Analysis of Complex Sand Waves in Raccoon Strait, San Francisco Bay

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ABSTRACT

College of Charleston BEAMS (Benthic Acoustic Mapping and Survey) Program students sailed aboard the eTrac, Inc. survey vessel S/V *Pulse* in December 2014 as part of a multibeam survey of Raccoon Strait, the channel separating Point Tiburon and Angel Island in San Francisco Bay. Multibeam data were processed using CARIS HIPS 9.0 software, revealing complex and dynamic bathymetry consisting of sand waves varying significantly in length, height, symmetry and orientation. Water depths within the strait range from 8 to 65 m and sand waves range in length from less than 5 m to more than 500 m, with one having a height exceeding 30 m. Wave symmetry, dimensions, and orientation were used to analyze the mechanisms influencing morphology including current direction, relative velocity, and channel width. Raccoon Strait is known to have some of the strongest tidal currents in the San Francisco Bay, due to both the narrow 1 km channel width and its proximity to the bay's mouth. The strait's southern margin sand waves are oriented northeastward towards the inside of the bay and northern margin sand waves are oriented southwestward towards the bay mouth, indicating forceful tidal currents in both flood and ebb directions, respectively. The distinctly different flow paths are the result of varying influences of both flood and ebb tidal currents acting within this large estuarine bay. This study shows how high resolution bathymetry can be used to study dynamic inshore sites. Repeated surveys of this area could be used to document migration of these large sand bodies.

INTRODUCTION

Raccoon Strait is located just north of the mouth of San Francisco Bay between Angel Island and Point Tiburon in California (Figure 1). San Francisco Bay is fed by the San Joaquin and Sacramento River systems making it the second largest estuary on the west coast of the United States. These rivers deposit between 2 and 4 megatons of sediment annually, originating from both the Sierra Nevada mountain range and nearby Marin headlands (Barnard et al., 2006; Barnard et al., 2013; Elias and Hansen, 2013). Large fields of sand waves in and around the mouth of the bay are generated by flux of sand from the rivers and shaped by tidal currents (Barnard et al., 2006; Barnard et al., 2013; Elias and Hansen, 2013). The sand waves are shaped by San Francisco Bay's strong mixed semidiurnal tidal currents, which have a range of approximately 3 m and reach up to 2.5 m/s through Raccoon Strait (Elias and Hanson, 2013). Raccoon Strait sand waves are spatially variable due to fluctuating tidal flow velocity and direction wtihin the channel. While much of the bay is dredged regularly to support the port economy, the sand waves in Raccoon Strait remain unaltered. However the waves in Raccoon Strait do provide information about tidal currents and other forces that affect the entire bay.

Sand waves are defined as being are greater than 2.0 m in height with wavelengths of 10 to 100 m, whereas megaripples are 0.5 to 1.5 m high with wavelengths between 1 and 15 m (Ashley, 1990). San Francisco Bay is home to some of the most dramatic sand wave fields in the world, especially concentrated in Raccoon Strait and in the Golden Gate channel at the mouth of the bay. The Golden Gate sand waves and mechanisms forming them have been studied extensively and provide a useful frame of reference in analyzing the similar bedforms in Raccoon Strait. Asymmetrical sand waves at the southern margin of the Golden Gate channel are oriented facing into the bay with flood tidal flow while sand waves at the northern margin are oriented facing the mouth of the bay with ebb tidal flow (Elias and Hansen, 2013). Tidal flow in the northern basin of the San Francisco Bay, which includes Golden Gate channel and Raccoon Strait at its most southern extent, exhibits counter clockwise rotation of tidal currents that hug the land cycling through the bay (Walters et al., 1985; Barnard et al., 2013; Elias and Hansen, 2013). As water enters San Francisco Bay with the flood tide, it has a Coriolis deflection to the right so that it hugs the southern margin of Golden Gate channel, and remains parallel to the shore of the northern basin in a counterclockwise motion for the duration of the tidal cycle (Walter et al., 1985; Li et al., 2014). When the ebb tidal current is pulling water out of the bay through the Golden Gate channel, it continues to hug the shore until it washes out past the northern margin of the bay. Raccoon Strait's proximity to the north of the bay's mouth makes it one of the last channels traveled by the strong ebb tidal currents before reaching the ocean, resulting in sediment transport and bedform feature formation in the ebb-orientation. Bedform distribution and morphology reveal information about tidal dominance and flow magnitude, bottom currents, spatial variability of currents, and sediment transport (Ashley, 1990; Elias and Hanson, 2013). The direction of current flow can be determined by comparing the relative lengths of a sand wave's stoss (back slope) side to its slip face side, as currents flow from the stoss side of a wave to the slip face side. Thus, asymmetric sand waves indicate unidirectional current flow, and symmetric waves indicate bidirectional flow.

Parker and others (2003) found that the Raccoon Strait bedforms are made up of fine to coarse-grained sand ranging from about 0.125 to 2.0 mm with coarser sediment towards the southern mouth of the strait. In the Golden Gate channel, high current velocity has scoured to the bedrock almost 100 m deep in the narrow region directly under Golden Gate Bridge (Barnard et al., 2006). Coarser sand grains between 0.5 mm and 4 mm are dropped out of the water column where the channel opens into the bay, decreasing current velocity and the capacity to transport large particles (Barnard et al., 2006).

METHODS

College of Charleston students were invited to participate in a seafloor mapping survey by BEAMS Program industry partner eTrac, Inc., whose offices are located in San Rafael, CA. Eight BEAMS students joined eTrac marine survey personnel aboard the eTtrac survey vessel S/V *Pulse* in December 2014 to collect bathymetric (water depth) data using an R2 Sonic 20/24 multibeam sonar system. These data were post-processed using CARIS HIPS 9.0 software to generate 2 m 0.5 m resolution CUBE BASE surfaces of seafloor bathymetry. To find unique flow patterns throughout the Raccoon Strait channel, the surface was analyzed as three distinct study areas, referred to as Areas 1, 2, and 3, each of which has distinct sand wave morphologies (Figure 2).

Sand wave orientations were determined by creating cross-sectional profiles with HIPS. The base of the wave was measured as the horizontal trough-to-trough distance, and the wave height was measured as the vertical distance between the base of the wave to the wave crest (Figure 3). The horizontal length along the base from the trough of each side of a wave to its crest position determines the wave's orientation, since the sand wave's slip face side is shorter than (or equal to) its back slope, or stoss side. A 2m resolution slope surface layer of the Raccoon Strait bathymetry was created using CARIS Base Editor 4.1 to more clearly illustrate the slip face of each sand wave (Figure 4). The stoss length and slip face length were both compared to the wave height to determine if one side of the sand wave grows more than the other relative to its height.

A symmetry index was developed by calculating the ratio of the stoss side length to the slip face side length for each sand wave. An index closer to 1 indicates symmetrical waves and therefore bidirectional flow, while smaller indices signify asymmetrical waves and a stronger unidirectional flow. The symmetry index was plotted against sand wave height to construct a regression analysis of the data to determine if a correlation exists between wave height and symmetry.

The width of Raccoon Strait was compared to the wavelength of each of the 27 sand waves to determine if wavelength is a function of channel width. To measure channel width, the 2m CUBE BASE surface was exported and overlain onto Google Earth. The width of the channel at the crest of each sand wave was measured using the ruler tool, measuring the shortest distance across the channel shore to shore. The width of the channel at the different locations of the sand waves was plotted against the wavelengths and examined using a regression analysis.

RESULTS

More than one hundred sand waves occur in the 3 km length of the channel with superposed sand waves and megaripples on most. For this study, seven sand waves were measured in Area 1 and ten were measured in each of Areas 2 and 3.

Area 1

All seven of the Area 1 measured sand waves were asymmetric, with five oriented southwest towards the mouth of the bay, and two oriented northeast towards the inside of the bay (Table 1). The largest sand wave present in Raccoon Strait, referred to here as the mega-sand wave, is found in Area 1. This mega-sand wave is 30 m tall, and over 500 m in length, with a wavelength exceeding 300 m. It is positioned on the channel's southern margin, oriented to the southwest. All of the sand waves in Area 1, including the two facing northeast, are superposed on the slip face of the 30 m mega-sand wave. The orientation of the waves indicates a net ebb tidal flow with a strong flood tidal flow at the southern margin of the channel.

Area 2

The smallest measured sand waves in Raccoon Strait are under 1 m in height and are found in Area 2. They are oriented both to the northeast (flood-oriented) and southwest (ebb-oriented) (Table 2). Waves oriented with flood flow are concentrated in the southern margin of Area 2 while waves oriented with ebb flow are concentrated at the northern margin. Varying orientations of the waves as well as the presence of symmetrical waves reflect the transitioning flow directions in Raccoon Strait associated with the ebb and flood tide. Further review of the bathymetry at higher resolution revealed ripples ranging from 0.5 m to less than 0.1 m superposed on the small sand waves in Area 2 that probably change orientation daily with the ebbing and flooding tides.

Area 3

All ten of the measured sand waves in Area 3 face southwest displaying strong net ebb tidal flow entering the northeast entrance to Raccoon Strait (Table 3). The waves in Area 3 are much larger than those in Area 2 indicating possibly a stronger current at the northern margin of the channel than in the middle.

Analysis

The height of each sand wave measured was plotted against its symmetry, and resulted in a weak negative correlation ($R^2 = 0.244$, n=27) (Figure 5), suggesting that smaller sand waves are more likely to be symmetric than larger waves. The length of the stoss side of the waves was found to have a very strong positive correlation to wave height ($R^2 = 0.972$, n=27) (Figure 6A), and the slip face length was also highly correlated ($R^2 = 0.889$, n=27) (Figure 6B). Larger wavelengths were only weakly correlated to increasing channel width ($R^2 = 0.385$, n=27) (Figure 7).

DISCUSSION

Bedform morphology reveals the mechanisms and processes shaping them including bottom current velocity, tidal patterns, and sediment transport. The scale of sand wave morphological changes over the span of less than 3 km reflects the spatial variability of the processes contributing to their shape. Raccoon Strait as a whole exhibits net ebb tidal driven currents since the majority of the waves measured are oriented southwest and are formed asymmetrically by ebb tidal flow toward the mouth of San Francisco Bay.

Sand Wave Orientation

The semi-diurnal tidal cycle in the bay favors ebb-dominant flow (Walters et al., 1986), which was observed in the net orientation of Raccoon Strait's sand waves. The sand wave orientation pattern observed in Raccoon Strait is similar to observations by Elias and Hansen (2013), specifically in Area 2 where the waves oriented with the ebb tide are concentrated at the northern margin, while the few waves oriented with the flood tide are concentrated at the southern margin. Also, in Area 1 the only flood tide oriented waves are the southernmost waves of the entire study area. The small flood-oriented sand waves in Raccoon Strait can also be associated with the channel's proximity to the mouth of the bay, still impacted by strong flood tidal currents. Large, rough sand waves diminish flow so it could also be possible that the flood tide does not flow with a higher velocity and farther into Raccoon Strait because the 30 m high sand wave concentrated at the southern channel opening decreases the velocity of the flood tide in the strait (Bernard et al., 2006). While this contradicts some studies on fluid dynamics and sediment transport, the scour behind the large sand wave in Area 1 may the source of the sand for Area. For this to happen, the current through the scoured part of the channel would maybe be too strong for sediment to be deposited, but weakens when the channel opens up to form the large wave. However, further work to examine in greater detail the grain size and current velocities would have to be done to be certain.

The spatially variable flow of tidal currents in Raccoon Strait results in spatially variable sediment transport. At the northern mouth of the strait high current velocity scours out an area almost 1.5 km long. The sand that was scoured from the northern end of Raccoon Strait is likely the sand that formed the 30 m high wave on the southern end. A strong positive correlation between wavelength and channel width in Raccoon Strait (with the mega-wave removed) indicates that as the channel width increases, sand waves get larger. The 30 m mega-sand wave is located in the broadest region of Raccoon Strait where Belvedere Cove opens and the channel width nearly doubles. These results indicate that as channel width decreases, sand wave size decreases. However, channel width increases would presumably cause flow velocities to decrease, which would instead result in smaller sand waves. Scouring and deposition also play a large role along with flow velocity in the sand wave growth in Raccoon Strait. The height of the wave caused by stronger ebb tidal flow may inhibit weaker flood tidal flow from having more force through the channel.

Area 2's smaller sand waves adjacent to the scour in Raccoon Strait could indicate a zone of weaker flow on the area's northern margin, allowing for the deposition of both large and small sand particles. The bidirectional flow revealed by those sand waves might be constricted to the northern margin of Area 2 while a strong ebb tidal current dominates the southern margin. Studies of the backscatter intensity or of sediment samples in Raccoon Strait could confirm this, but these data were unavailable for this study.

Sand Wave Symmetry

Sand wave height and asymmetry could also be functions of fluctuating current velocity through Raccoon Strait. The strong correlation between the back slope length and the wave height indicates that as back slope length increases, so does wave height.

However, the same correlation calculated between slip face length and wave height was much weaker suggesting that the slip face and back slope grow at different rates relative to height in Raccoon Strait, creating large and asymmetrical waves. When plotted against each other, the symmetry index and wave height have a negative correlation indicating that the formation of symmetrical sand waves in Raccoon Strait is more likely if the waves are smaller. A study performed by Wever (2004) off the coast of the Netherlands showed that sand wave migration decreases with increasing height, and that sand waves higher than 1 m change orientation much less frequently than smaller waves that might change orientation daily. The growth of Area 2 waves may be inhibited by the transition of tidal direction causing lower flow velocity, resulting in smaller and more symmetrical waves. The superposed ripples in Area 2 visible in the higher resolution bathymetry are oriented in the directions of both tides in almost even proportions, indicating constant and active transport in a transitional zone between the two tidal flow directions within the strait. The currents that formed the larger sand waves in Area 1 and Area 3 are not transitional so the waves are able to grow to greater heights and have orientations that are not as greatly impacted by the daily reverses in tidal flow.

CONCLUSION

Bedform shapes, sizes, and orientations are extremely useful for studying transport mechanisms, current velocities, and large-scale forces influencing marine dynamics. The sand waves in Raccoon Strait potentially provide information about the movement of sediment within the San Francisco Bay necessary for enhanced information on habitat building and for the port system, particularly in dredging operations.

Multibeam surveys and further studies on the eastern edge of the bay might augment knowledge of how the Coriolis Effect influences the movement of water in estuaries if evidence can be found of bed forms produced by stronger flood tidal flow resulting from Coriolis deflection within the bay. The study of the Coriolis Effect on sediment transportation in busy ports could be used to predict dredging requirements and channel building. Similarly, knowing the causes and functions of sand wave kinetics is vital in the San Francisco Bay due its high economic value and since it is shrinking from disproportional deposition of sand from the rivers to sand leaving the bay.

The results shown here indicate a strong ebb tidal flwo through Raccoon Strait, as would be expected with a mixed semidiurnal tide. However, the Coriolis force shapes much of the bay's bathymetry, Raccoon Strait's being no exception. High resolution multibeam sonar data is effective for evaluation dynamic change of seabed morphology and future studies of Raccoon Strait could show the change over time. The value of the data would be increased with sediment analyses and backscatter to confirm the role sediment size has on the wave formation in Raccoon Strait.

REFERENCES CITED

Ashley, G.M., 1990, Classification of large-scale subaqueous bedforms: a new look at an old problem – SEPM bedforms and bedding structures. *Journal of Sedimentary Research*, v. 60.

Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E., & McKee, L. J., 2013, Sediment transport in the San Francisco Bay coastal system: An overview. *Marine Geology*, v. 345, p. 3-17.

Barnard, P. L., Hanes, D. M., Rubin, D. M., & Kvitek, R. G., 2006, Giant sand waves at the mouth of San Francisco Bay. *Eos*, v. 87, p. 285-286.

Elias, E. P., & Hansen, J. E., 2013, Understanding processes controlling sediment transports at the mouth of a highly energetic inlet system (San Francisco Bay, CA). *Marine Geology*, v. 345, p. 207-220.

Li, M., Ge, J., Kappenberg, J., Much, D., Nino, O., & Chen, Z., 2014, Morphodynamic processes of the Elbe River estuary, Germany: the Coriolis effect, tidal asymmetry and human dredging. *Frontiers of Earth Science*, v. 8, p. 181-189.

McCave, I. N., & Langhorne, D. N., 1982, Sand waves and sediment transport around the end of a tidal sand bank. *Sedimentology,* v. 29, p. 95-110.

Parker, K. A., White, L. D., Vavro, M., Tran, J., Basconcillo, N., Kheradyar, T., and Pestrong, R., 2003, Sediment Distribution in Central San Francisco Bay in the Vicinity of Raccoon Strait. Abstract ED42A-1203 presented at Fall Meeting, AGU, San Francisco, CA, 8-12 December.

Walters, R. A., Cheng, R. T., & Conomos, T. J., 1985, Time scales of circulation and mixing processes of San Francisco Bay waters. Temporal dynamics of an estuary: San Francisco Bay. pp. 13-36. Springer Netherlands.

Wever, T. F., 2004, Bedforms and bedform migration: a data review. International workshop on Marine Sand Wave and River Dune Dynamics, University of Twente, Enschede, The Netherlands.

TABLES

Table 1. Area 1 sand waves reflect net ebb flow with strong asymmetry in the southern margin of Raccoon Strait.

Wave ID	Height (m)	Back Slope (Stoss Side) Length (m)	Slip Face Length (m)	Symmetry Index	Flow Direction	Tidal Current Orientation
1	1.40	16.0	4.0	0.250	NE	flood
2	0.25	8.0	4.0	0.500	NE	flood
3	33.60	317.0	63.0	0.199	SW	ebb
4	4.40	65.2	6.8	0.104	SW	ebb
5	3.95	53.8	10.5	0.195	SW	ebb
6	2.15	18.0	6.0	0.333	SW	ebb
7	4.85	30.0	8.0	0.267	SW	ebb

Table 2. Area 2 sand waves are the smallest in Raccoon Strait. While Area 2 is dominated by ebb flow, several waves are also oriented with flood tide and bidirectional flow.

Wave ID	Height (m)	Back Slope (Stoss Side) Length (m)	Slip Face Length (m)	Symmetry Index	Flow Direction	Tidal Current Orientation
1	2.00	19.0	8.0	0.421	NE	flood
2	2.30	9.0	6.0	0.666	NE	flood
3	1.62	9.8	8.2	0.837	NE	flood
4	0.36	3.1	2.8	0.905	SW	ebb
5	0.48	6.0	6.0	1.00	BD	both
6	2.54	40.0	14.0	0.350	SW	ebb
7	1.56	10.0	8.0	0.800	SW	ebb
8	0.87	8.0	8.0	1.00	BD	both
9	2.30	25.6	14.3	0.559	SW	ebb
10	1.11	22.1	5.9	0.267	SW	ebb

Table 3. Area 3 sand waves are all oriented southwest with the ebb tide and are strongly symmetrical.

Wave ID	Height (m)	Back Slope (Stoss Side) Length (m)	Slip Face Length (m)	Symmetry Index	Flow Direction	Tidal Current Orientation
1	0.69	11.4	4.6	0.403	SW	ebb
2	1.48	12.0	11.0	0.917	SW	ebb
3	0.44	10.0	4.0	0.400	SW	ebb
4	2.50	18.0	4.0	0.222	SW	ebb
5	0.69	7.0	5.0	0.714	SW	ebb
6	3.75	23.0	15.0	0.652	SW	ebb
7	3.09	40.0	20.0	0.500	SW	ebb
8	3.40	47.7	19.0	0.398	SW	ebb
9	2.30	40.5	9.5	0.235	SW	ebb
10	1.34	23.0	7.5	0.326	SW	ebb

FIGURES

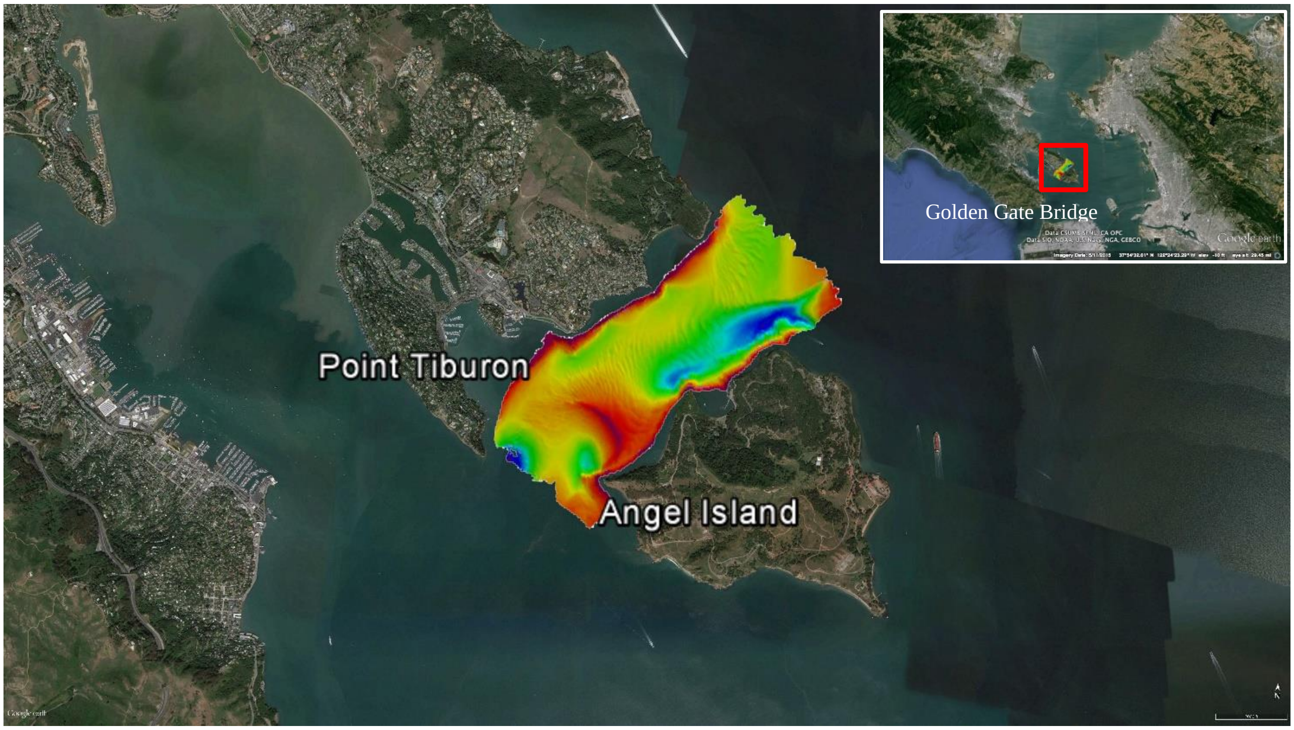

Figure 1. Raccoon Strait is located in San Francisco Bay between Point Tiburon and Angel Island. The inset map shows the surveyed study area outlined in red. Base layer images from Google Earth.

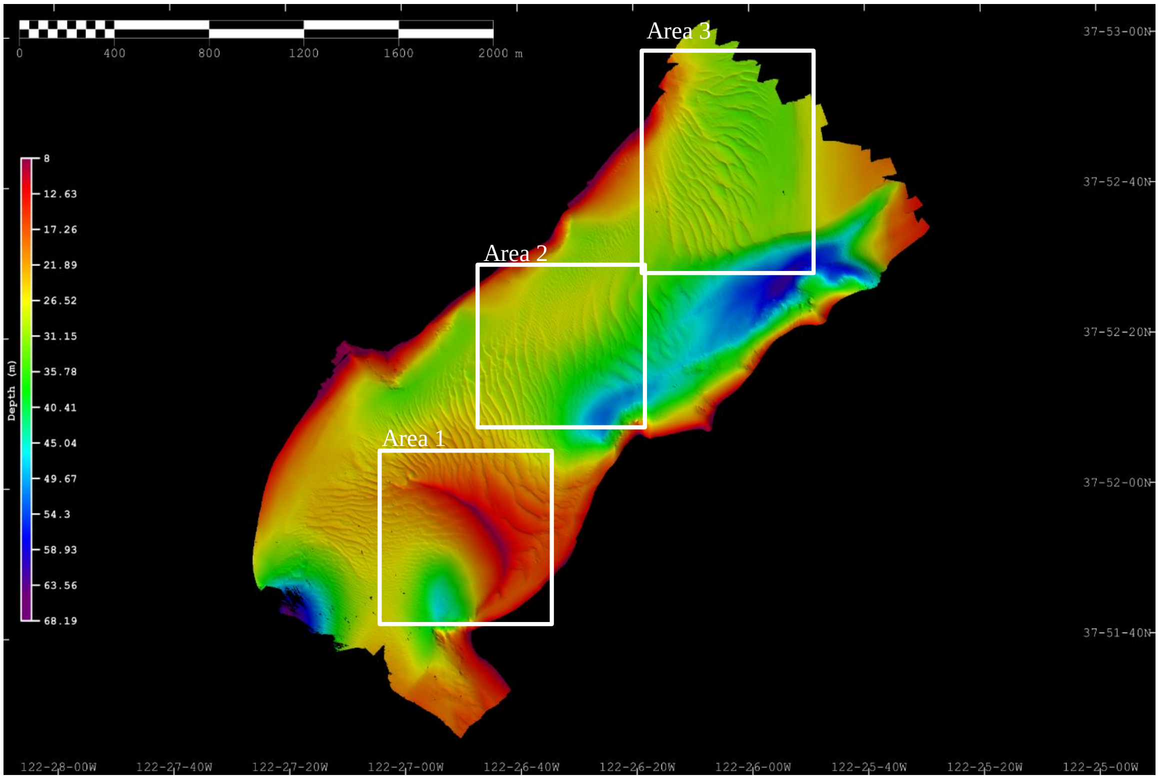

Figure 2. The sand waves of the Raccoon Strait, shown on a 2 m resolution CUBE BASE surface, were analyzed in three regions with distinct wave orientation and morphology. Vertical exaggeration = 2X.

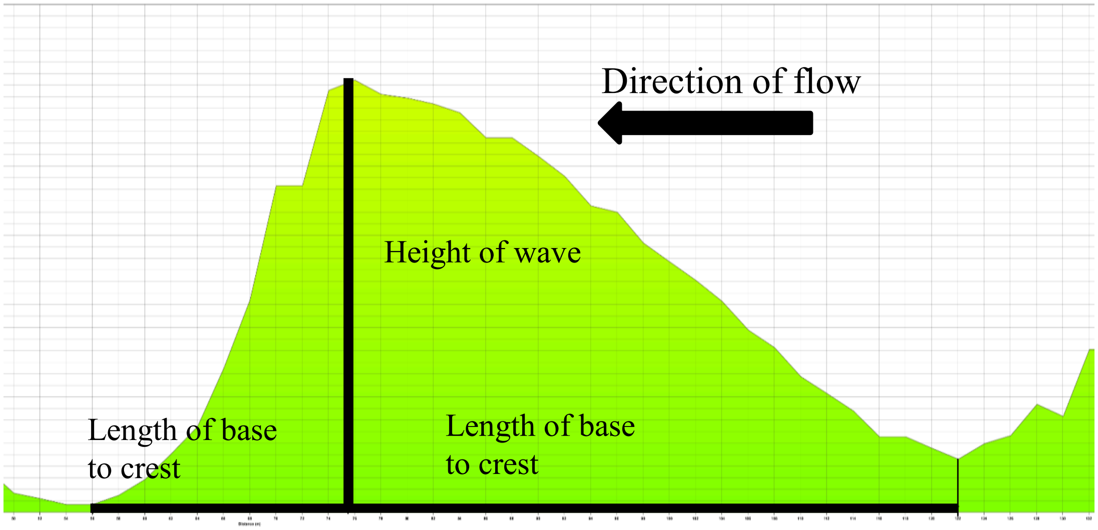

Figure 3. The orientation of a sand wave was determined by measuring the horizontal length of each side from the trough to the crest. The slip face side of a sand wave is shorter than the back slope, or stoss side, so the direction of flow is defined by comparing the lengths of the two bases.

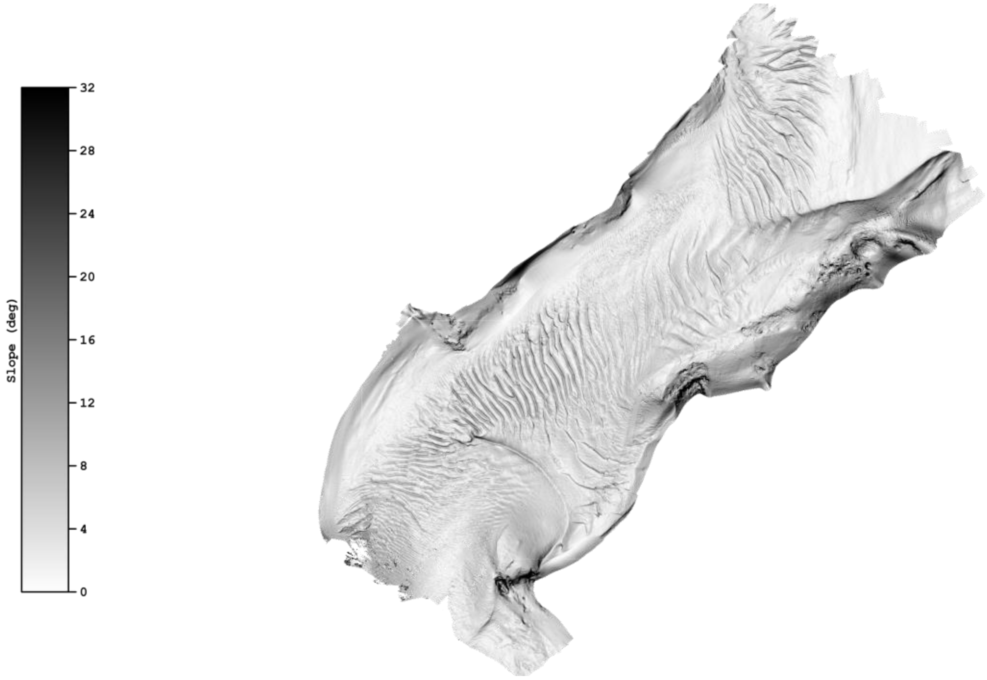

Figure 4. The slope layer calculated the change in degrees of slope on the original BASE surface and was used to more easily identify the steeper slip face of each sand wave.

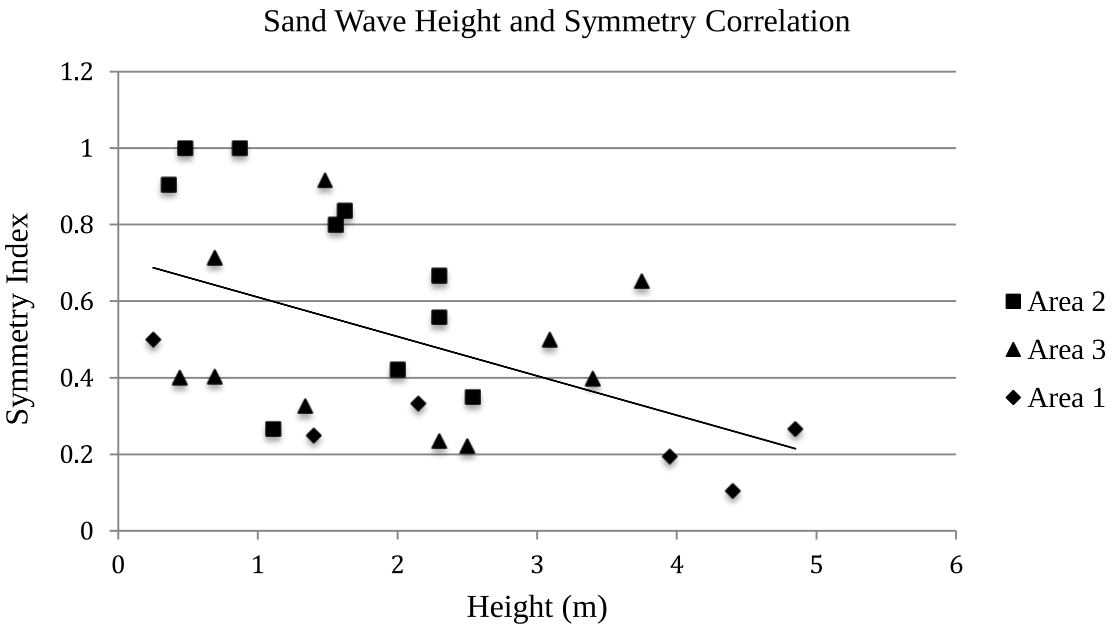

Figure 5. A weak negative correlation ($R^2 = 0.244$, n=27) was found to exist between wave height and symmetry. A small sand wave is more likely to be symmetrical than larger waves. Note that the 30 m tall sand wave from Area 1 has been omitted as an outlier.

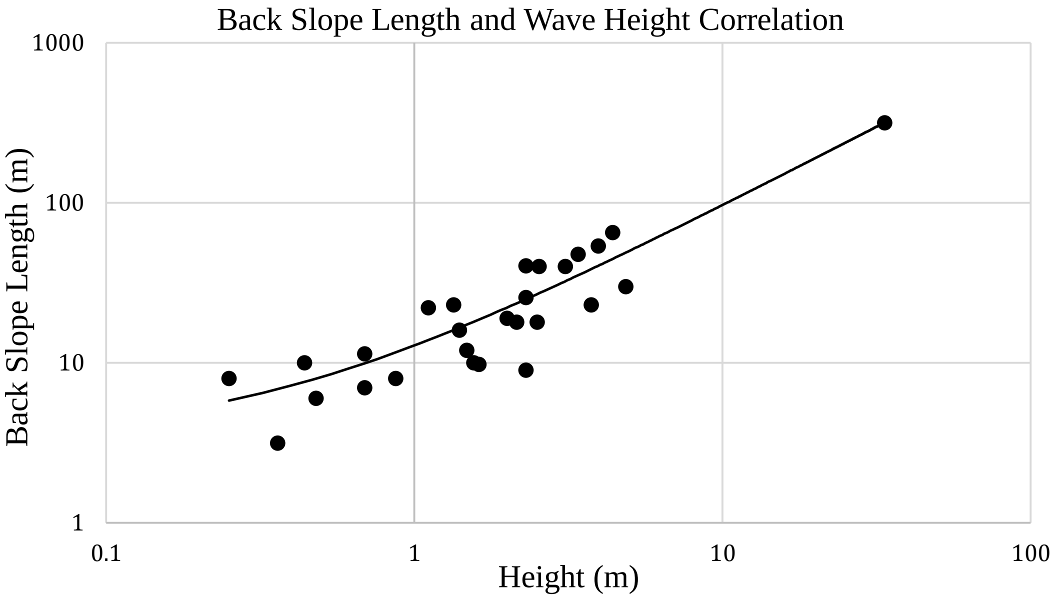

Figure 6. The length of the back slope, or stoss side of a sand wave has a strong positive correlation to the height (R^2 = 0.972, n=27) meaning that higher sand waves have longer stoss sides. The same correlation calculated using the slip face side instead of the back slope side produced a weaker correlation (R^2 = 0.889, n=27), which is a function of increasing asymmetry with height. Both are logarithmic regressions.

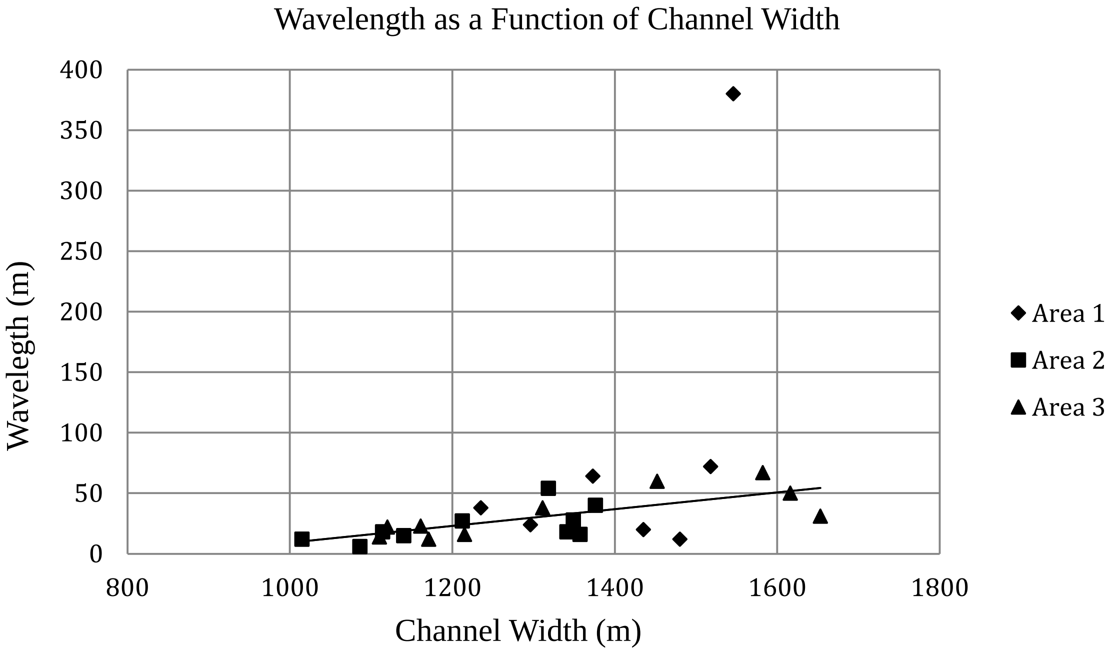

Figure 7. Increasing wavelength is weakly correlated to increasing channel width in Raccoon Strait (R^2 = 0.385, n=27).