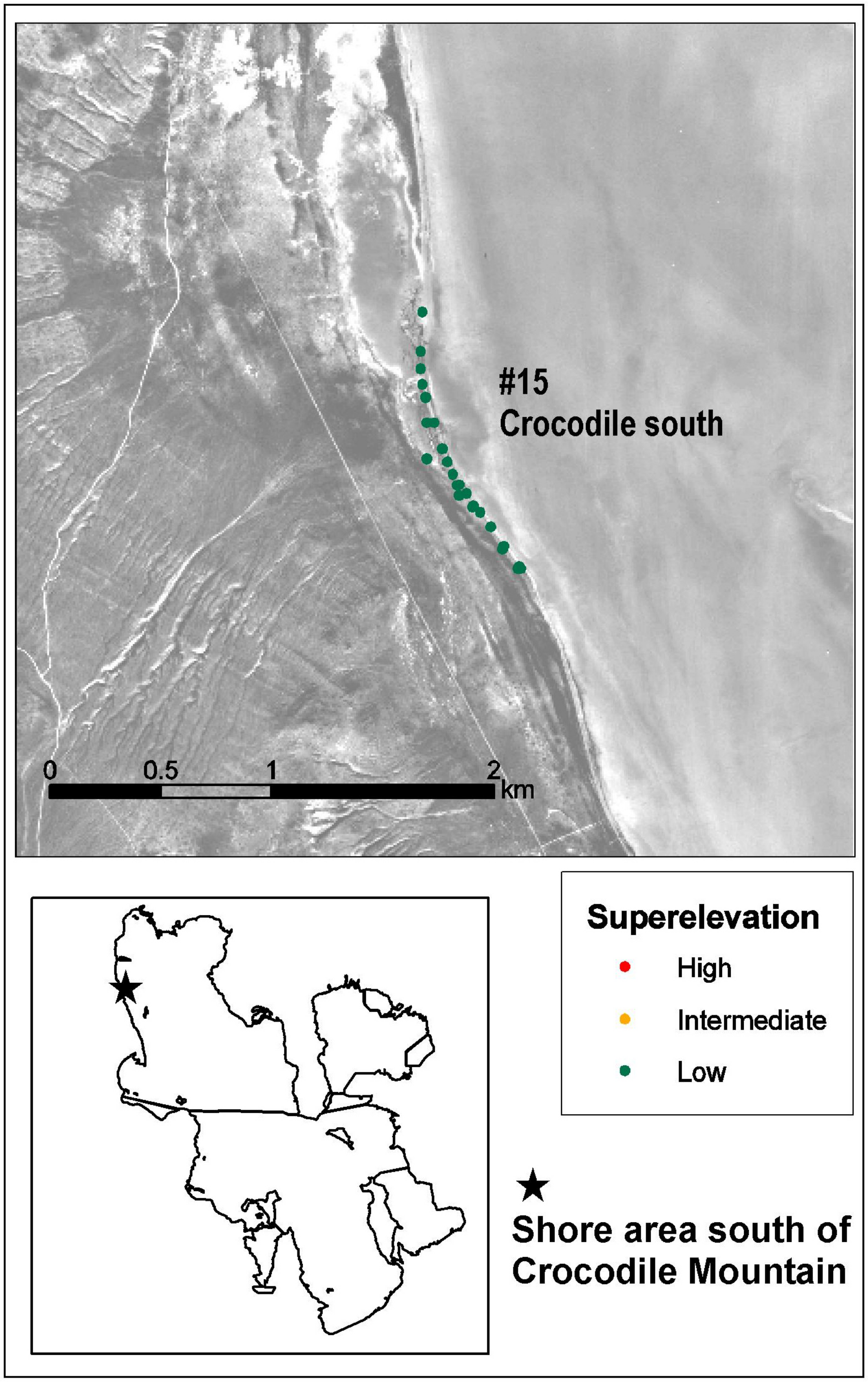
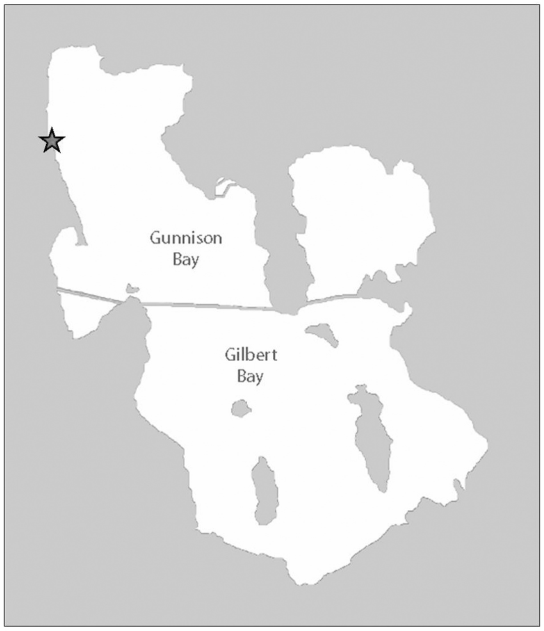
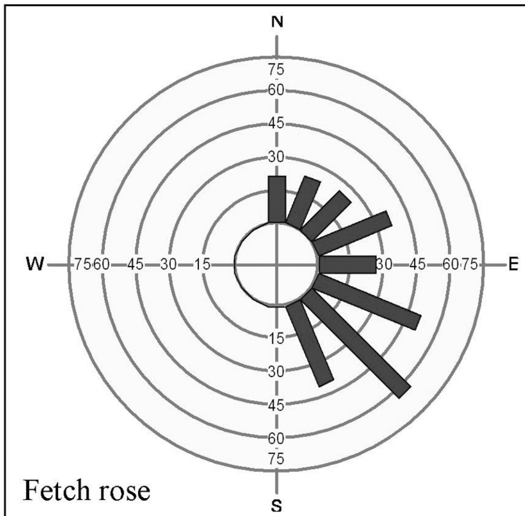


Figure B.21. Surveyed shore south of Crocodile Mountain.
One shore segment is used for analysis of shoreline superelevation, map locations #15 of Figure 5.2. Crocodile south is classified as generally low shoreline superelevation.

CROCODILE SOUTH





Fetch rose

Shoreline superelevation
Low
Abbreviation: **CrocSo**

#15 on location maps

Gunnison Bay	
Length of longest fetch	63 km
Direction of longest fetch	SE
General aspect of the shore	E
Length of fetch N and NW	18
Location along bay axis	Intermediate
Slope in degrees between 4200 ft and 4220 ft contours	0.06°
Elevation of near-flat, off-shore lake bed	4206
Bedrock between 4200 and 4220 ft a.s.l.	No

Coastal morphology: Straight coast. Upper shelf with 1980s and possibly older debris. Undercut scarp with 1-3 m drop-off. Exceptionally flat, shallow lakebed lakeward of scarp.
Analogue: Southeast shore of Antelope Island, such as south of the Ranch House.
Other: 1980s debris has washed across a 3-to-40 m complex of low-relief lagoons.

Figure B.22. Geomorphic characteristics of Crocodile south.

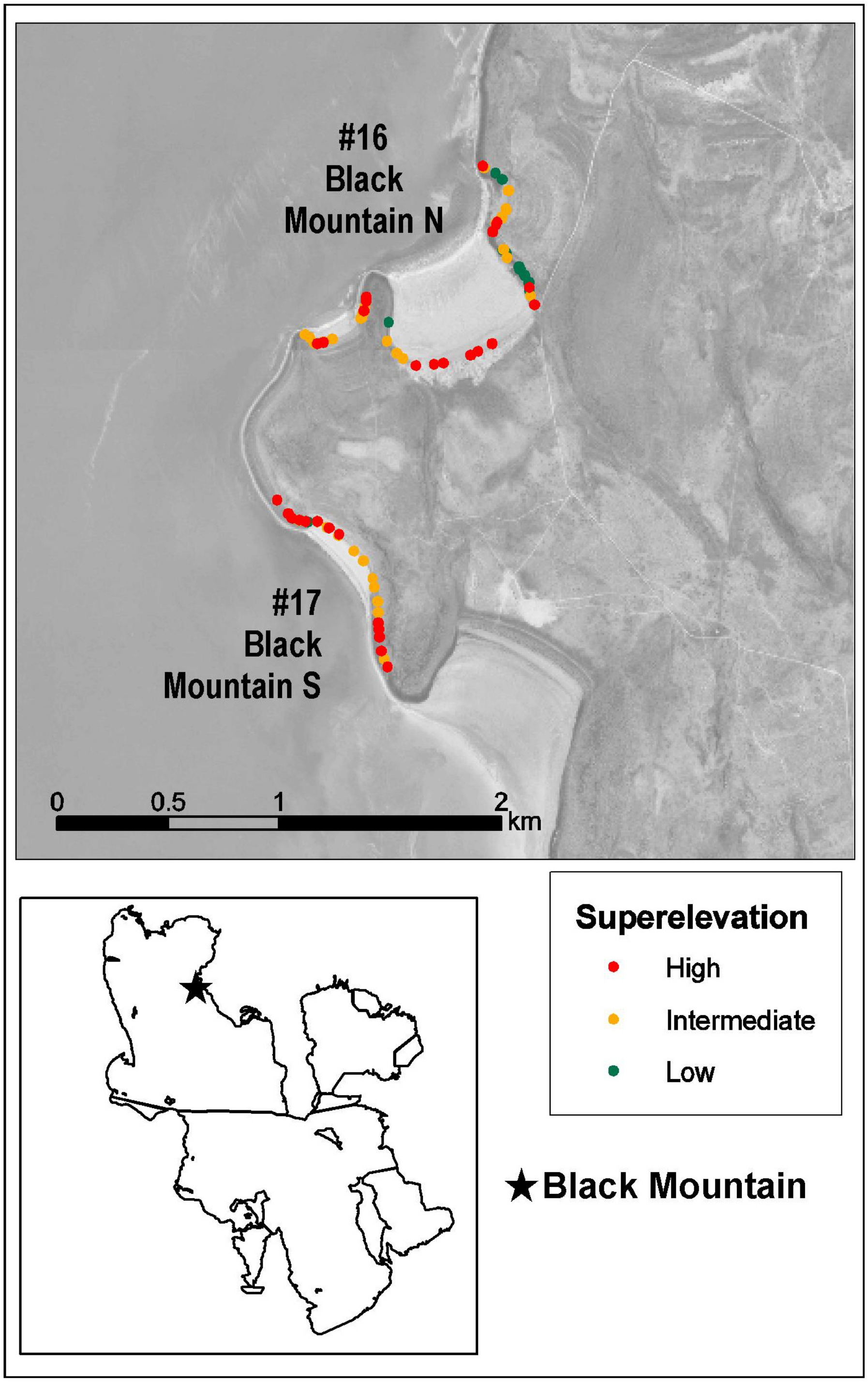
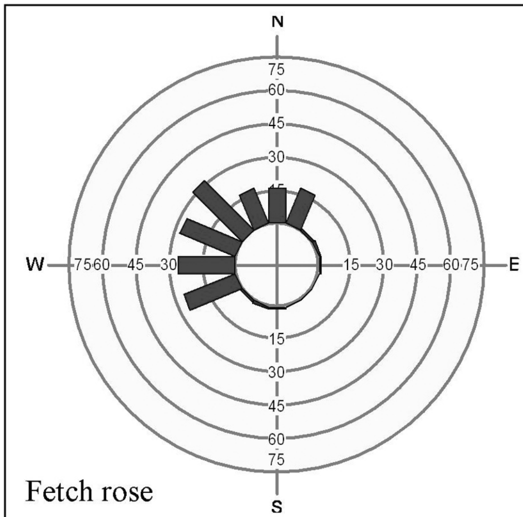


Figure B.23. Surveyed shores of Black Mountain.
Two shore segments are used for analysis of shoreline superelevation, map locations #16 and #17 of Figure 5.2. Both Black Mountain N and Black Mountain S are classified as generally high shoreline superelevation.

BLACK MOUNTAIN N



Fetch rose

Shoreline superelevation
HIGH
Abbreviation: **BlkMtN**

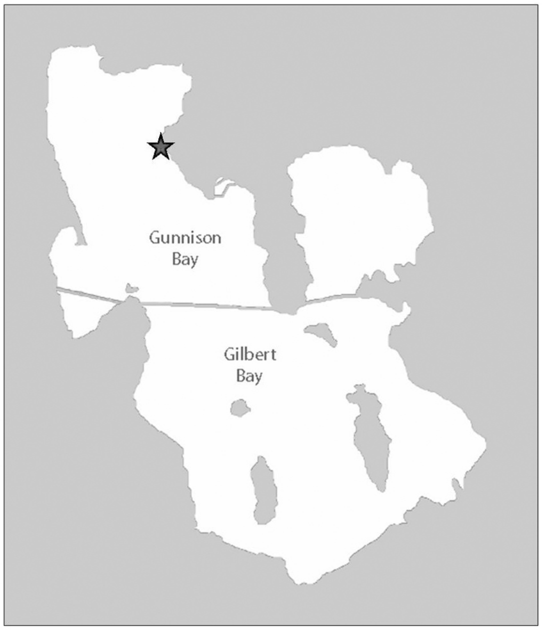
#16 on location maps

Gunnison Bay	
Length of longest fetch	32 km
Direction of longest fetch	NW
General aspect of the shore	NW
Length of fetch N and NW	31 km
Location along bay axis	Intermediate
Slope in degrees between 4200 ft and 4220 ft contours	11°
Elevation of near-flat, off-shore lake bed	4197
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Bedrock headlands, points, coves, and bays. Erosional stretches are rough, rocky coast. Depositional beach faces have multiple steps.
Analogue: Northwest Antelope Island, such as White Rock Bay, Bridger Bay, and Buffalo Point.
Other: 1980s shoreline is well preserved except where disrupted by marina for brine shrimp operations. Shoreline evidence is missing on bedrock headlands. Shoreline evidence of 1860s-70s found along easternmost bay.

Figure B.24. Geomorphic characteristics of Black Mountain N.

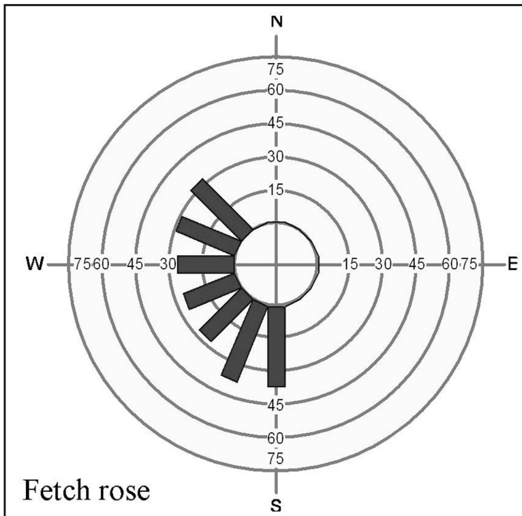
BLACK MOUNTAIN S



Shoreline superelevation
INTERMEDIATE
Abbreviation: **BlkMtS**

#17 on location maps

Gunnison Bay	
Length of longest fetch	37 km
Direction of longest fetch	SSW
General aspect of the shore	WSW
Length of fetch N and NW	32 km
Location along bay axis	Mid-lake
Slope in degrees between 4200 ft and 4220 ft contours	4°
Elevation of near-flat, off-shore lake bed	4197
Bedrock between 4200 and 4220 ft a.s.l.	Yes



Fetch rose

Coastal morphology: Bay and bedrock points. Beach face of bay consists of several <1 m steps. High debris on west-facing exposure of westernmost bedrock point.
Analogue: Western bays of Antelope Island, such as the northern section of White Rock Bay.
Other: Well-preserved evidence of 1980s shoreline and possible evidence of 1860s-70s.

Figure B.25. Geomorphic characteristics of Black Mountain S.

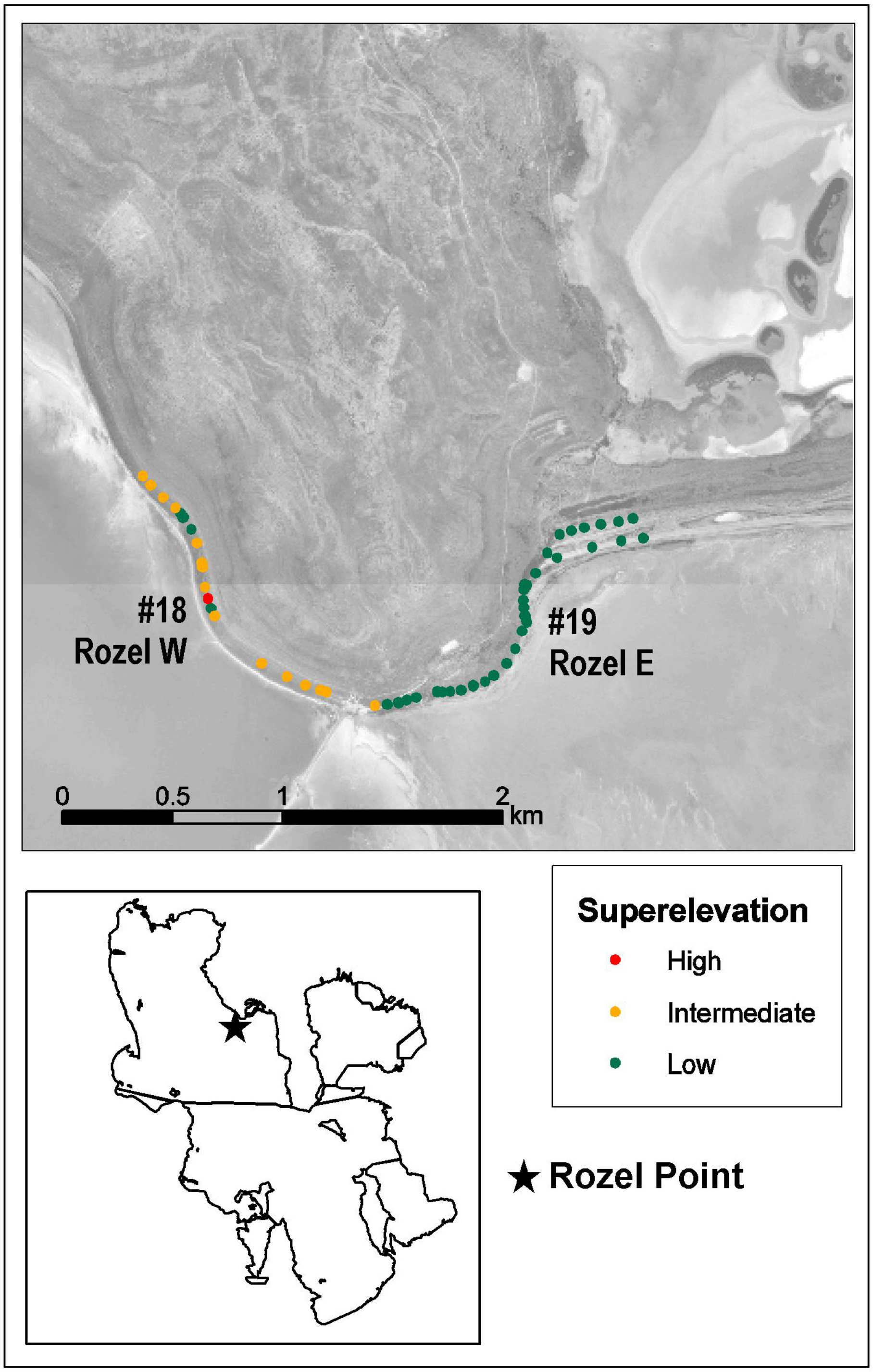
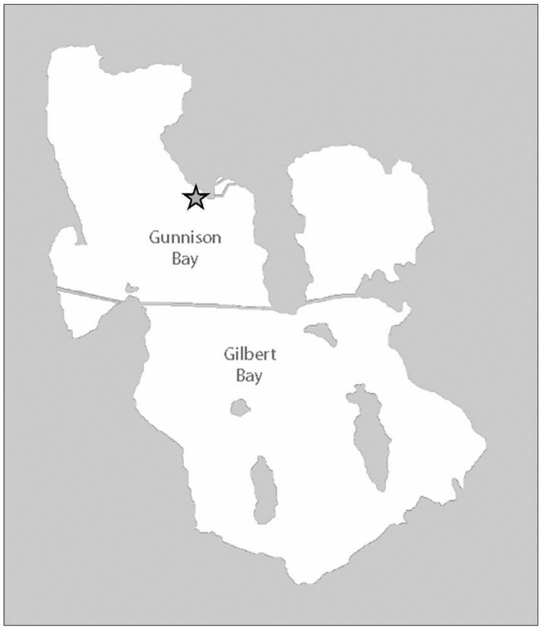


Figure B.26. Surveyed shores of Rozel Point.
Two shore segments are used for analysis of shoreline superelevation, map locations #18 and #19 of Figure 5.2. The Spiral Jetty is located along Rozel Point W and was submerged during 1986-1987. Rozel Point W is classified as generally intermediate shoreline superelevation. Rozel Point E is classified as generally low shoreline superelevation.

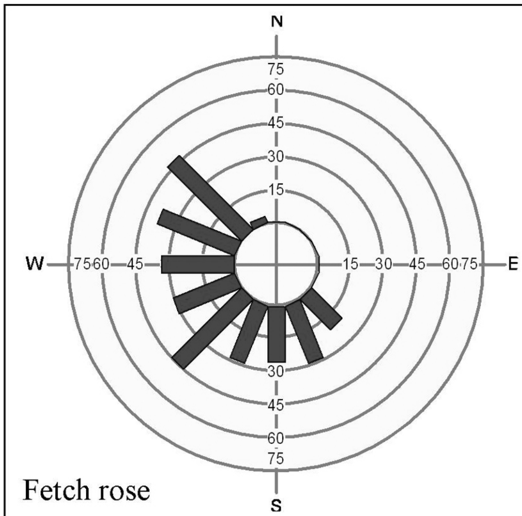
ROZEL POINT W



Shoreline superelevation
INTERMEDIATE
Abbreviation: **RozPtW**

#18 on location maps

Gunnison Bay	
Length of longest fetch	47 km
Direction of longest fetch	NW
General aspect of the shore	SW
Length of fetch N and NW	47 km
Location along bay axis	Node
Slope in degrees between 4200 ft and 4220 ft contours	9°
Elevation of near-flat, off-shore lake bed	4193
Bedrock between 4200 and 4220 ft a.s.l.	Yes

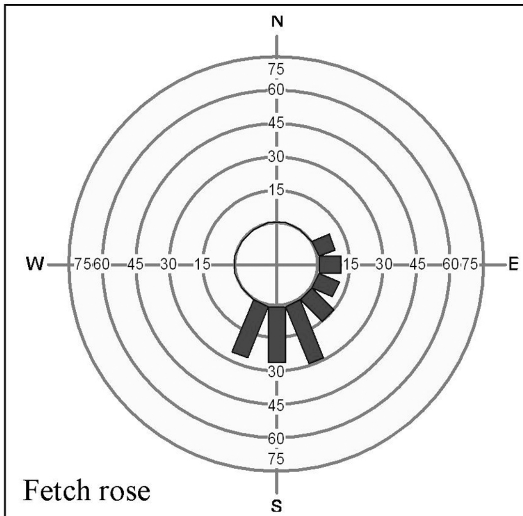


Fetch rose

Coastal morphology: Convex, rugged, rocky coastline that transitions into a gently concave embayment. Boulder beach face. Abrupt vegetation and soil changes at 1980s shoreline.
Analogue: Southwest Antelope Island, such as along Indian Bight to south point.
Other: Human disturbances include roads, dikes, canals, equipment for oil exploration and development, and the Spiral Jetty landscape sculpture.

Figure B.27. Geomorphic characteristics of Rozel Point W.

ROZEL POINT E	
	Shoreline superelevation **Low** Abbreviation: **RozPtE** **#19 on location maps**
Gunnison Bay	
Length of longest fetch	28 km
Direction of longest fetch	SSE
General aspect of the shore	SE
Length of fetch N and NW	NA
Location along bay axis	Node
Slope in degrees between 4200 ft and 4220 ft contours	0.44°
Elevation of near-flat, off-shore lake bed	4205
Bedrock between 4200 and 4220 ft a.s.l.	No



Fetch rose

Coastal morphology: Two coastal segments: a convex coastline with beach face of multiple steps; the other, concave, with multiple, active barrier beaches and lagoons.
Analogue: Northeastern Antelope Island, Tin Lambing Shed.
Other: This coastline continues to the east and becomes a barrier beach and lagoon complex of grand scale with no analogue on Antelope Island.

Figure B.28. Geomorphic characteristics of Rozel Point E.

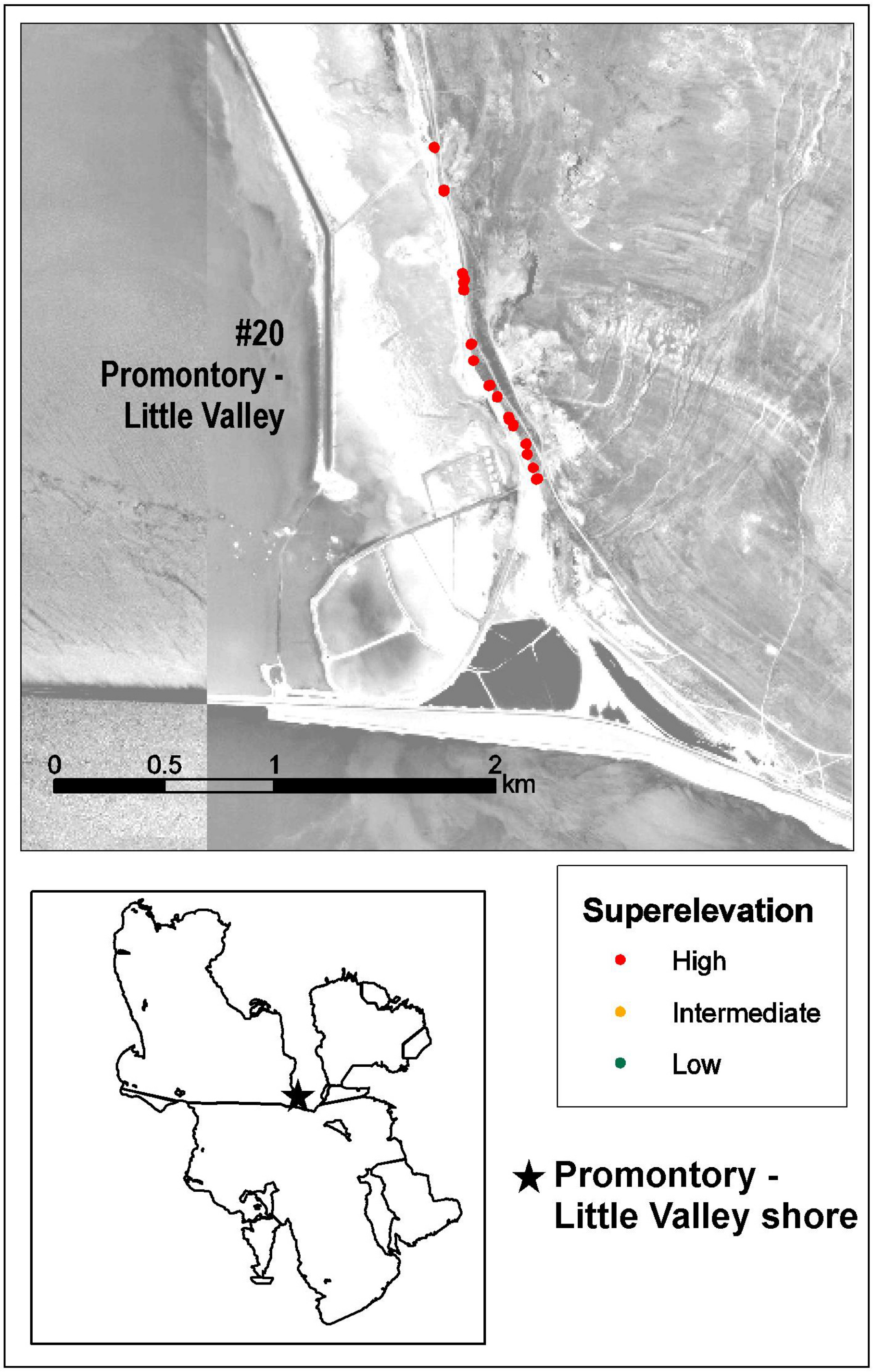
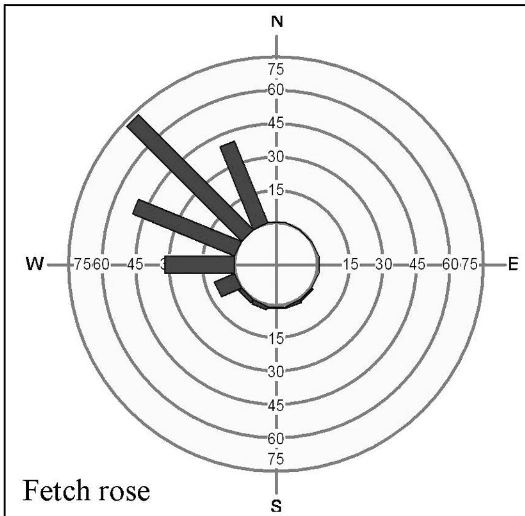


Figure B.29. Surveyed shores north of Promontory Point near Little Valley harbor. One shore segment is used for analysis of shoreline superelevation, map location #20 of Figure 5.2. Promontory - Little Valley is classified as generally high shoreline superelevation. The harbor at Little Valley was flooded during 1986/87; however, the railroad maintained the causeway above lake level.

PROMONTORY - LITTLE VALLEY



Fetch rose

Shoreline superelevation
HIGH
Abbreviation: **PrmLtv**

#20 on location maps

Gunnison Bay	
Length of longest fetch	73 km
Direction of longest fetch	NW
General aspect of the shore	W
Length of fetch N and NW	73 km
Location along bay axis	Edge
Slope in degrees between 4200 ft and 4220 ft contours	5°
Elevation of near-flat, off-shore lake bed	4199
Bedrock between 4200 and 4220 ft a.s.l.	Yes

Coastal morphology: Relatively straight, gently convex coast. The 1980s beach face is steep, bouldery, and rugged. The 1986/87 shoreline expression is demarcated by limited flotsam, by an erosional line where fines have eroded from colluvium, and by sharp vegetation contrasts.
Analogue: Southwestern Antelope Island, such as Indian Bight; and east-central Antelope Island, such as along Anschutz shore.
Other: Human disturbances include extensive offshore construction including channels.

Figure B.30. Geomorphic characteristics of Promontory-Little Valley.

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