Shoreline Superelevation, Clues to Coastal Processes of Great Salt Lake

Genevieve Atwood[1], Tamara J. Wambeam[2], and Charles G. Oviatt[3]

[1]*Earth Science Education, Salt Lake City, Utah, genevieveatwood@comcast.net*

[2]*Salt Lake City, Utah*

[3]*Department of Geology, Kansas State University, Manhattan, Kansas*

10.31711/ugap.v51i.138

ABSTRACT

Coastal processes create the shoreline evidence of Great Salt Lake. Shoreline superelevation is the difference in elevation between still water lake level and the shoreline evidence produced by the lake at that level. Processes of formation include effects of wind strength, fetch, beach attributes, coastline aspect, and coast morphology. A series of field studies from 1986 through 2000 concluded strong storm winds from the northwest contribute to the patterns and magnitude of shoreline superelevation. Weather data for 2020-2023 for Gunnison Island and Hat Island document strong storm winds from the north and northwest for Gunnison Bay and with more complexity for Gilbert Bay. The strongest wind patterns are consistent with the geologic evidence of shoreline superelevation produced by the high lake stands of 1986-1987.

Wind strength, fetch, and storm duration cause Great Salt Lake wave regimes. The wave-regimes of Great Salt Lake are fetch-limited due to the size and morphology of the water body. In contrast, the long fetch of large lakes such as Lake Bonneville (the enlarged manifestation of the Great Salt Lake lacustrine system), determines the magnitude and patterns of their shoreline superelevation. Geologic evidence of shoreline superelevation of modern- and paleo- fetch-limited lakes similar to Great Salt Lake may be durable evidence of storm wind direction.

INTRODUCTION

Great Salt Lake (GSL) is a closed-basin lake located in the lowest region of the GSL drainage basin, and it has no surface outlet (Figure 1). Its shorelines and lake bottom sediments record lake conditions. GSL shoreline elevation fluctuates as the lake's volume fluctuates in response to the balance of water entering the lake by direct precipitation and runoff, and water leaving the lake by evapotranspiration. Therefore, patterns of shoreline elevations are interpreted as patterns of climate. Understanding the chronology of lake fluctuations underpins interpretations of changed climate over time. However, the details of the history of climate changes have not yet been deciphered for post-Lake Bonneville time from the geomorphic and stratigraphic records (Oviatt and others, 2021).

Shoreline materials also contribute to the understanding of lake processes (Gilbert, 1890). Terrigenous materials deposited by waves become the geologic record. If a paleoshoreline defines a horizontal plane, it can be used to distinguish post-depositional change. Examples of the use of this assumption include studies of isostatic rebound, tectonic displacements, and effects of wind and waves (Gilbert, 1890; Tackman, 1993; Adams and Wesnousky, 1998; Tackman and others, 1998; Adams and others, 1999; Adams and Bills, 2016; and Chen and Maloof, 2017). However, should initial shoreline conditions not define a horizontal plane, the original non-horizontality introduces uncertainty to interpretations (Gilbert, 1890, Currey, 1982).

This paper summarizes a series of field studies documenting the shoreline left by Utah's 1980s wet cycle (1982-1987). In 1986 and again in 1987, GSL reached its historic highstand elevation, 4212.15 ft (Arnow and Stephens, 1990). It left pristine, undisturbed, continuous evidence around the perimeter of Antelope Island as lines of organic and inorganic debris. This paper explores the coastal processes that caused the original non-horizontality of the 1986-1987 shoreline. Wind waves that are higher and more energetic in some places than others cause patterns of shoreline superelevation. The following definitions contribute to understanding "superelevation" (Figure 2). Lake setup is "elevated lake surface caused by any process whether or not storm-related." Wind setup is "the component of lake setup caused by wind" and is accompanied by lake setdown, a lowered lake level. Lake seiche is "the oscillation of the lake's surface initiated by lake setup." Wave runup is "the rush of water with entrained sediment landward and upward to

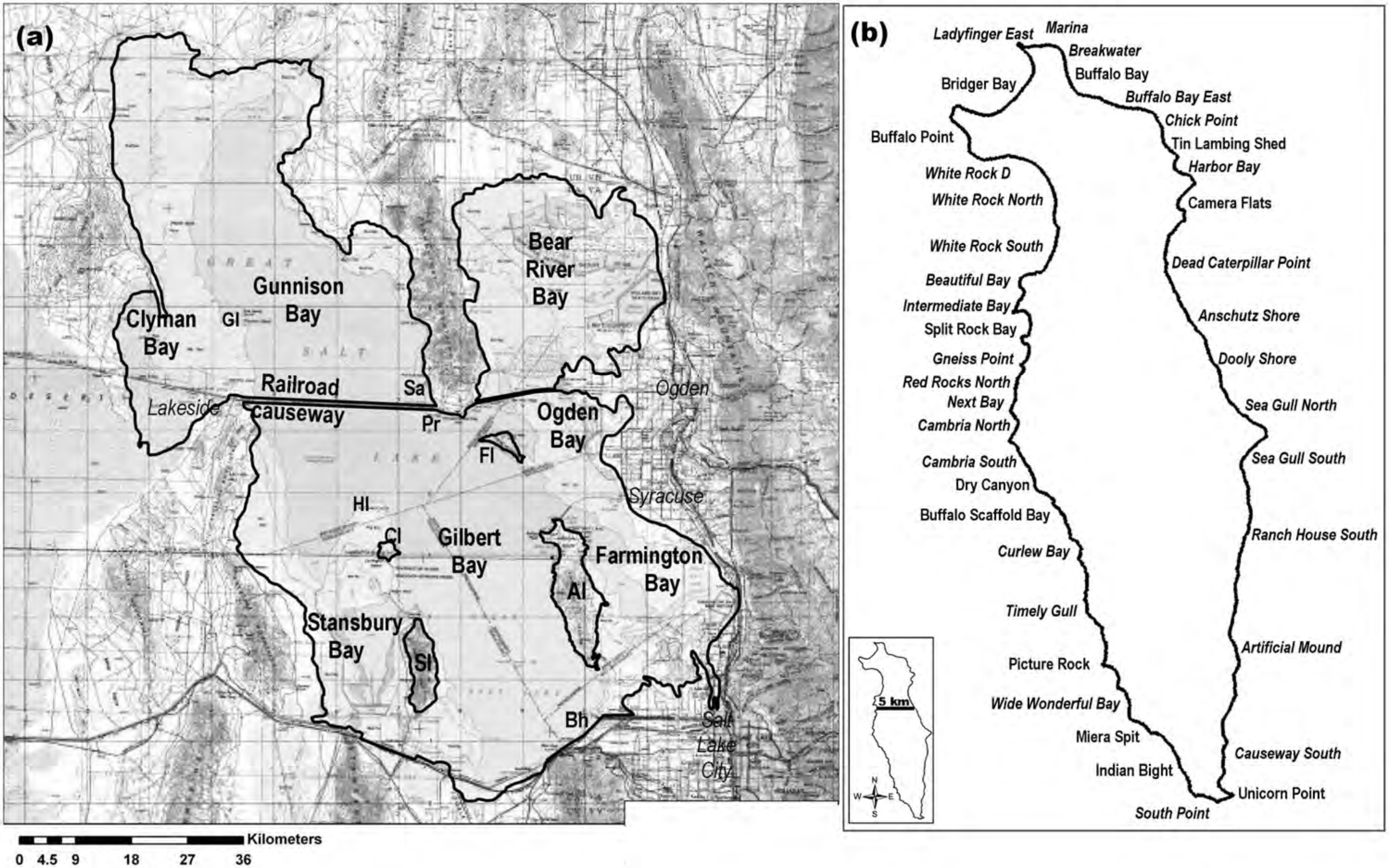

Figure 1. *Location Maps for Great Salt Lake and Antelope Island. Adapted from Atwood (2006) (a). Great Salt Lake: Place names include bays of Great Salt Lake and major islands: Antelope Island (AI), Carrington Island (CI), Fremont Island (FI), Gunnison Island (GI), Hat Island (HI), and Stansbury Island (SI). Lake-level monitoring gages are Saltair Marina Boat Harbor (Bh), Promontory (Pr), and Saline (Sa). Names of communities are shown in italics. The dark line indicates the extent of 1986-1987 highstand flooding. (b). Antelope Island: Formal and informal names (in italics) for locations of shoreline superelevation surveyed during 1997-1998.*

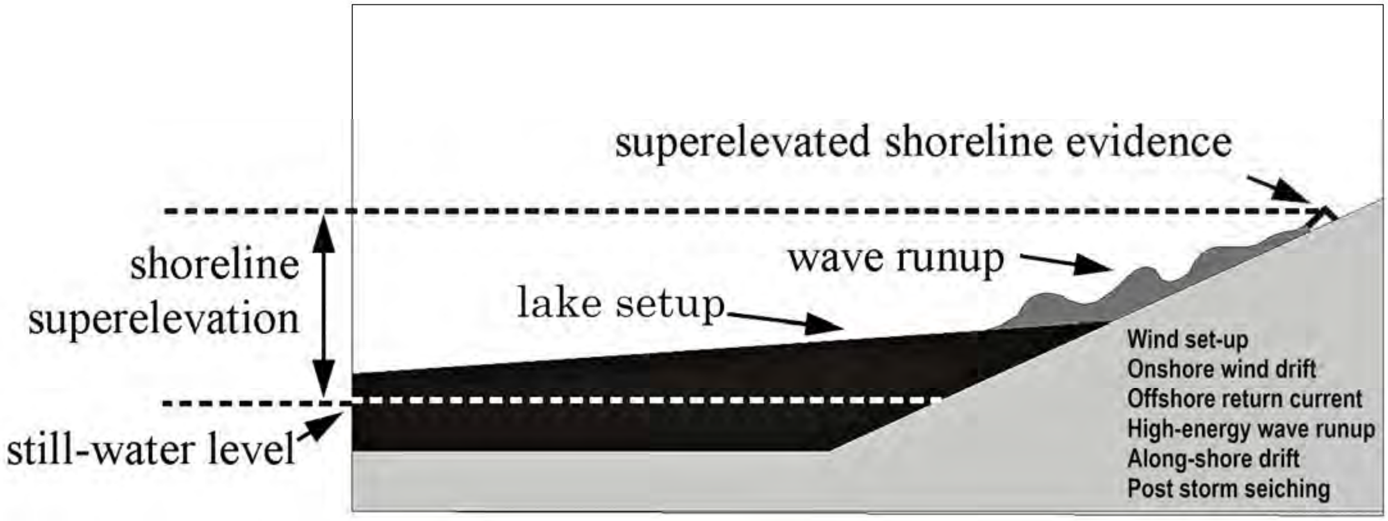

Figure 2. *Shoreline superelevation, evidence of interactions of Earth systems. The schematic simplifies and summarizes diverse conditions and processes that result in shoreline superelevation. Under strong winds or as storms progress, waves develop, and lake water is pushed up against windward shores. Winds blow across the surface causing waves, and the waves deposit the terrigenous debris that becomes the durable geologic evidence of lake elevation. Patterns of shoreline superelevation include interactions among the atmosphere, the hydrosphere, the geosphere, and the biosphere.*

its highest shoreline expression." Wave runup is the highest elevation reached by waves, and the entrained sediment deposited by the waves provides a record of shoreline superelevation. Shoreline superelevation is the difference in elevation between the shoreline evidence and the independently monitored still water elevation. (Atwood 2006).

Earlier field studies documented patterns of shoreline superelevation and suggested that the patterns were the effects of wind strength and direction as well as of fetch (distance across open water). This paper reports how present-day meteorological data supplement the findings of field surveys of 1986-2000 (Atwood, 2006), which did not have the advantage of 2020-2023 records from weather stations on Hat and Gunnison Islands. The strongest winds across GSL blow from the north and west, corroborating the geomorphic evidence. Patterns of shoreline superelevation document the effects of wind strength and direction because GSL is fetch-limited. "Fetch-limited" refers to water bodies where the size of the wave generation area limits wave height and energy.

METHODS AND DATA

Purpose and Methods of the Field Surveys, 1986-2000

Several surveys conducted between 1986 and 2000 by D.R. Currey, D.R. Mabey and G. Atwood provide field-based data for the present paper. A summary of methods, data, and results is given below and is set out fully in Atwood (2006). Shoreline features were observed, described, and their elevations were measured directly in the field during, immediately after, and in the decades following the 1986-1987 GSL highstand. Unmistakable floated debris (e.g., wood, plastic, and windrows of organic matter), as well as fresh gravel ridges, identified 1986-1987 shoreline evidence that persisted for over a decade (Figure 3). Surveyed shoreline debris defined shoreline superelevation patterns. Over the past four decades, some of that evidence has degraded, but gravel ridges remain in many places where they can be spotted by their vegetation (sunflowers).

1986 Survey - Currey and Mabey on the Eastern Shore of Antelope Island

The purpose of the 1986 survey was to repeat G.K. Gilbert's survey in 1877 of the evidence of the 1870s highstand shoreline (Gilbert, 1890). Mabey and Currey (Mabey, 1986), concerned that the rising lake would rework and destroy the 1870s evidence, repeated Gilbert's survey on the east shore of Antelope Island using hand-held equipment similar to Gilbert's era. They identified three places on aerial photographs and surveyed them on the ground using the United States Geological Survey (USGS)-monitored still water level for vertical control. In the century between Gilbert's survey in 1877, and the work of Currey and Mabey in 1986, the shoreline evidence had become difficult to recognize, except as patterns on aerial photographs and patches of gravel.

According to Mabey (1986), "In the spring of 1986 when the lake was at a level of 4211.85 ft, a storm line was formed on the east side of Antelope Is-

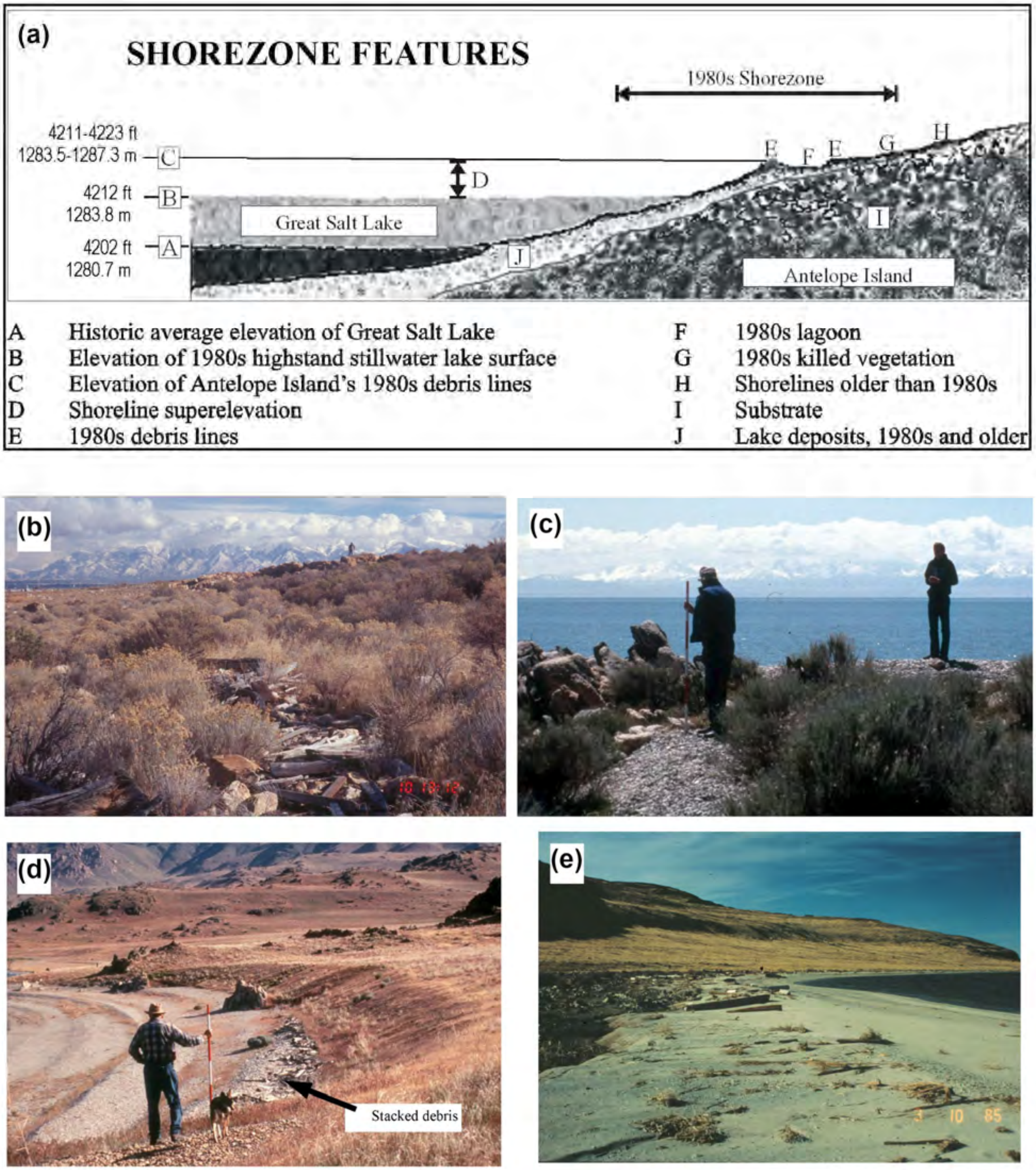

Figure 3. *Evidence of shoreline superelevation. Adapted from Atwood (2006). (a). The sketch illustrates the shorezone features relative to shoreline superelevation. The difference between the 1986 and 1987 USGS-monitored still water elevation (4212 ft) and the 1986-1987 highstand debris lines on Antelope Island is shoreline superelevation. Shore features include lagoons, killed vegetation, and higher and older shorelines. (b). The photograph taken in 1998 looks east along the northern exposure of Ladyfinger East. The 1986-1987 shoreline expression, foreground, includes terrigenous debris of cobbles, gravel, and sand. Contrasts in vegetation patterns, the upper center of the photograph, and lumber and timber in the beach zone are evident a decade after the 1986-1987 flooding. (c). The photograph taken in 1998 looks northeast toward the intersection of the northern and southern expressions of the spit at Unicorn Point. The man with the rod stands on the northern, northeast-facing, lower expression, and the younger man stands on a southeast-facing expression. (d). The photograph taken in 1998 looks north from Timely Gull Bay toward Curlew Bay along the west side of Antelope Island. Note the stacked timber and lumber at the south of the bay indicating transport by wind waves from the northwest. (e). The photograph taken in 1986, during the highstand years, looks north along the eastern exposure of Tin Lambing Shed, south of Harbor Bay. Note the terrigenous wash-over deposits of sand and 20th-century evidence of lumber.*

land at 4213.5 ft, the same elevation measured by Gilbert for the storm line formed in the 1870s." The shoreline evidence of both surveys was superelevated compared to the USGS-monitored still water elevations (Gilbert, 1890; Mabey, 1986). Based on records of the elevation of the highstand taken along the south shore of GSL, Gilbert estimated shoreline superelevation of one foot on the eastern side of Antelope Island.

1986 Survey by Atwood and Mabey

In 1986 G. Atwood and D.R. Mabey conducted a survey to compute the frequency of Holocene flooding of GSL (Atwood and Mabey, 2000). The idea was to survey the 1986 shoreline evidence and to count the shorelines between the historic highstands (1870s and 1980s) and Murchison's (1989) "Holocene high" of approximately 4217 ft. For the 1986 survey, we used an electronic measuring device (EDM) to measure elevations. Initially, we expected that the 1986-1987 highstand evidence would provide the horizontal datum from which to survey the higher, older shoreline elevations. However, the 1986-1987 shoreline evidence did not define a horizontal plane. Therefore, we used only the USGS-monitored still water lake level as vertical control for the survey.

The evidence of the 1986-1987 highstand was unmistakable and included debris lines of floated debris, gravel ridges and beaches, erosional steps, and vegetation lines (salt-kill zones). Floated debris included 20th-century wood and anthropogenic material (such as plastic). Terrigenous evidence included well-sorted cobbles, coarse and fine gravel, and sand. Shoreline evidence of 1986-1987 had no observable surface staining in contrast to older shorelines. In places, erosional steps had been cut into poorly consolidated, sandy sediments.

The evidence of Murchison's (1989) "Holocene high" at an elevation between 4217 and 4222 ft was discontinuous, subtle, and subject to interpretation, consisting of widely scattered gravel and cobble patches and subtle breaks in slope. For detailed discussion of Holocene lake fluctuations, see Oviatt and others (2021).

A summary of the findings of the 1986 survey on Antelope Island is as follows (Atwood and Mabey, 2000):

(a) The plot of shoreline elevations (Figure 4) indicated at least three highstand shorelines between the 1986-1987 highstand and 4226 ft. Counting the two historic excursions to 4212 ft in 1986 and 1987, GSL had risen a minimum of five times to elevations equal to or higher than 4212 ft.

(b) The 1986-1987 shoreline debris did not define a horizontal plane from which to measure relative elevations of Holocene shorelines. Evidence of the 1986-1987 GSL highstand was consistently superelevated, well-above the USGS-monitored still water lake level. The elevations of the higher, older shorelines appeared to have trends of superelevation resembling those of 1986-1987.

1997-1998 Atwood and Mabey Survey of 1986-1987 Highstand Evidence on Antelope Island

The 1997-98 survey aimed to document the character of the 1986-1987 highstand shoreline in detail before ephemeral evidence became unrecognizable (Atwood, 2006). We documented elevations of the 1986-1987 highstand evidence and recorded shorezone characteristics around the island's perimeter using a Sokia total station to survey elevations and Global Positioning System (GPS) data loggers to record horizontal positions of observations of shorezone characteristics. The USGS-monitored still water lake level provided vertical control. Throughout the day, we used a survey staff to measure water-level changes for the purpose of maintaining accurate vertical control. We also corroborated our elevations with Davis County Public Works' road elevations. Elevations were surveyed on the upper surface of the most-inland terrigenous deposits at 1,228 locations along the 64 km shoreline of Antelope Island. The data were downloaded into a geographic information system database, projected to a single route using ESRI Arc/Info linear referencing, and analyzed with simple spatial statistics (Atwood, 2006).

A decade after the 1986-1987 GSL highstand, much of the 1986-1987 flotsam (windrows of brine-fly carapaces, vegetative evidence, and automobile tires) was lost to disintegration, fire, and trash collection. Large debris, which included lumber and timber, became reliable evidence and it persisted long after deposition. Some smaller debris persisted included plastic and other 20th-century debris. Gravel ridges and sand beaches were intact. Erosional steps were evident but no longer had the angular shape of 1986-1987. Vegetation, specifically sunflowers, grew on the 1986-1987 gravels.

Patterns of shoreline superelevation along the 1986-1987 shoreline were consistent with observations of the 1986 survey. Patterns of shoreline superelevation were not random. They did not define a horizontal plane from which post-depositional change could be measured with confidence.

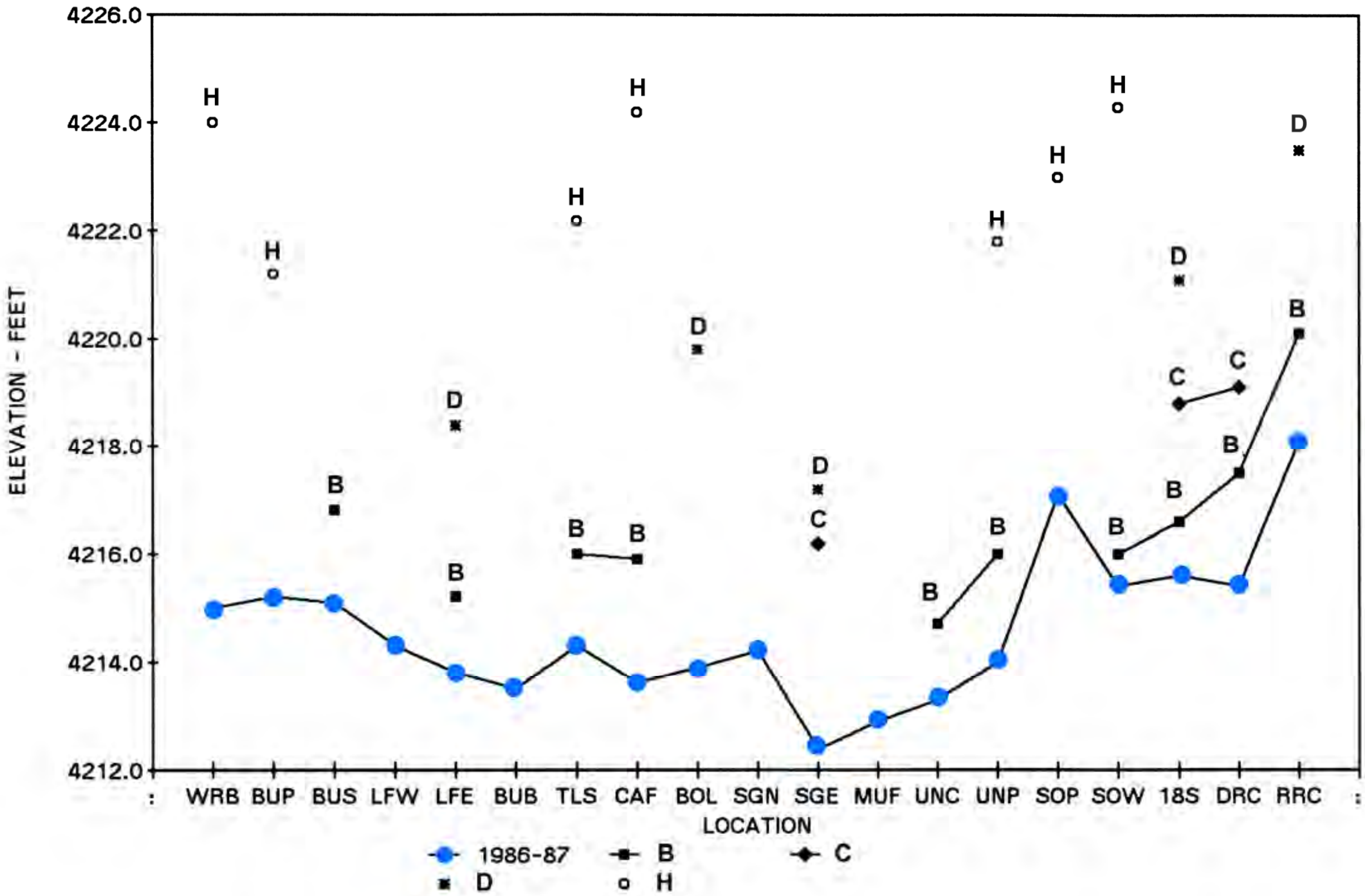

Figure 4. *Great Salt Lake shoreline elevation data of the 1987-1988 survey on Antelope Island. Plot of elevation (ft) at a progression of surveyed locations clockwise around Antelope Island beginning at White Rock Bay (WRB), continuing to Lady Finger Point (LFW, LFE), to Seagull Point (SGN, SGE), to Unicorn Point (UNC, UNP), to Dry Canyon (DRC) (refer to Fig. 1(b) for locations. Blue dots show surveyed elevations of shoreline debris of the 1986-1987 highstand. Black dots show surveyed elevations of older, higher shoreline evidence around Antelope Island. Lines between locations indicate lateral correlation of shorelines. The blue dots, surveyed locations of 1986-1987 debris, consistently lie above 4212 ft, the elevation of the USGS-monitored still water level and documented flooding hazards above still water lake level. The lettered points (B, C, D, H) were grouped based on trends and position relative to the 1986-1987 shoreline evidence at each location. Adapted from Atwood and Mabey, 2000.*

Patterns of shoreline superelevation were compared with patterns of shorezone characteristics (Figures 5 and 6). Variations of shoreline superelevation from place-to-place record relative wave energy modified by diverse factors. Shoreline evidence was found consistently above still water lake level because, when there is no wind, there are no waves to rework materials and deposit evidence.

Wind waves are the most significant agents of coastal processes that affect lake shorelines (Komar, 1998). Waves erode and deposit the shoreline evidence. Wave height and wave energy largely determine shoreline superelevation.

However, other factors affect coastal dynamics. Wind setup and wind setdown due to atmospheric conditions lead to lake seiche (Wang, 1978). Seiche alone has little effect on shoreline erosion and deposition but may affect the magnitude of shoreline superelevation due to wind setup. Interference and harmonics of normal "gravity waves" create widely spaced infra-gravity waves (Bertin and others, 2020). Offshore and on-shore currents affect wind wave processes and wave heights. These factors make the initial, generally higher lake levels from which waves run up the shore.

Shoreline superelevation records the net effect of wave energy and shorezone conditions, including aspect, fetch, steepness, and materials. Aspect (the direction that the beach faces) was used as a proxy for wind direction. Figures 7, 8, and 9 show contrasts of Antelope Island shores. High shoreline superelevation correlates with long fetch and with north and northwest aspect. Low shoreline superelevation correlates with short fetch and geomorphic shielding. This observation implied that wind might be a recognizable contributing factor to shoreline superelevation of GSL in addition to the effects of fetch (Figure 10).

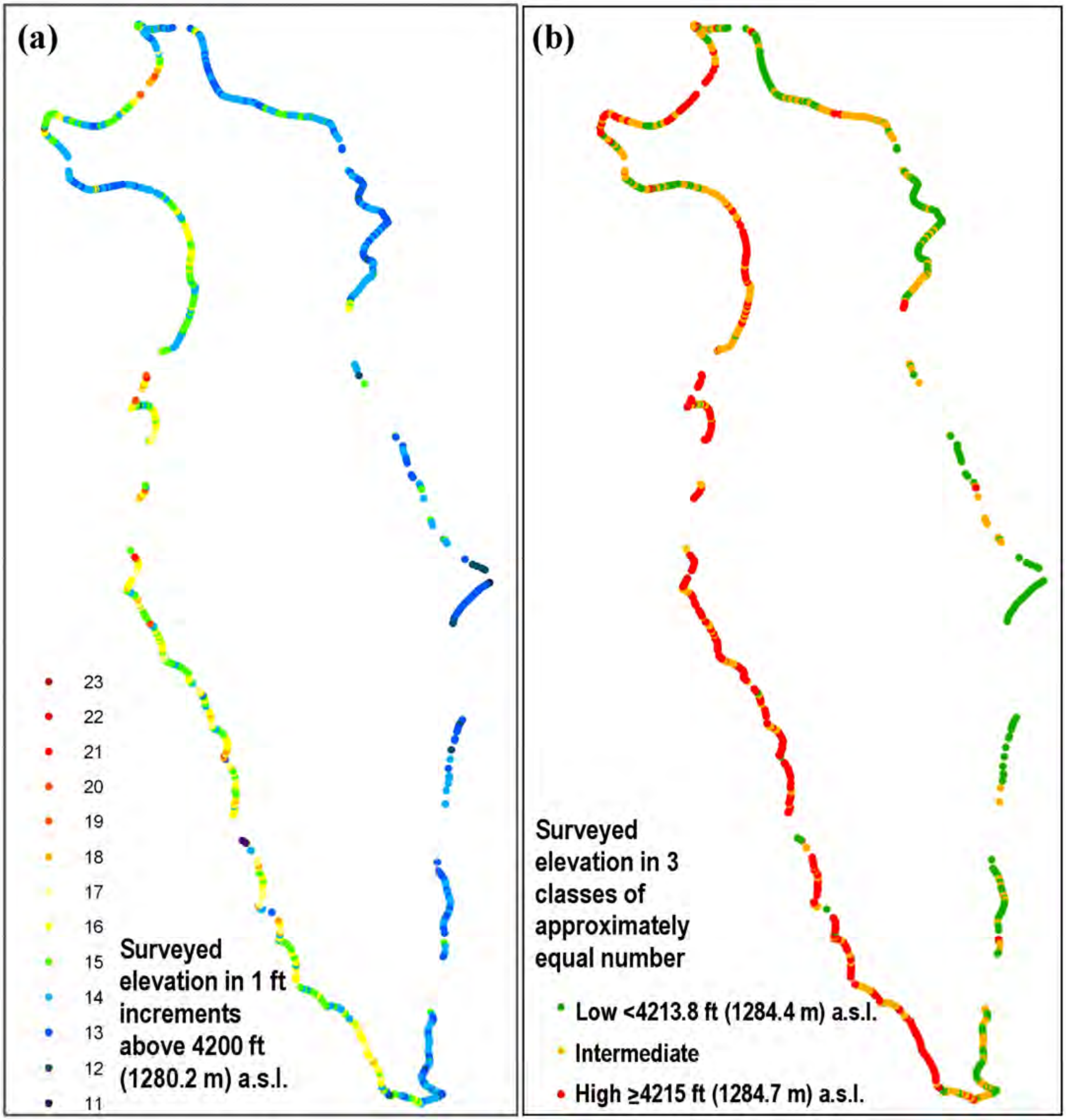

Figure 5. *Superelevation of shoreline evidence of Antelope Island, surveyed in 1998-1999. Adapted from Atwood (2006). Two maps of surveyed locations on Antelope Island showing shoreline superelevation in equal increments versus shoreline superelevation classes. (a). Shoreline superelevation displayed in equal 1-ft increments above the 4200 ft datum of the field study. Shoreline evidence ranged from 4211 ft to 4223 ft (11 to 23 on the key). Shoreline superelevation elevations ranged from at or slightly below USGS-monitored still water level along vegetated shore stretches to the highest levels, 11 ft above still water lake level, on bedrock outcrops bordering pocket beaches. (b). Shoreline superelevation classified in approximately equal populations. High superelevation is superelevation equal to or greater than 3.4 feet. Intermediate superelevation is superelevation between 2.2 and 3.4 feet. Low superelevation is superelevation less than 2.2 feet. Each of the three classes consists of approximately 400 surveyed elevations.*

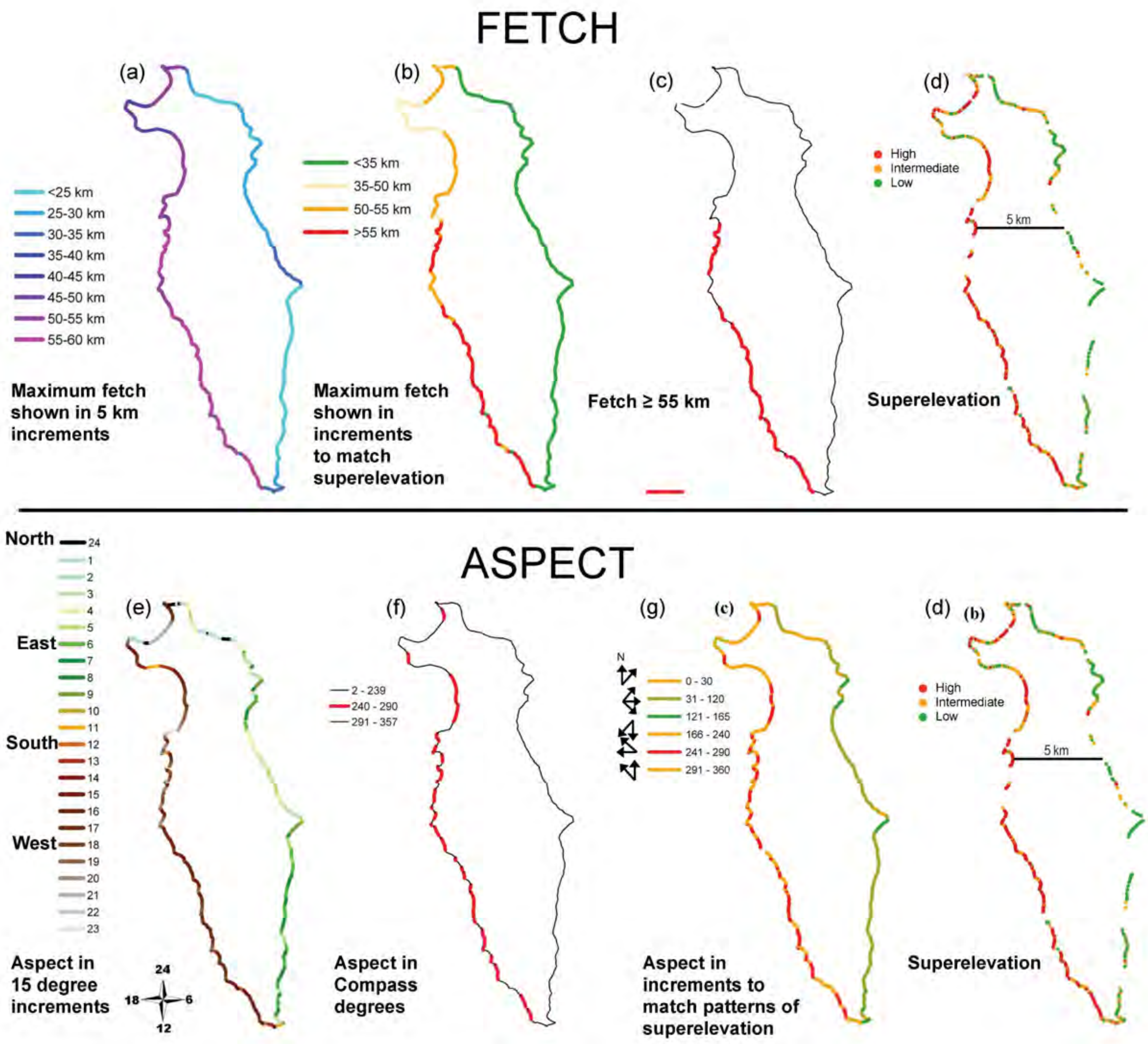

Figure 6. *Associations of shoreline superelevation with fetch and aspect. The two sets of maps show associations of maximum fetch, aspect in 15-degree increments, and shoreline superelevation. Visual inspection indicated correlations among shoreline superelevation, fetch, and aspect. Adapted from Atwood (2006).*

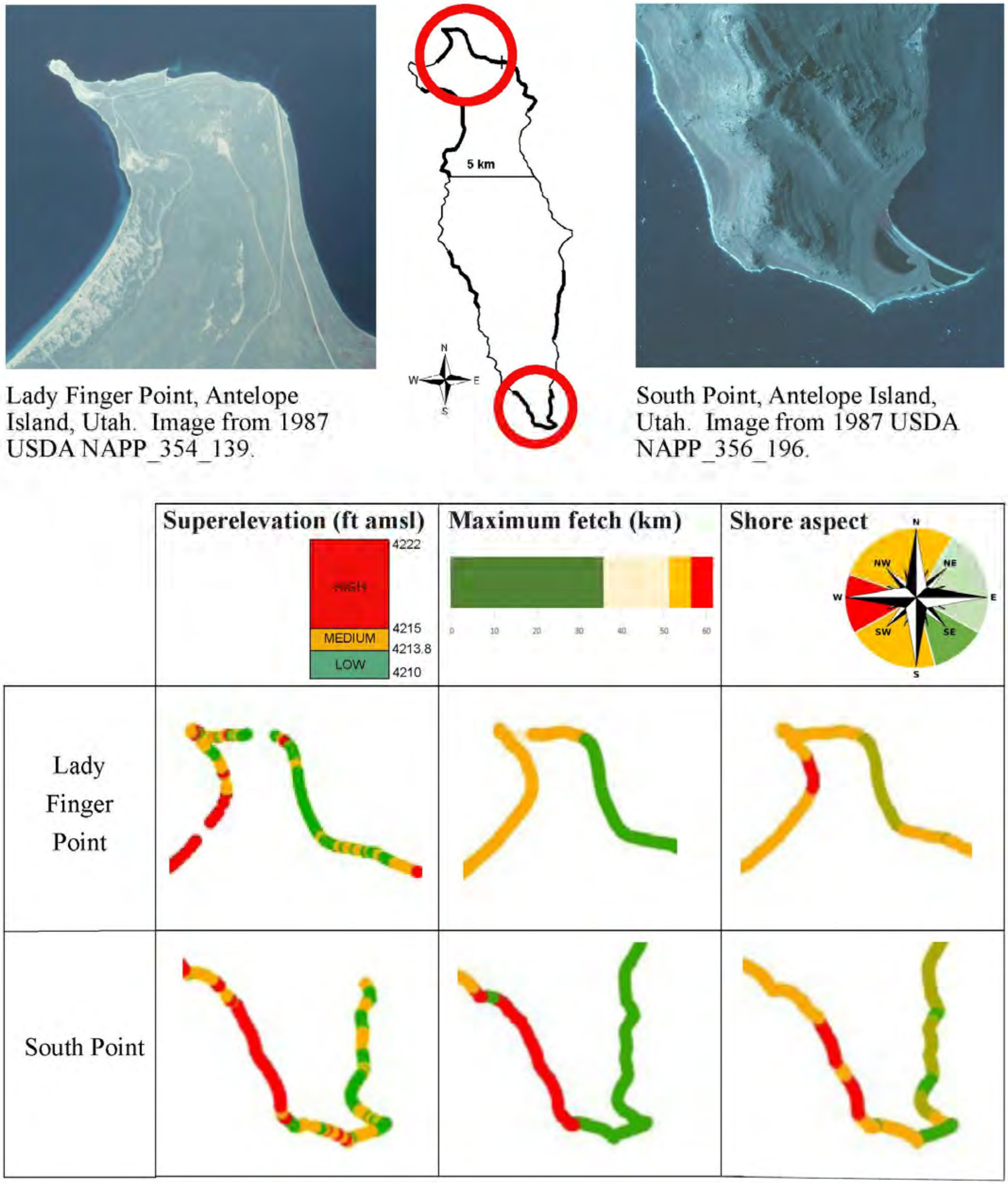

Figure 7. Lady Finger Point and South Point patterns: superelevation, maximum fetch, and shore aspect. The orthophotos show Great Salt Lake near its highstand at the two red-circled locations on the map. Lady Finger Point juts into Gilbert Bay as a bedrock headland. Unicorn Point immediately to the east of South Point is named for the "unicorn" described by its 1986-1987 lagoons and spits. The table relates high shoreline superelevation, at a detailed scale with maximum fetch and shore aspect. The dots of the table entries indicate locations surveyed in the 1997-1998 Antelope Island survey. Shoreline superelevation was surveyed, whereas maximum fetch and aspect were interpreted from maps. The patterns show west-east contrasts. At Lady Finger Point, high shoreline superelevation correlates visually with medium fetch and western aspect. At South Point, high shoreline superelevation correlates visually with maximum fetch and shore aspects facing west and southwest.

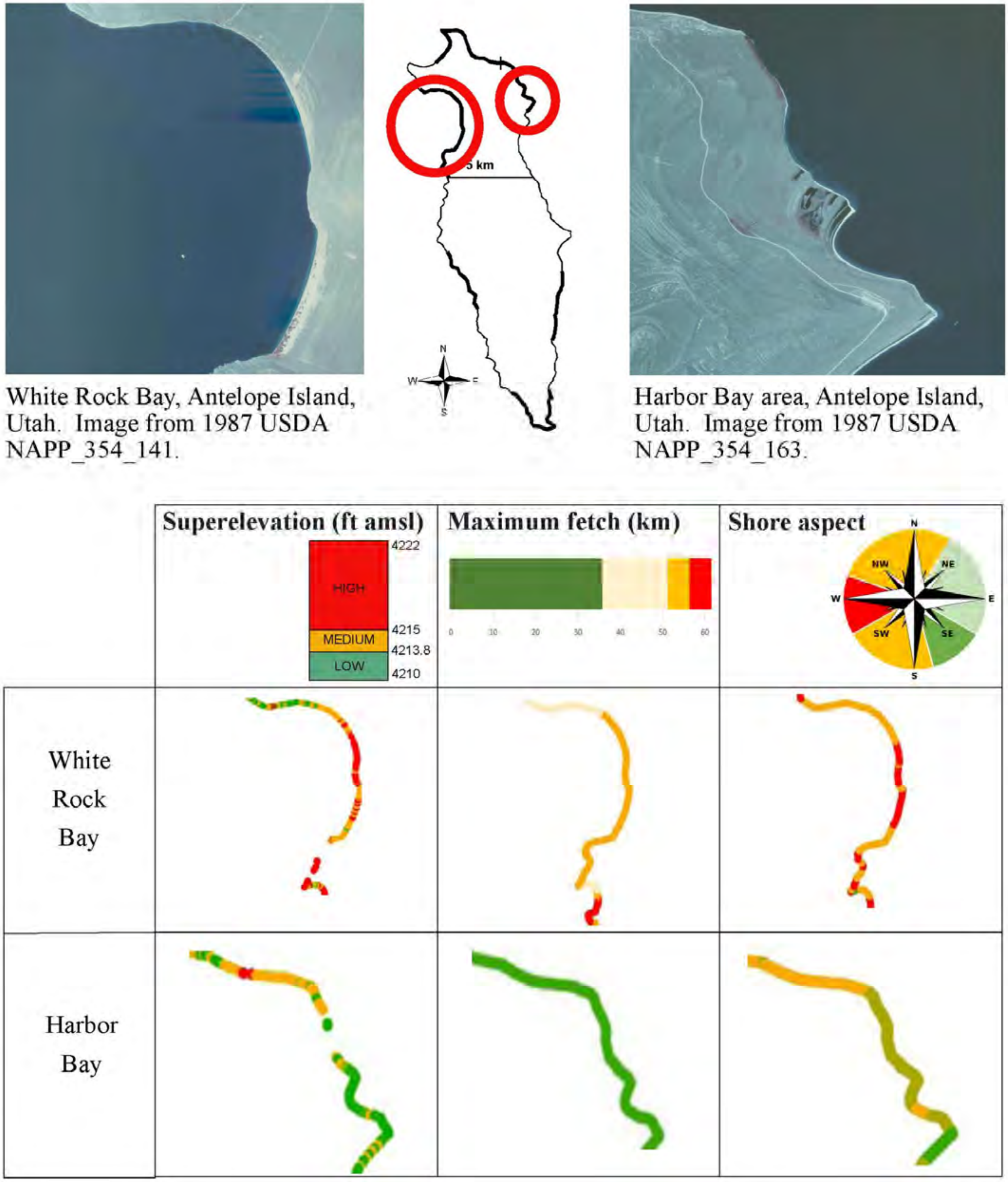

Figure 8. *White Rock Bay and Harbor Bay patterns: superelevation, maximum fetch, and shore aspect. The orthophotos show Great Salt Lake near its highstand at the two red-circled locations on the map. White Rock Bay, a broad, shallow bay opens to the west. Harbor Bay, a complex bay opens to the north and east. The dots of the table entries indicate locations surveyed in the 1997-1998 Antelope Island survey. Shoreline superelevation was surveyed, whereas maximum fetch and aspect were interpreted from maps. The patterns show west-east contrasts. At White Rock Bay, high shoreline superelevation correlates visually with medium fetch and western aspect, while low shoreline superelevation does not appear to correlate with fetch or aspect and may result from sheltering by geomorphic features. Harbor Bay has limited high shoreline superelevation with low shoreline superelevation correlating visually with low fetch and aspects facing southeast.*

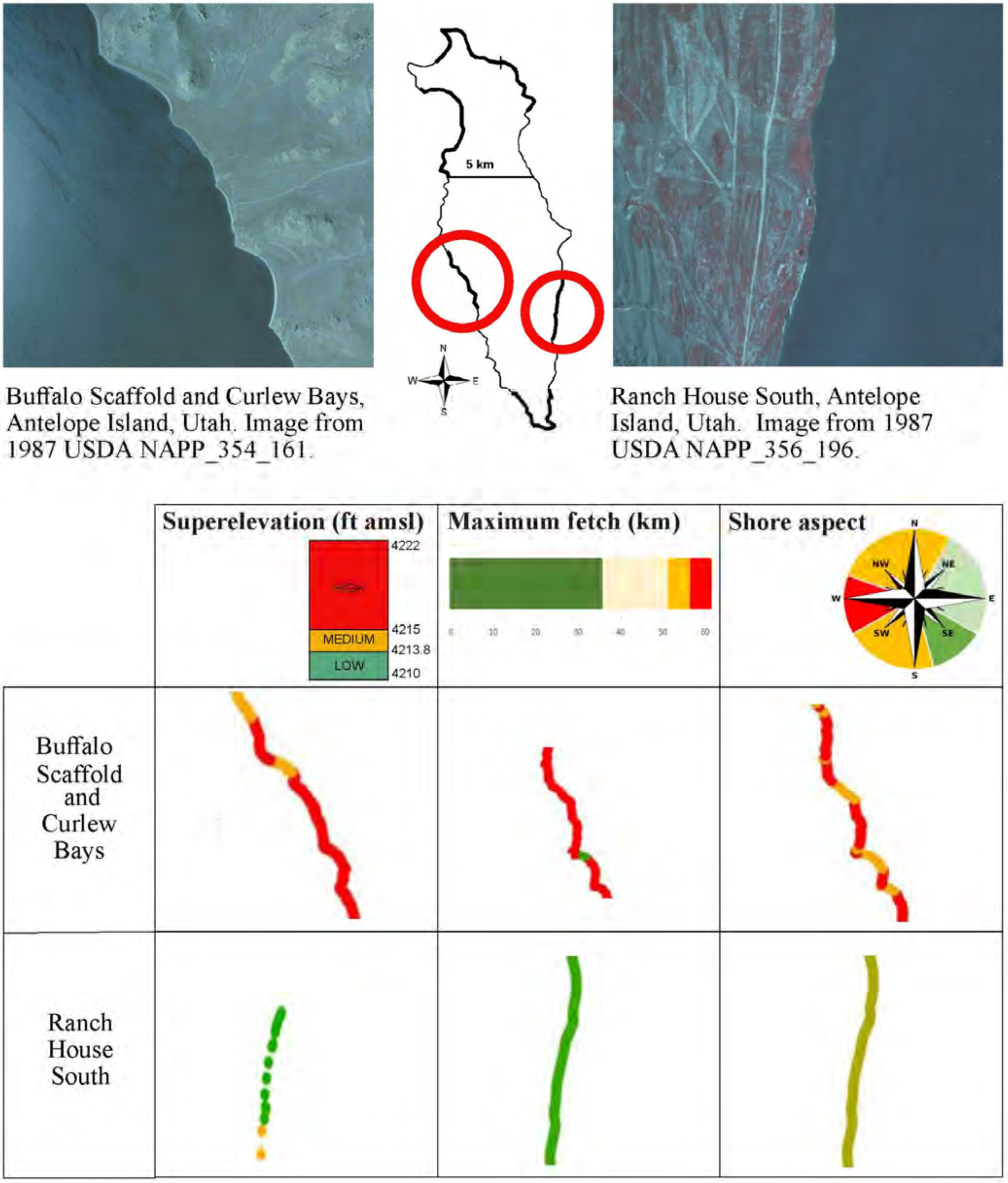

__Figure 9.__ Buffalo Scaffold - Curlew Bays and Ranch House South patterns: superelevation, maximum fetch, and shore aspect. The orthophotos show Great Salt Lake near its highstand at the two red-circled locations on the map. The bays and headlands of Buffalo Scaffold - Curlew Bay on the southwestern shore of the island contrast with the straight shore of Ranch House South. The dots of the table entries indicate locations surveyed in the 1997-1998 Antelope Island survey. Shoreline superelevation was surveyed, whereas maximum fetch and aspect were interpreted from maps. The patterns show west-east contrasts. At Buffalo Scaffold and Curlew Bays, high shoreline superelevation correlates visually with maximum fetch and with western aspects. At Ranch House South, low shoreline superelevation correlates visually with low fetch and eastern aspect.

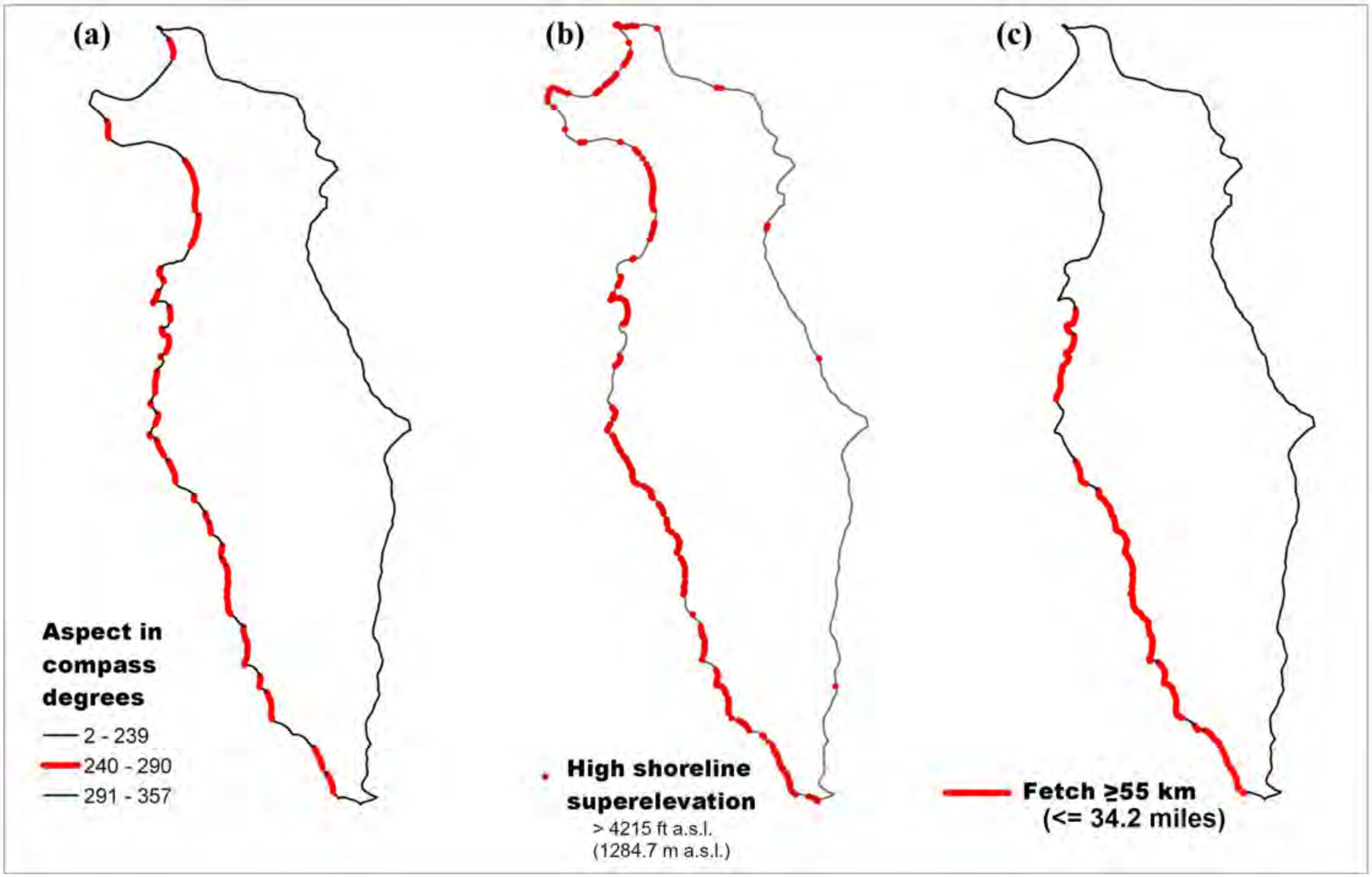

Figure 10. *Associations of high superelevation, long fetch, and aspects facing north and west. Series of three maps showing aspect, superelevation, and fetch. Patterns of (a) west-facing shores; (b) high shoreline superelevation; and (c) longest fetch are similar. Of the 400 surveyed locations with 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. On Antelope Island, because the patterns of fetch and aspect so closely resemble each other, it is difficult, if not impossible, to distinguish the relative importance of wind from fetch on shoreline superelevation. Adapted from Atwood (2006).*

As with previous surveys, elevations of shoreline evidence were not at the USGS 1986-1987 monitored still water lake level. Patterns of shoreline superelevation were not random and could be quantified. For example, highest shoreline superelevation was associated with fetch greater than 55 km and on shores facing north, northwest, and west. Shoreline superelevation ranged from as low as 4211.1 ft to 4223.4 ft. with a mean of 4214.5 ft. The shoreline superelevation of the west side of the island was generally higher and more variable than of the east side of the island.

The patterns of shoreline superelevation of the 1986-1987 shorelines on Antelope Island provide evidence of the geomorphic effects of wind waves. But because both the longest fetch and the strongest winds were from the northwest, patterns of shoreline superelevation on Antelope Island could not clarify the relative contributions of fetch and aspect to wave energy.

G.K. Gilbert observed shoreline superelevation on the southern shores of Lake Bonneville and cautioned that fetch, not wind strength or wind direction, caused the superelevation of Lake Bonneville shores. Gilbert (1890, p.107) expressed his recognition of the effects of long fetch in the following quote, which conveys his surprise, humility, and acceptance that long fetch, regardless of wind strength and direction, accounted for the high shoreline superelevation of Lake Bonneville's shores.

> 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 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.

Might processes of a fetch-limited lake such as GSL at its highstand level leave long-lasting evidence of wind strength and direction and therefore lasting geomorphic clues to storm conditions and weather patterns?

Atwood and Mabey 1999-2000 Survey at Places Around Gilbert and Gunnison Bays

The 1999-2000 survey (Atwood 2006) aimed to confirm whether patterns of shoreline evidence along the shores of Gilbert and Gunnison Bays resembled those along the shores of Antelope Island. We explored relationships among fetch, aspect, and shoreline superelevation. Disturbance of 1986-1987 shoreline evidence, accessibility, and inadequate vertical survey control limited the choice of locations with which to compare diverse conditions of fetch and aspect (Figure 11).

For the 1999-2000 survey, we followed the same procedures as for Antelope Island in 1997-1998. We used the same equipment, including the Sokia total station and the GPS data loggers. Vertical control was carried from first-order survey markers and/or from USGS-monitored still water lake level. We interpreted factors of fetch such as length and direction of the longest fetch, length of fetch north and northwest, the distance from the bay axis, shorezone aspect, shorezone slope, elevation of the lake shore bed, and bedrock outcrops between 4200 and 4220 ft a.s.l. from maps.

Much of the non-terrigenous evidence of the 1986-1987 shoreline had been lost to natural disintegration, land cultivation, and development onto the lakebed as GSL retreated. Orthophotos documented shore features of 1986-1987. That evidence and 20th-century debris, such as large logs and railroad ties, confirmed field identification of the 1986-1987 highstand in contrast to higher, older shorelines.

The survey data were plotted on orthophotos and checked against geomorphic features. Figure 12 shows contrasts of patterns of shoreline superelevation at Strongs Knob near the southwestern shore of Gunnison Bay with those of Rozel Point along Gunnison Bay's eastern shore. The classifications of high, medium and low superelevation are those of the Antelope Island survey.

Patterns of shoreline superelevation of Gilbert and Gunnison Bays shores resembled those of Antelope Island. They confirmed that shoreline superelevation was a lake-wide phenomenon. As with the findings on Antelope Island, patterns of shoreline superelevation were not random and were quantifiable. Differences in elevation from place to place were easily detected. The 1986-1987 shoreline around Gilbert and Gunnison Bays, just as around Antelope Island, did not define a horizontal plane.

Coastal processes of GSL cause shoreline superelevation. We used a series of steps to explore whether fetch alone caused spatial variations in shoreline superelevation of Gunnison and Gilbert Bays (Figures 13 and 14). We assumed that equal fetch causes patterns of equal shoreline superelevation. Fetch lengths between surveyed locations on opposite sides of the lake were plotted on a diagram with midpoints placed on a center point.

If fetch alone, as Gilbert noted for Lake Bonneville (a fetch-dominated, much-larger version of the lake system), controlled the magnitude of shoreline superelevation for GSL, then the magnitude of shoreline superelevation would be similarly high at both ends of GSL in the direction of the longest fetch. In the direction of the shortest fetch, superelevation would be low at both ends of GSL. In addition, if fetch were the dominant control on superelevation, the midpoint patterns would resemble a bullseye. However, a pattern of the midpoint diagrams that showed trends of low to high superelevation could indicate that wind strength, in addition to fetch, caused the differences in shoreline superelevation. The patterns shown in Figure 14 indicate strong storm winds from the northwest (Atwood, 2006). Wind data for Gunnison and Gilbert Bays were not available in 2006 to corroborate or refute these conclusions.

2023 – Analysis of Patterns of Shoreline Superelevation and 2020-2023 Wind Data

In 2023, wind data from weather stations on Hat Island in Gilbert Bay and Gunnison Island in Gunnison Bay was analyzed to corroborate or refute interpretations of the earlier studies. Atwood (2006) suggested that patterns of shoreline superelevation were influenced by wind direction and strength, not simply by fetch. In 1990-2000, regional meteorological data, other than for Salt Lake International Airport, were unavailable, and the Salt Lake International Airport records were considered possibly non-representative of the open-lake conditions of Gilbert and Gunnison Bays. Instead, Atwood (2006) used estimates of wind parameters by W. Alder, Utah State Meteorologist, as

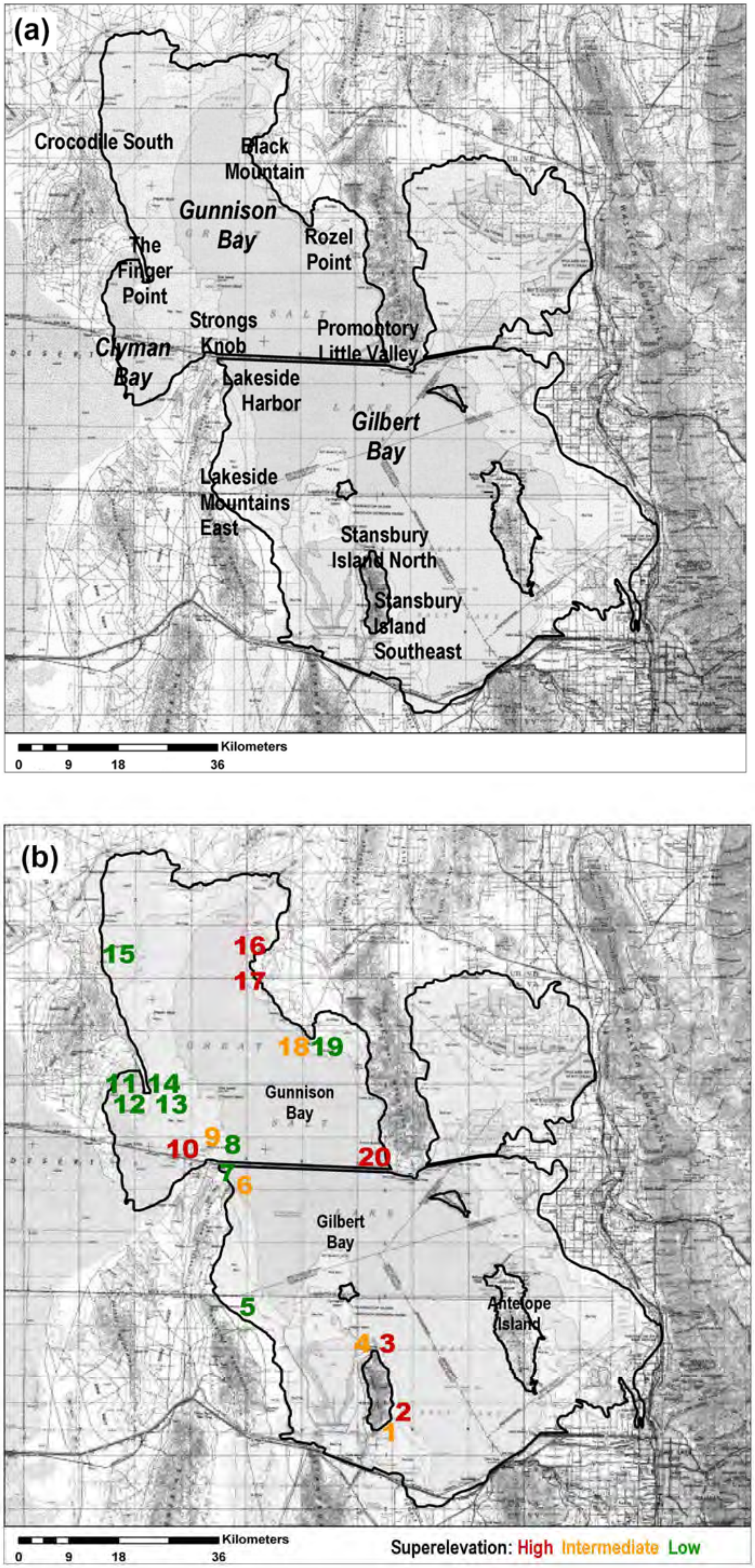

Figure 11. *Maps of the Great Salt Lake perimeter surveys 1999-2000. Adapted from Atwood (2006). (a). The map shows the names of the ten places along the perimeter of Great Salt Lake selected to test the findings of the 1997-1998 Antelope Island field surveys and explore relationships among aspect, fetch, and shoreline superelevation. (b). The numbers identify surveyed stretches at places along the perimeter of Gilbert and Gunnison Bays. They indicate the 20 contrasting shores of the field survey, classified as generally high (red), intermediate (orange), or low (green) shoreline superelevation using the criteria of the 1997-1998 Antelope Island survey.*

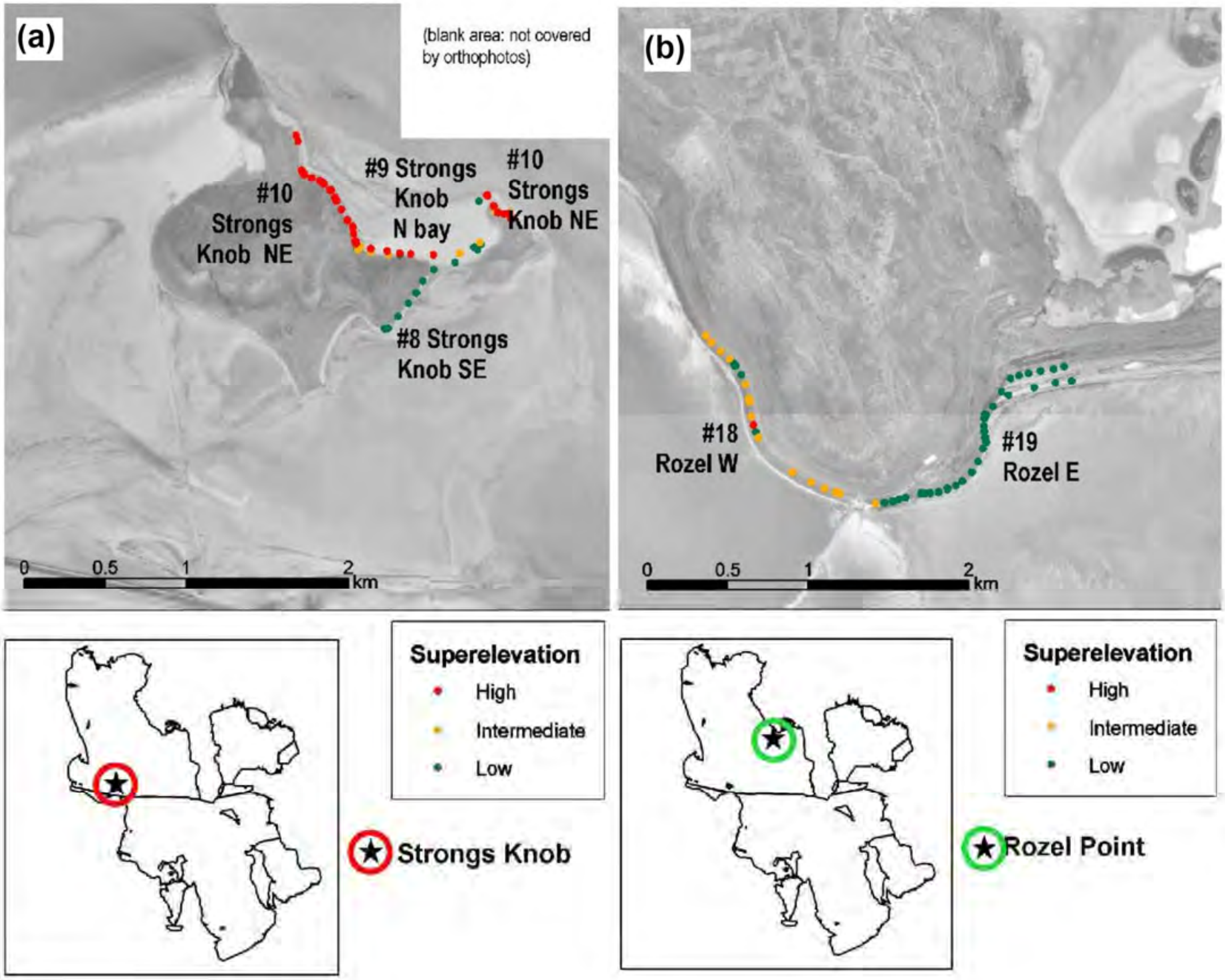

Figure 12. *Patterns of shoreline superelevation at Strongs Knob and at Rozel Point. Two location maps with two orthophotos showing survey locations in contrasting areas of Gunnison Bay. (a). Plot of surveyed places on the three shorezone stretches (8, 9, 10) of Strongs Knob. Strongs Knob, an island during 1986-1987, is located in southwestern Gunnison Bay immediately north of the railroad causeway. During the 1986-1987 highstand, Location #8 with southeast aspect and long fetch, had low shoreline superelevation. Location #9, a bay, had two northerly aspects. The northeast aspect had long fetch and high shoreline superelevation. The north-facing shore had long fetch and low shoreline superelevation. Location #10, two separate shores with east-facing aspect had long fetch and high shoreline superelevation. (b). Plot of surveyed places on the two shorezone stretches (18, 19) of Rozel Point. Rozel Point is located mid-bay on the east shore of Gunnison Bay. The rise of Great Salt Lake flooded the Spiral Jetty immediately offshore. Location 18 had a southwest aspect, intermediate fetch, and intermediate shoreline superelevation. Location 19 had south and southeast aspects, short fetch, and low shoreline superelevation.*

the empirical basis for definitions of wave environments for 1986-1987 (personal communication, reported in Atwood, 2006; Alder, 1986, 1987). University of Utah MesoWest weather stations on Gunnison and Gilbert Bays (www.mesowest.utah.edu) now provide real-time wind data for GSL. J.D. Horel (Atmospheric Sciences, University of Utah, personal communication, 2023) provided the wind roses shown in Figure 15. Figure 16 displays the wind rose patterns combined with patterns of shoreline superelevation. Downwind patterns explain patterns of GSL's physical evidence of shoreline superelevation. They corroborate interpretations that the strongest winds that form the waves that cause shoreline superelevation come from the north, northeast and northwest.

The cartoon sketches of Figure 17 show the progression of a low-pressure system from offshore the Pacific Northwest, across California and Nevada to Utah and GSL (Shafer and Steenburgh, 2008). South winds precede the front's arrival, followed by strong northerly winds during and after the front's passage. This substantiates the field surveys' findings that the durable geologic evidence of shoreline superelevation in GSL documents strong storm winds from the northwest.

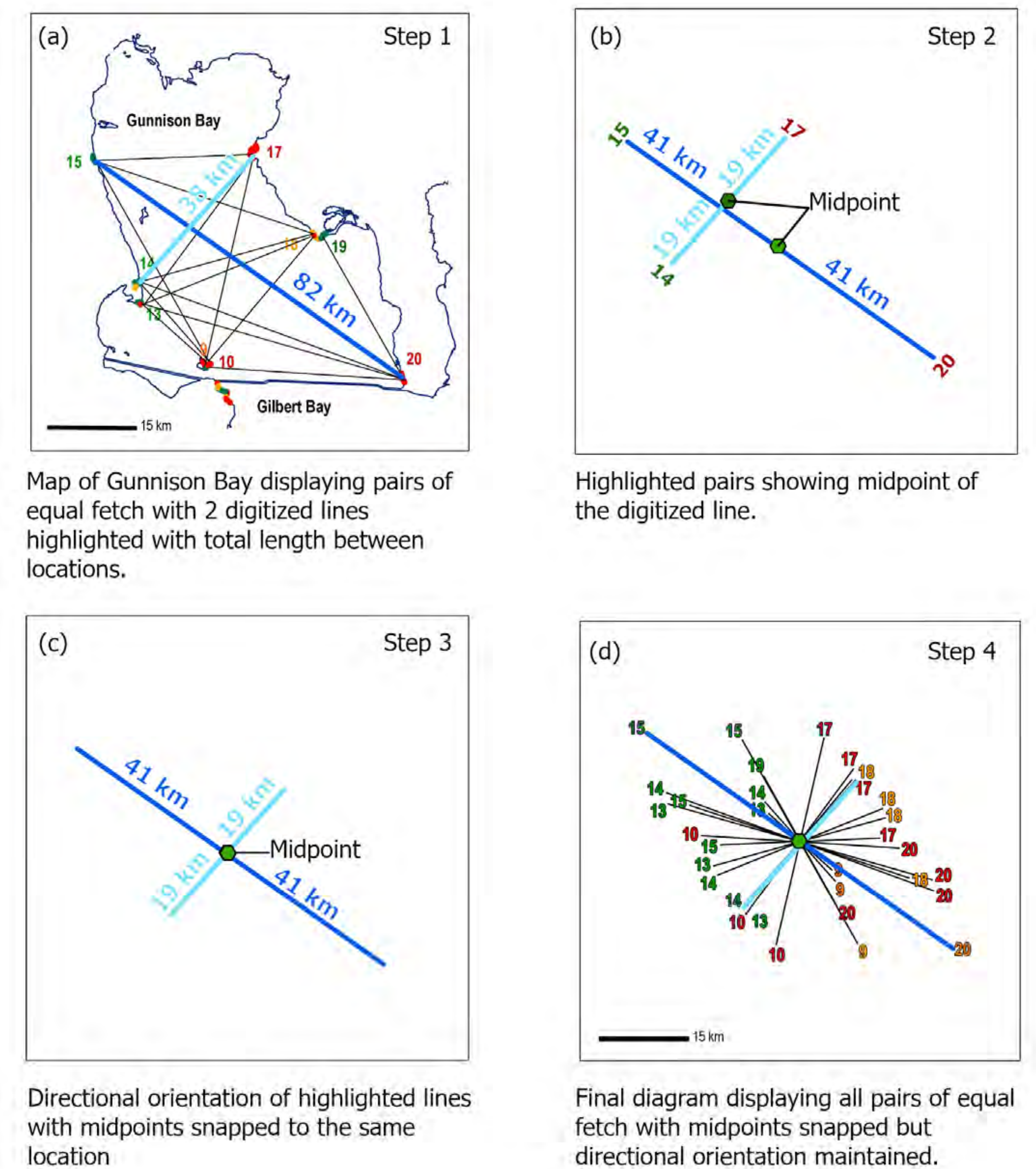

Figure 13. *Pairings of surveyed locations. Adapted from Atwood (2006). The four figures represent four steps to display fetch vectors at a center point. (a). Step 1. Locate places of surveyed shoreline superelevation. The numbers represent the surveyed places in Gunnison Bay on Figure 12 with the number's color indicating the generalized superelevation. Draw lines representing fetch digitally between all pairs of places. Obviously, the distance, for example, from place 15 to place 20 (82 km) is the same as from place 20 to place 15. The lines represent distance and direction both ways. (b). Step 2. Locate the midpoint of each line. (c). Step 3. Copy each line digitally. Snap the lines across each other at their midpoints. (d). Step 4. Create the diagram that compares the effects of wind direction for places of fetch of equal length. The snapped diagram shows equal fetch to both ends. The color dot of the endpoints indicates relative shoreline superelevation, high (red), intermediate (yellow), and low (green).*

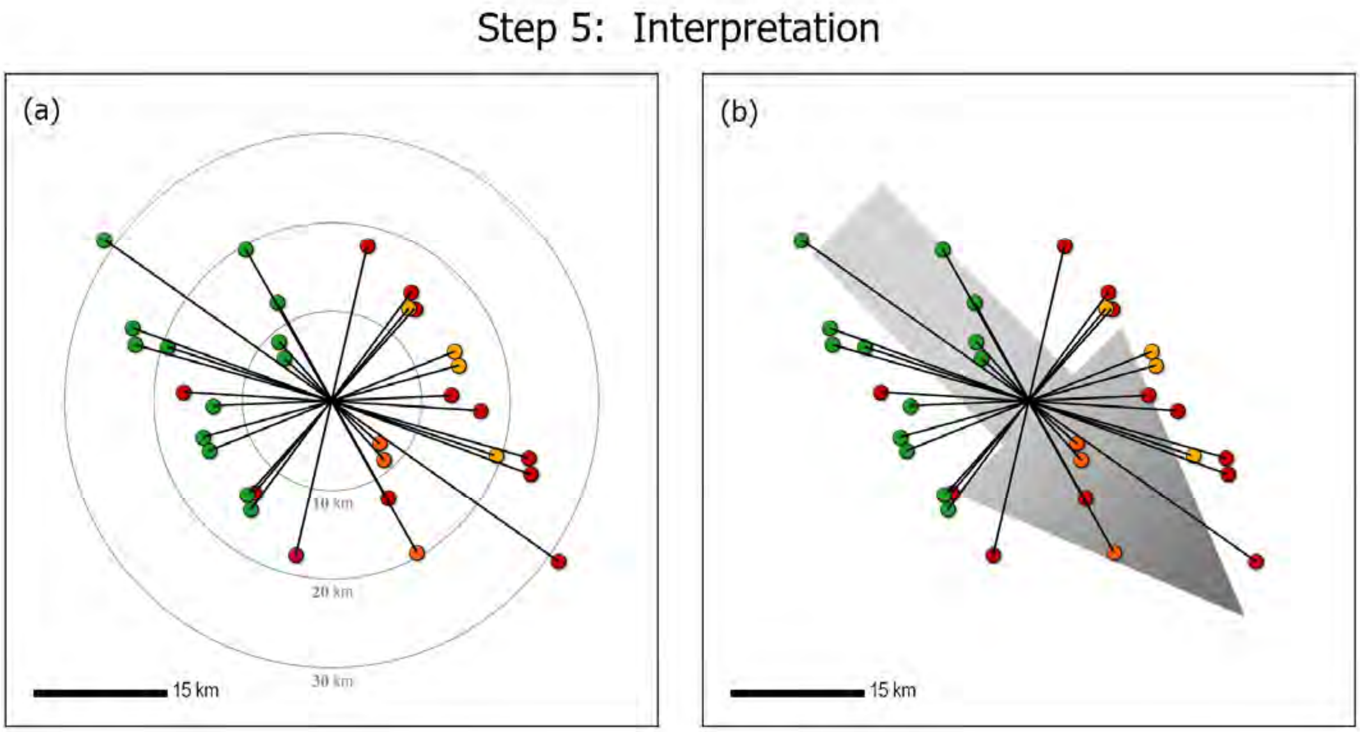

Figure 14. *Visual analysis of the fetch vector diagram. Adapted from Atwood (2006). (a). If fetch alone accounted for shoreline superelevation, the pattern of the colored endpoints would resemble a bull's eye. The green dots representing low superelevation would cluster closer to the center and red dots representing high superelevation away from the center. The color dots on the bullseye diagram do not have a bullseye pattern. (b). The pattern of the dots indicates generally lower shoreline superelevation for northwestern, upwind locations and higher shoreline superelevation for southeastern, downwind locations. This trend implies that strong storm winds from the northwest contribute to patterns of shoreline superelevation of Great Salt Lake, and both wind strength and fetch contribute to shoreline superelevation.*

DISCUSSION

Wave theory and wave dynamics, including the interaction of waves with coastlines and beaches, have generated extensive literature. Scientific aspects have been discussed, for instance, by Munk (1951), Wright and Short (1984), Komar (1998), and WMO (2018). Bertin and others (2020) recently reviewed infra-gravity waves. Coastal landforms, morphodynamics, and processes of fetch-limited shorelines have been documented and discussed by Cooper and others (2007) and Freire and others (2009). Fiedler and others (2020) provide a numerical modeling approach to beach erosion, wave overtopping, and street flooding from storm wave runup and superelevation where historical data are scarce or lacking. In contrast to the shoreline features of GSL, Theuerkauf and others (2021) present the patterns and processes of geomorphic change caused by coastal storms on the shorelines of longer-fetch Lake Michigan. Applequist (2013) presents a framework for assessing hazards in coastal environments linked to climate change, increasingly recognized as a factor in the evolution of weather patterns and storm intensity. From Gilbert (1890) to Schofield and others (2004) and Jewell (2007) fetch has been a subject of shore processes of Lake Bonneville, a lake with wave environments not limited by fetch.

Wind transfers energy from the atmosphere into the water, creating wind waves (Fontaine, 2013). The stronger and longer the wind blows, the higher and more energetic the wind waves. The transfer generates a chaos of wave heights and wave trajectories in a storm zone. The waves interact. As waves travel from a storm zone across a large open lake, the lake surface becomes progressively organized into a "fully arisen sea" of swell. Swell transfers energy with negligible energy loss toward shore. The "sea" becomes more organized with longer fetch. Wave energies and wind waves do not become fully organized if a lake is not big enough. Wave development may be cut off during regime growth by lack of fetch, and this defines fetch-limited conditions (Komar, 1998).

Under strong winds and as storms progress, waves develop, and lake water is pushed up against windward shores (wind setup). Waves lose energy as they encounter the shoreface and then break. More energetic waves run farther up the shore, depositing their entrained and floated debris above the still water level. The entrained and floated debris becomes the su-

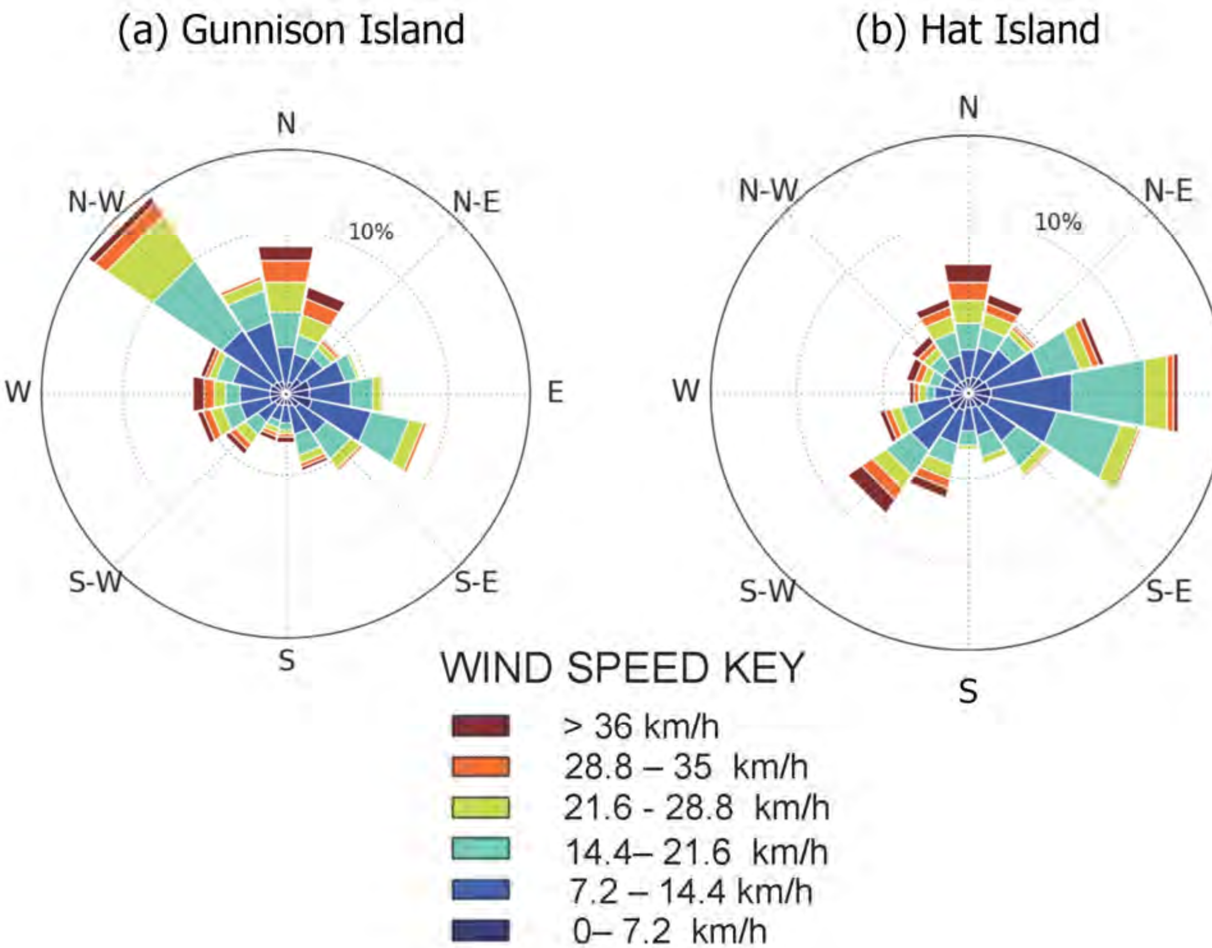

Figure 15. *Wind data for Gunnison and Gilbert Bays. The wind roses show wind direction and wind strength from over 300,000 total observations per location by MesoWest for 2020 to 2023 (J.D. Horel, Atmospheric Sciences, University of Utah, personal communication, 2023). Each wedge represents one of 16 cardinal directions. The length of the wedge represents the percent of the total observations for that site. The colors of the wedge represent the observations that fall in each of the speed classifications. (a) The wind rose for Gunnison Island in Gunnison Bay shows about 14% of the winds come from the northwest. Most of the strong winds come from the north and west and not from the south and east. (b) The wind rose for Hat Island in Gilbert Bay shows about 13% of the winds come from the east, about 8% from the north and 9% from the southwest. Most of the strong winds come from the north and southwest with fewer from the east.*

perelevated shoreline evidence of still water lake level. Winds directed straight at the shoreline inevitably produce greater superelevation than those of oblique incidence. Storm duration, wind strength, and fetch determine the energy input into wind waves. Complicating factors that affect wave runup and therefore shoreline superelevation, include wave setup, wind setup, wind-driven currents, the slope of the shore, shoreline morphology, lakebed and shoreline materials, and geographic features such as headlands that create sheltered zones. For example, Antelope Island shelters its eastern shore from most winds coming from the northwest. Shoreline superelevation at any one location, although dominated by the triad of wave energy, wind setup, and wave setup, is the cumulative effect of all contributing factors.

The US Army Shore Protection Manual (CERC 1984) treats the subject of coastal protection comprehensively and provides the empirical SMB-84 nomograph developed by Sverdrup and Munk (1947) and modified by Bretschneider (1952). The SMB-84 chart is a simple graphical method to identify fetch-limited wave regimes such as GSL. Figure 18, and Figure 19 its key present a nomogram for GSL modified from CERC (1984). It indicates that wave regimes of GSL are fetch-limited. Lo Re and others (2016) found that simple empirical wind-wave models, such as SMB-84, give reliable results, and they remain popular among coastal engineers.

The dark green line of the nomogram of Figure 18 indicates that neither Gunnison nor Gilbert Bay has sufficient fetch to develop a fully developed wave regime in response to storm winds. Strong winds across bays of GSL transfer energy into the waves that cause shoreline superelevation under fetch-limited conditions. Although maximum fetch across any direction of either Gunnison or Gilbert Bay (Figure 6) is too short for the wave environment to become fully developed during storm conditions, gentle winds over a long period of time can produce a fully developed re-

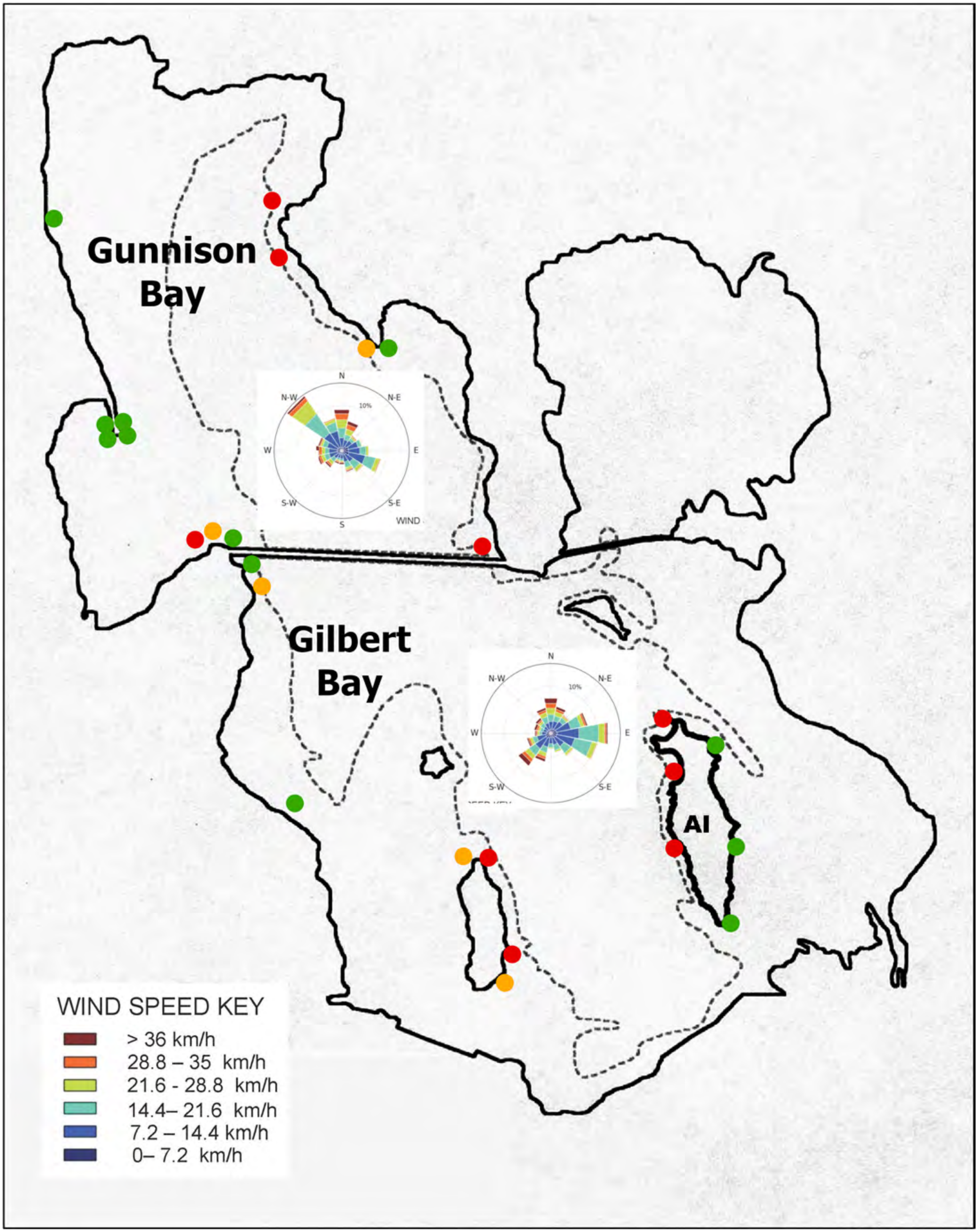

Figure 16. *Gunnison and Gilbert Bays: wind patterns and patterns of shoreline superelevation. Map of Great Salt Lake overlaid with the data from Figure 12 and wind roses from Figure 16. The dark line indicates the extent of the 1986-1987 highstand. The wind rose diagrams of wind direction and strength appear to explain some of the patterns of shoreline superelevation of Gunnison Bay. Patterns are more complex for Gilbert Bay.*

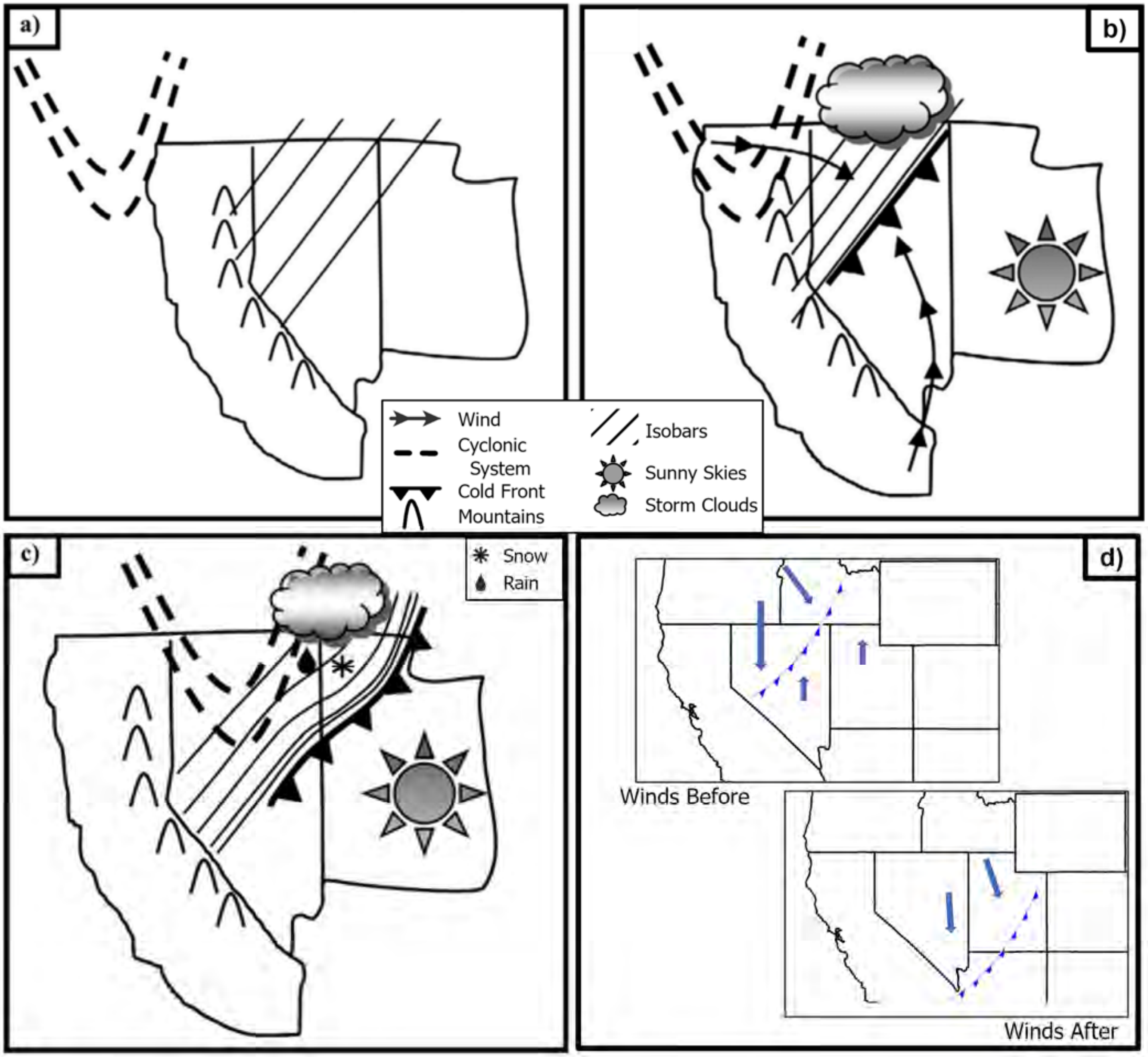

__Figure 17.__ Cartoon of the progress of a low-pressure storm system. Source: Figure a), b), c) adapted from Shafer and Steenburgh (2008). Key added. Figure d), from J.D. Horel, personal communication (2023). The low-pressure system progresses from offshore the Pacific Northwest coast to Great Salt Lake, where its winds create wind waves that leave evidence of shoreline superelevation. a). A cyclonic system arrives at the Pacific Northwest coast. b). The system digs in and progresses across the Great Basin. c). The cold front arrives and crosses Great Salt Lake. d). The two maps show wind direction and strength before and after a cold front crosses Great Salt Lake. Strong winds from the south precede the front's passage. Strong winds from the north and northwest follow. Strong winds transfer energy into the lake surface and create the wave regime that results in the superelevation of shoreline evidence.

gime (wind energy at equilibrium with wave energy that arrives on GSL shores), as indicated by the small yellow triangle in Figure 18. Rowers and sailors commonly observe swell less than 1-2 ft on GSL (G. Atwood and T. Wambeam, personal observations). Those conditions may affect currents and sedimentation patterns but are not the wave environments that leave evidence of storm wind direction.

Wind speeds recorded for Hat Island and Gunnison Island, from 2020 through 2023 (J.D. Horel, Atmospheric Sciences, University of Utah, personal communication, 2023), together with limits of fetch, provide constraints on wave regimes represented by the green rectangle on Figure 18. A possible path of wave regime development over time under storm winds is plotted on the chart as a succession of three green stars (1, 2, 3). The blue star representing the empirical evidence of 1986-1987 conditions lies on the trajectory.

The values given by the blue polygon on Figure 18 for Gilbert Bay wave environments, for the lake at its 1986-1987 highest historic level, were based on in-

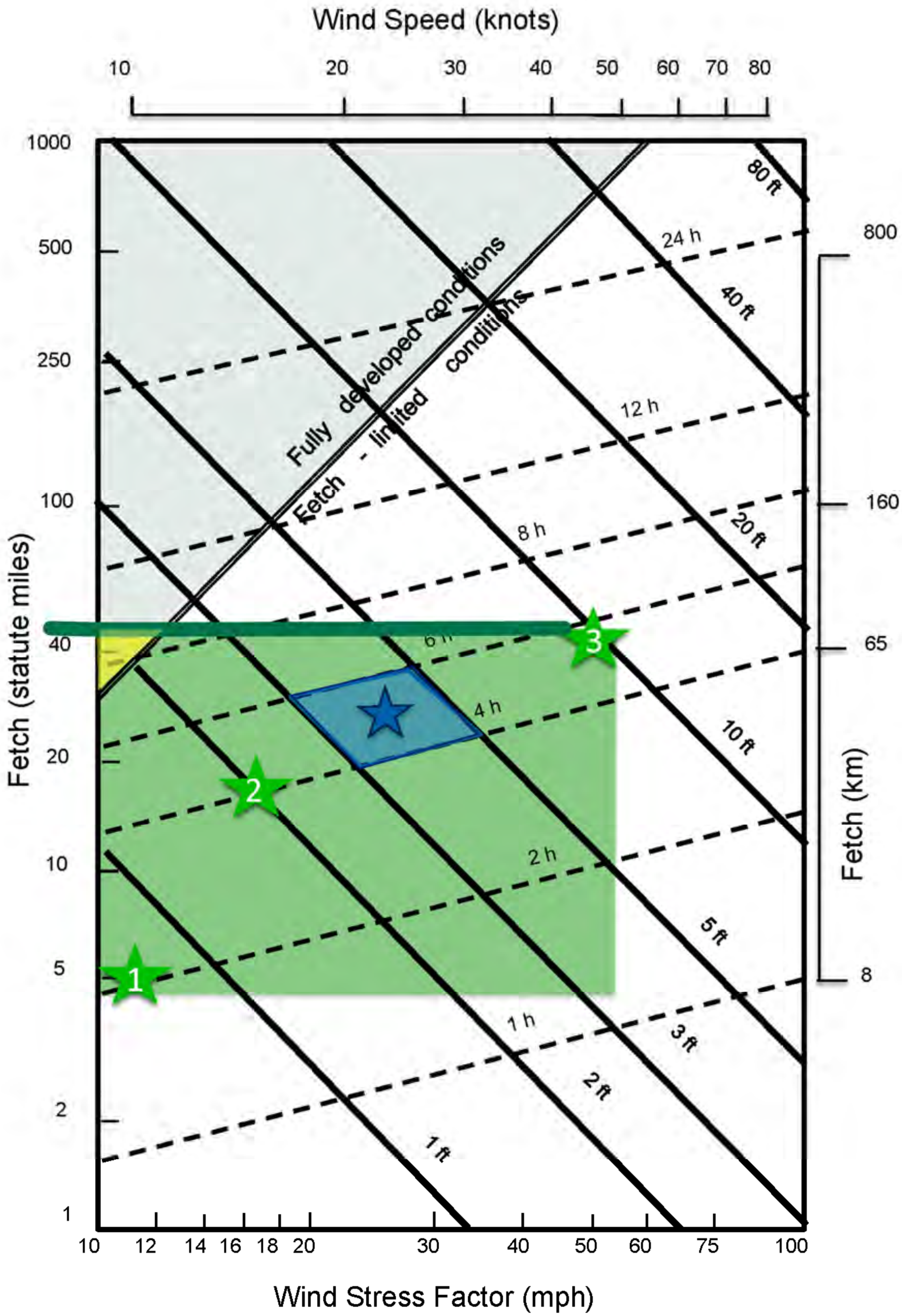

Figure 18. *Wave regime chart for Gilbert Bay. The wave regime chart (see key next page) has four variables: a) wind stress in miles per hour and knots; b) fetch in miles and kilometers; c) duration of strongest winds in hours; and d) significant wave height in feet (the average height of the tallest one-third of waves). This chart (adapted from the SMB-84 nomograph in CERC, 1984) summarizes the complex wave environment for given conditions. It shows a plot (blue polygon) for the conditions for Gilbert Bay reported in 1986-1987 (Atwood, 2006). The wind speeds of Figure 15 together with fetch suggest constraints on the limits of wave regime development in Gilbert Bay at that time (green rectangle). See the key and text for an explanation of the stars.*

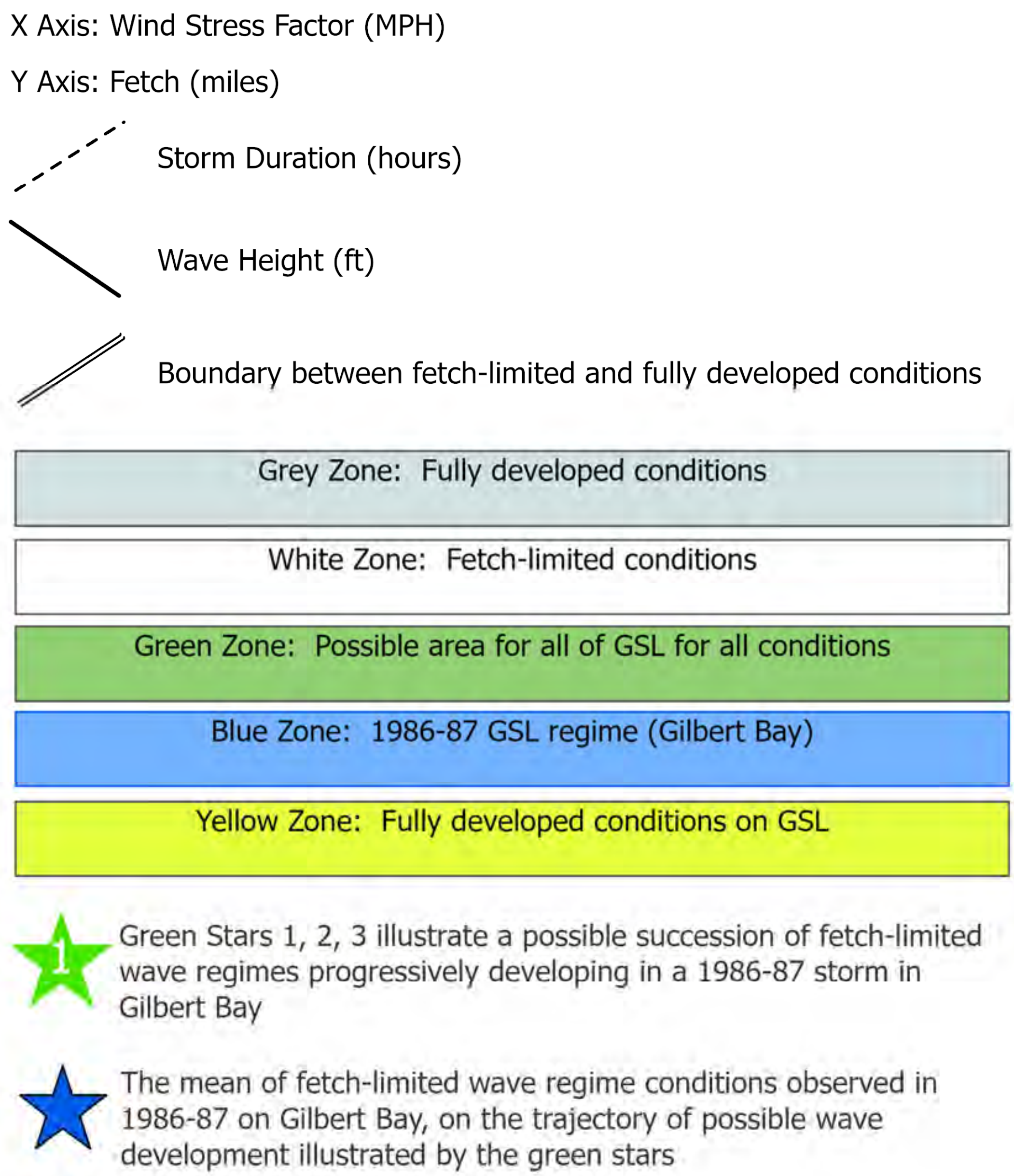

Figure 19. *Key to Figure 18*

terviews with W. Alder, Utah State Meteorologist, who estimated the duration of strongest storms and wind speeds and David Shearer, harbormaster of GSL Saltair Boat Harbor Marina, who estimated significant wave height and wind stress (Atwood, 2006). Fetch was measured from maps. The values for these four parameters define the blue polygon of Figure 18, lying well within fetch-limited conditions (the white region of the chart).

Summary of GSL Lake Processes

Shoreline superelevation is evidence of the lake processes of GSL. Wind develops waves and transfers energy into them. Under strong winds, lake water stacks up against windward shorelines (wind setup). Waves dissipate energy as they encounter the shoreface, run up, break, and deposit their entrained materials well above the static still water level monitored by the USGS.

Storm duration, wind strength, and fetch determine the energy input for the waves that leave the superelevated shoreline evidence. Factors affecting wave run-up on shorelines include wave setup, wind setup, wind-driven currents, the slope of the shore, shoreline morphology, from convex to straight to concave, lakebed and shoreline materials, and geographic features that block winds or create sheltered zones. The cumulative effect of these diverse contributing factors is that shoreline superelevation may at any one location, although dominated by wave energy, includes wind set up and wave set up. The patterns of shoreline superelevation of Antelope Island 1986-1987 shoreline were caused by differences in the energy of wind waves arriving on shore. Those energy differences, although primarily due to differences in fetch, were noticeably affected by wind strength.

Insights from documentation of shoreline superelevation on Antelope Island, corroborated by the recent analysis of winds across Gunnison Bay, suggest that geomorphic patterns of shoreline superelevation of fetch-limited paleolakes can provide evidence of strongest wind direction and clues to regional paleoclimate and weather.

CONCLUSIONS

Previous papers by the authors defined and presented evidence to quantify shoreline superelevation of the 1986-1987 highstand on GSL, documenting that geomorphic shoreline evidence is not at the still water level of the lake and does not define a horizontal plane from which to measure post-depositional change with confidence. This paper extends the findings of earlier work with empirical evidence of wind patterns across Gilbert and Gunnison Bays from wind records from weather stations at Hat and Gunnison Islands. We further explore the processes of shoreline superelevation. Because GSL is fetch-limited, its geomorphic evidence at the highstand has a signal of wind direction and strength. Wind records of weather stations on GSL indicate the strongest winds across GSL are from the north and northwest and correlate with geomorphic evidence. Patterns of shoreline superelevation of gravel ridges and other geomorphic features along the shores of GSL are durable evidence of the direction of the strongest storm winds as well as effects of fetch. Examination of shoreline superelevation of additional modern- and paleo- fetch-limited lakes will lead to better understanding of their regional wind direction and strength and perhaps regional climate.

ACKNOWLEDGMENTS

We gratefully acknowledge Robert Baskin for his knowledge of GSL and his assistance with figures. We appreciate how William Alder, David Shearer, and John Horel shared knowledge via personal communications. This paper was completed with the knowledge and encouragement of Peter W. Homewood and Monique Mettraux, Geosolutions, Trd. Cameron Scharrer assisted with figures 13 and 14. We appreciate the 1986-2000 collaboration of the Utah Geological Survey, the University of Utah, and U.S. Geological Survey colleagues who worked together to better understand GSL 1986-1987 shorelines as evidence of lake processes. We are grateful to Ian Schofield and Daren Nelson, whose reviews improved this paper.

REFERENCES

Adams, K.D. and Wesnousky, G.G., 1998, Shoreline processes and the age of the Lake Lahontan highstand in the Jessup embayment, Nevada: Geological Society of America Bulletin, v.110 (10), p 1318-1332.

Adams, K.D., Wesnousky, G.G., and Bills, B.G., 1999, Isostatic rebound, active faulting, and potential geomorphic effects in the Lake Lahontan basin, Nevada and California: Geological Society of America Bulletin, v. 111, issue 12, p. 1739-1756.

Adams, K.D., and Bills, B.G., 2016, Isostatic rebound and palinspastic restoration of the Bonneville and Provo shorelines in the Bonneville basin, UT, NV, and ID, in Oviatt, C.G., Shroder, J.F., Jr., editors, Lake Bonneville: A scientific update. Developments in Earth Surface Processes 20: Elsevier, p. 145-164.

Alder W., 1986, 1987, daily journal entries: unpublished: Salt Lake City UT.

Applequist L.R., 2013, Generic framework for mesoscale assessment of climate change hazards in coastal environments: Journal of Coastal Conservation, v. 17, p. 59–74.

Arnow, T., and Stephens, D., 1990, Hydrologic characteristics of the Great Salt Lake, Utah: 1847-1986: U.S. Geological Survey Water-Supply Paper 2332, 32 p., map scale 1:125,000

Atwood, G., 2006, Shoreline Superelevation, evidence of coastal processes of Great Salt Lake, Utah Geological Survey, Miscellaneous Publication 06-9, 231 pp.

Atwood, G., and Mabey, D.R., 2000, Shorelines of Antelope Island as evidence of fluctuations of the level of Great Salt Lake, *in* King, J.K., and Willis, G.C., eds., Geology of Antelope Island, Davis County, Utah: Utah Geological Survey Miscellaneous Publication 00-1, p. 85-97.

Bertin, X., Martins, K., de Bakker, A., Chataigner, T., Guérin, T., Coulombier, T. and de Viron, O., 2020, Energy transfers and reflection of infragravity waves at a dissipative beach under storm waves: Journal of Geophysical Research: Oceans, v. 125, no. 5, e2019JC015714.

Bretschneider, C.L., 1952, The generation and decay of wind waves in deep water: Transactions American Geophysical Union, vol 33, p 381-389.

CERC (U.S. Army Coastal Engineering Research

Center), 1984, Shore protection manual, 4th edition: U.S. Government.

Chen, C.Y., and Maloof, A.C., 2017, Revisiting the deformed high shoreline of Lake Bonneville: Quaternary Science Reviews, v. 159, p. 169-189.

Cooper J.A.G., Lewis D.A., and Pilkey O., 2007, Fetch-limited barrier islands: Overlooked coastal landforms: Geological Society of America Geology, Geology Today, v. 17, no. 3, p. 4-9.

Currey, D.R., 1982, Lake Bonneville: selected features of relevance to neotectonic analysis of Great Salt Lake and vicinity, in Gwynn, J.W., ed., Great Salt Lake: a scientific, historical and economic overview; Bulletin 116: Salt Lake City, Utah Geological and Mineral Survey, p 69-82.

Fiedler, J.W., Young, A.P., Ludka, B.C., O'Reilly, W.C., Henderson, C. Merrifield, M.A. and Guza, R.T. 2020, Predicting site-specific storm wave run-up: Natural Hazards, v. 104, p. 493–517.

Fontaine, E., 2013, A theoretical explanation of the fetch- and duration-limited laws: Journal of Physical Oceanography, v.43, p. 233-247.

Freire, P., Ferreira, Ó., Taborda, R., Oliveira, F.S.B.F., Carrasco, A.R., Silva, A., Vargas, C., Capitão, R., Fortes, C.J., Coli, A.B., and Santos, J.A., 2009, Morphodynamics of fetch-limited beaches in contrasting environments: Journal of Coastal Research SI 56, Proceedings of the 10th International Coastal Symposium, p. 183-187.

Gilbert, G.K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Jewell, P.W., 2007, Morphology and paleoclimatic significance of Pleistocene Lake Bonneville spits, Quaternary Research v. 68, p. 421-30.

Komar, P.D., 1998, Beach processes and sedimentation (2nd edition): Prentice Hall, Upper Saddle River, New Jersey, 544 p.

Lo Re, C., Cannarozzo, M., and Ferreri, G.B., 2016, Present-day use of an empirical wave prediction method: Maritime Engineering, v. 169, issue MA1, 14 p.

Mabey, D.R., 1986, Notes on the historic high level of Great Salt Lake: Utah Geological and Mineral Survey, Survey Notes, v. 20, no. 2, p. 13-15.

MesoWest, www.mesowest.utah.edu

Munk, W.H., 1951, Origin and generation of waves: Proceedings of the 1st Coastal Engineering Conference, Long Beach, California, p. 1–4, doi: 10 .9753/ icce, v1 .1.

Murchison, S.B., 1989, Fluctuation history of Great Salt Lake, Utah, during the last 13,000 years: Salt Lake City, University of Utah, Ph.D. dissertation, 137 p.

Oviatt, C.G., Atwood, G., and Thompson, R.S., 2021, History of Great Salt Lake, Utah, USA, since the termination of Lake Bonneville, in Rosen, M.R., Finkelstein, D., Park-Boush, L., and Pla-Pueyo, S., editors, Limnogeology: Progress, Challenges and Opportunities: A tribute to Beth Gierlowski-Kordesch: Syntheses in Limnogeology no. 2, New York, Springer Nature AG, p. 233-271.

Schofield, I., Jewell, P.W., Chan, M., Currey, D.R., and Gregory, M., 2004, Shoreline development, longshore transport and surface wave dynamics, Pleistocene Lake Bonneville, Utah: Earth Surface Processes and Landforms, v. 29, p. 1675-1690.

Shafer, J.C., and Steenburgh, W.J., 2008, Climatology of strong Intermountain cold fronts: Monthly Weather Review, v 136, 784-807.

Sverdrup, H.U. and Munk, W.H., 1947, Wind, sea, and swell theory of relationships in forecasting: US Dept. of the Navy Hydrographic Office Publication, No 601.

Tackman, G.E., 1993, Middle and late Pleistocene hydrologic history of Diamond Valley, Eureka and Elko Counties, Nevada, with climatic and isostatic implications: Salt Lake City, University of Utah, Masters of Science thesis, 192 p.

Tackman, G.E., Currey, D.R., Bills, B.B., and James, T.S., 1998, Paleoshoreline evidence for postglacial tilting in Southern Manitoba: Journal of Paleolimnology, v. 19, 443-463.

Theuerkauf, E. J., Mattheus, C.R., Braun, K.N. and Bueno, J., 2021, Patterns and processes of beach and foredune geomorphic change along a Great Lakes shoreline: Insights from a year-long drone mapping study along Lake Michigan: Shore & Beach, v. 89, no. 2, p. 46-55.

WMO (World Meteorological Organization), 2018, Guide to wave analysis and forecasting. World Meteorological Organization report WMO No 702, 189 p.

Wang, P., 1978, Seiches in the Great Salt Lake: Salt Lake City, University of Utah, Ph.D. dissertation, 119 pp.

Wright, L.D., and Short, A.D., 1984, Morphodynamic variability of surf zones and beaches: a synthesis: Marine Geology, v. 56, p. 93–118.