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The Occurrence, Morphology, and Sedimentology of Sediment Streaks in the Swash Zone

by

David Alton Pepper

A Dissertation
Submitted to the Faculty of Graduate Studies and Research through the Department of Geography in Partial Fulfillment of the Requirements for the Degree of Master of Arts at the University of Windsor

Windsor, Ont., Canada

1996

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Abstract

Ephemeral, flow-parallel streaks of sorted sediment are common in the swash zones of many beaches, although they are largely undocumented in the literature. Streaks were studied under a variety of conditions on four beaches along the northern shore of Lake Erie. They were always visible on two beaches and never visible on the others. As similar wave conditions were observed on all beaches, this suggests that the occurrence of visible streaks is governed by beach characteristics, particularly sedimentology, rather than wave parameters or swash velocity. Streaks were found to consist of sediment that was more coarse-grained and richer in dark minerals than sediment from the adjacent spaces. Mobile sediment in the swash zone had a similar mineralogical composition to streak sediment, but was not similar in shape, and was similar in size on only one beach. Streak width (generally 2 to 4 cm) and spacing (generally 1 to 2.5 cm) were largely unaffected by variations in wave conditions and swash velocity, but were significantly greater on fine-grained than coarse-grained beaches. Attempts to detect flow-parallel sedimentary variations in the swash zone when streaks were not visible were unsuccessful. Although the mechanism responsible for streak formation is unknown, it is likely related to one of three processes: turbulent bursting in the boundary layer; helicoidal flow in the nearshore zone; or laminar, oscillatory flow streaking.
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I would first like to thank my advisor, Dr. Alan Trenhaile, for his guidance and support; his willingness to participate in field work, often on very short notice, was crucial to the completion of this project. I would also like to thank Dr. Chris Lakhan, who was always available for consultation during late-night hours, Dr. Frank Simpson, who provided valuable input during various stages of the thesis, and Dr. P.D. Lavalle, who guided me through several statistical problems. Further, I would like to thank Mr. Dave Webster for his computer assistance, and my fellow graduate students for their advice and friendship; of particular note, I would like to mention Mr. Andrew Brooks, who provided valuable suggestions regarding mobile sediment collection, and Mr. Derek Nardini, who provided answers to several of my computer enquiries. I would also like to thank Parks Canada for allowing me free admission to Point Pelee National Park, where much of the research was conducted. Last, but not least, I would like to thank my parents, Mr. and Mrs. Barry and Lorraine Pepper, who contributed to this project in both a specific sense (participation in field work, loan of a vehicle, and construction of sampling equipment) and a more general way, through their support and encouragement.
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1.0 Introduction

Flow-parallel streaks of sorted sediment, two to four centimetres in width, continuously form and re-form in the swash zones of many sandy beaches. Visible streaks apparently consist of higher concentrations of dark-coloured sediment grains than the intervening spaces. Surprisingly, however, streaks are largely undocumented in the literature and little appears to be known about their cause or nature. This thesis is an attempt to analyze the occurrence, morphology, and sedimentology of swash zone sediment streaks on selected beaches along the northern shore of Lake Erie.
2.0 Region Under Study

Data were collected in the swash zones of beaches along the shores of Lakes Erie, although the study could have been conducted at virtually any coastal location where breaking waves produce a significant swash zone. Four beaches were studied: the East, the Northwest, and the West Beaches of Point Pelee National Park (42°00' N, 82° 30' W); and Seacliff Beach, located in the town of Leamington (42° 01' N, 82° 32' W) (Fig. 1).

Two major components of the study areas are relevant to this thesis: the wave conditions, which are manifested in the resultant beach state; and the sedimentary characteristics of the beach. All study beaches on Point Pelee have similar summer beach states. All are steep, reflective and incident-wave-dominated. Plunging breakers are dominant, and all beaches have a short uprush-downrush cycle and subharmonic edge wave activity, as commonly expressed by cusp formation. Similarly, Seacliff Beach is incident-wave-dominated and has a short uprush-downrush cycle; however, unlike the other beaches, it is gently sloping and dissipative. Breakers at Seacliff Beach tend to be either spilling or plunging.

The beaches experience somewhat different modal wave regimes. Most importantly, wave height on the exposed beaches of Point Pelee tends to be greater than at Seacliff Beach, which is partially protected from direct wave activity by the Leamington Dock. The beaches also differ in terms of sediment size and mineralogy. Generally, the East, Northwest and West Beaches are composed of coarse, mixed sands, although they have different grain size distributions and heavy mineral components. Sediment on Seacliff Beach, on the other hand, is composed largely of medium- and fine-grained sand. The
Sedimentary characteristics of the study beaches will be discussed further in the Analysis and Discussion section. Thus, while the beaches are similar in many respects, there are significant differences, particularly between the Point Pelee beaches and Seacliff Beach.

Source: Rough, Stansbury & Associates, 1973

Fig. 1: The study area.
3.0 Literature Review

Although several workers have studied the form and origin of flow-parallel sedimentary features in fluvial and marine environments, sediment streak occurrence in the swash zone has not been discussed in the literature. Laboratory and field work have, however, identified three mechanisms that may potentially explain sediment streak formation: turbulent bursting; secondary, helicoidal flow; and laminar, oscillatory flow streaking.

Turbulent bursting, and the resultant pattern of alternating high and low velocity streaks in the boundary layer, have been examined in several laboratory experiments (Kline et al., 1967; Grass, 1971; Williams & Kemp, 1971; Offen & Kline, 1975; Sumer & Oguz, 1978; Sumer & Deigaard, 1981; Weedman & Slingerland, 1985). Various authors have also speculated on the sedimentological and geological implications of bursting in the nearshore zone (Colinson & Thompson, 1982; Leeder, 1982; Allen, 1985; Trenhaile, in press). The earliest laboratory research was conducted by Kline et al. (1967), who used the flow of hydrogen bubbles to observe a series of regularly-spaced, low-velocity streaks close to the bed. The streaks appeared to be generated through a process of "gradual 'lift-up', then sudden oscillation, bursting and ejection" (Kline et al., 1967, p.741). The lateral spacing of these streaks ($\lambda$) was primarily determined by the shear velocity of the flow ($u_\ast$) and the kinematic viscosity of the fluid ($\nu$), and could be represented by the equation:

$$\lambda \approx \frac{u_\ast}{\nu} \times 100.$$ (Equation 1)
These findings were later supported by Grass (1971), who augmented the use of the hydrogen bubble technique with high-speed photography.

A more detailed laboratory study of the nature of turbulent bursting, which also employed hydrogen bubble flow visualization, was conducted by Offen and Kline (1975). Their model for the burst cycle included the formation of a stretched and lifted vortex, which could be interpreted as a transverse vortex, a streamwise vortex, or wavy growth, depending upon the angle at which it was viewed. The formation of this lifted vortex is associated with the elevation of a low velocity streak in the viscous sublayer by a three-dimensional disturbance, which eventually produces a complex recirculation cell. As this cell circulates, its rapidly flowing leading edge strikes the bed, causing a sweep event, while the lower velocity flow associated with the cell's trailing edge settles on the bed, initiating a burst (Fig. 2). Although Offen and Kline did not represent the turbulent bursting process mathematically, they provided a functional model for the type of boundary layer flow which is responsible for the formation of streaks.

Several researchers have studied the relationship between flow in the boundary layer and sediment transport. The first to do so were Williams and Kemp (1971), who incorporated many of Kline et al.'s (1967) and Grass' (1971) conclusions into their model for ripple formation on a flat sandy bed. While their laboratory work did not specifically relate to boundary layer streaking, it did provide support for the ability of turbulent bursting to transport sediment.

Sumer studied boundary layer sediment transport by means of a two-part laboratory study, the first conducted with Oguz (1978), and the second with Deigaard (1981). Using
Fig. 2: Turbulent Bursting (Source: Allen, 1985)
a stereo-photogrammetric system coupled with a stroboscope, the researchers were able to observe and measure particle suspension over smooth and rough boundaries. They concluded that the overhead passage of a sweep can expose particles on the bed to adverse pressure gradients, causing them to become suspended within the main flow structure. These suspended particles may then be acted upon by lifting forces from successive sweeps, enabling them to remain in suspension. Sumer and Oguz (1978) and Sumer and Diegaard (1981) were thus able to explain the specific boundary layer mechanism by which sediment may be suspended over both smooth and rough boundaries.

Weedman and Slingerland (1985) confirmed Kline et al.'s (1967) equation for streak spacing, while pointing out its limitations. They studied the spacing of sand streaks generated in a wave flume, using sediment of varying size and abundance. Their results for small to moderate amounts (bedload concentrations less than 15%) of fine- to medium-grained sand were consistent with those of Kline et al.; however, they did find that increasing the size or abundance of sand grains in the flume led to the formation of more widely spaced, and increasingly irregular streaks. Of particular note, their research indicated that dense lanes of sediment laden fluid, two to eight centimetres wide, often form under high shear velocities and grain concentrations. These "lanes" are virtually identical in width to swash zone sediment streaks, and as such, Weedman and Slingerland's work may provide a crucial bridge between laboratory and field research.

Although a fairly large amount of research has been conducted on turbulent bursting in the laboratory, there has been much less discussion of its possible implications for coastal zones. Nonetheless, several authors have stated that bursting is responsible for
producing a variety of sedimentary structures which may be preserved geologically, including parting lineations (Jackson, 1976; Leeder, 1982; Collinson and Thompson, 1982; Allen, 1985). Jackson suggested that the nature of features which may be produced by bursting in oscillatory wave environments is extremely unpredictable. Allen, however, reported that the average transverse spacing of parting lineations, which ranges from a few millimetres to a centimetre, is inversely proportional to both the grain size of the sediment, and the velocity of the flow. Trenhaile (in press) discussed the bursting process and its possible role in the formation of linear sedimentary features. He suggested that in addition to parting lineations, the sorting of light carbonate and heavy mineral sands into streaks on the southern coast of St. Vincent may have been caused by turbulent bursting in the boundary layer. He cautioned, however, that not all flow-parallel features (sand ribbons, for example) are related to bursting cycles. Therefore, while reference to boundary layer turbulent bursting is made in the geomorphological and geological literature, its possible role in the formation of sediment streaks in the swash zone is unclear.

A second possible explanation for swash zone sediment streaking involves the formation of secondary flows consisting of pairs of longitudinal, counter-rotating, helical vortices (Fig. 3). While similar vortex pairs often occur during turbulent bursting (Allen, 1985; Weedman & Slingerland, 1985), they also exist on a much larger scale. Dyer (1982), for example, stated that longitudinal vortices are responsible for the formation of flow-parallel sedimentary ridges and furrows with spacings of five to 50 metres. Brenninkmeyer et al. (1977) proposed that high concentrations of suspended sediment are
associated with the presence of vortices and helices within the surf zone. Karcz (1973) suggested that helical vortices may lead to the formation of current-aligned features over an extremely wide range of scales, from current lineations, a few millimetres in width, to longitudinal dunes over 100 metres wide. Of particular relevance, Karcz described features he called "bands", which range from two to eight centimetres in width, and appear to be similar to those observed in the laboratory by Weedman and Slingerland (1985). Perhaps, the scale of a particular current aligned structure is a result of whether it is a manifestation of the kinematic flow pattern within the sublayer, within the boundary layer, or within the main flow (Karcz, 1973). If this is the case, turbulent bursting and secondary helicoidal flows may merely be the same process operating at different scales.

The third explanation for the formation of swash zone streaks is related to a laminar flow process which occurs beneath near-breaking, oscillatory waves (Conley and Inman, 1992). Using video cameras, pressure sensors, current meters, and hot film anemometers on beaches, the investigators determined that grain motion under a wave crest can be divided into three distinct regimes: streaking, rolling, and pluming (Fig. 4). During the
Fig. 4: Streaking beneath near-breaking waves (Source: Conley and Inman, 1992).
streaking phase, grains begin to roll and rapidly become aligned into a series of flow-parallel sand streaks. These become visible when large, light-coloured, grains are separated from small dark ones along lateral shear lines, which delineate the plane between moving and residual sand (Inman et al., 1966). While this sorting mechanism seems appropriate, the spacing of these streaks (approximately 4 - 5 mm) is considerably smaller in magnitude than that of sediment streaks in the swash zone.

In summary, the author is unaware of any literature which refers specifically to sediment streaks in the swash zone. On the other hand, considerable research has been conducted on mechanisms which are responsible for the formation of other, possibly related, flow-aligned sedimentary features in marine environments. This research suggests that turbulent bursting, laminar flow streaking, or the formation of helicoidal secondary flows may be responsible for the formation of streaks in the swash zone.
4.0 Conceptual Basis of the Study

Previous work has indicated that both turbulent and laminar flows commonly consist of alternating, flow-parallel streaks which differ in their capacity to transport sediment. These are known to be responsible for the development of bedforms in marine environments, probably including the streaks of dark-coloured sediment that the author has observed in the swash zones of several beaches. The conceptual model and hypotheses advanced in this section are therefore based on literature, and on observations made by the author during reconnaissance work in the field.

Visible sediment streaks are expected to occur only under certain circumstances with respect to wave parameters, swash velocity, and beach sedimentology. Clearly, the initiation of grain motion is necessary for sediment to be sorted into streaks. This can only take place when the shear stress on the bottom ($\tau_b$) exceeds the grain movement threshold ($\tau_{mov}$). The grain movement threshold is largely determined by grain size, although it also depends upon a grain’s shape and density. Shear stress, on the other hand, is a function of fluid density ($\rho$) and shear velocity ($u_\ast$): $\tau_b = \rho u_\ast^2$. Since fluid density is constant, and shear velocity can be assumed to be proportional to the fluid velocity (Carter, 1988), it is expected that swash velocity will be the most important factor in determining shear stress.

Sorting of grains into streaks further requires the existence of two or more sediment populations which are distinct in terms of size, shape, or density (mineralogy). Although sorting by size or shape is expected to result in flow-perpendicular grain variations in the swash zone, these would not likely be visible to the human eye. The presence of both light
and dark-coloured grains with differing mobilities could, however, lead to the formation of visible streaks.\textsuperscript{1} This may occur as small dark grains are mobilized and separated from large light-coloured grains, which tend to remain concentrated in areas of low shear stress (Inman \textit{et al.}, 1966). The author has observed an apparently similar phenomenon on two of the study beaches, where dark, "streak" grains appeared to be in motion, while lighter grains remained motionless on the bed. Therefore, swash velocity, mean grain size, and the presence of distinct sediment populations are expected to determine whether flow-perpendicular variations will exist in the swash zone. Whether these variations become visible as streaks depends upon the occurrence of a population of dark, mobile grains and another of sedentary, light-coloured minerals grains.

Streak width and spacing are also expected to be related to swash velocity and grain size. Although the cause of swash zone streaks is unclear, it seems likely that they are a result of a process analogous to turbulent bursting. As such, predictions of streak width and spacing can probably be premised on the work of Kline \textit{et al.} (1967) and Allen (1985). According to Equation 1, streak spacing decreases as the shear velocity (which is proportional to swash velocity) increases. Likewise, the spacing of parting lineations, which are caused by turbulent bursting in the swash zone, is inversely proportional to flow velocity and grain size. Therefore, streak width and spacing are expected to decrease with increasing grain size and swash velocity, until at some point, the streaks merge and

\textsuperscript{1} Dark-coloured grains are expected to be more dense than light-coloured ones, since heavy minerals (those with a specific gravity greater than 2.85) tend to be dark in colour. However, large sand grains are often rock fragments consisting of several minerals. Therefore, while the colour of a grain may provide some indication of its density, it cannot be stated categorically that dark-coloured grains are denser than light-coloured ones.
disappear.

As swash velocity is obviously related to wave conditions, it is expected that streak width and spacing will be influenced by wave height and period. Although there are no equations relating swash velocity to wave parameters, it is assumed that for similar breaker types (spilling, plunging, collapsing, or surging) an increase in wave energy, as indicated by the wave height, will cause an increase in swash velocity, and thus a decrease in streak width and spacing. Furthermore, a minimum wave height may be required for flow-perpendicular variations to occur, while a maximum height may cause these variations to become so closely spaced that they disappear.

On this basis, a model was constructed (Fig. 5) and the following five hypotheses were forwarded:

1. When the swash velocity is sufficient to initiate grain motion, the swash zones of beaches with two or more distinct grain populations will be characterized by quasi-regular variations in grain mobility factors (size, shape, and density) parallel to the waterline.

2. These variations will become visible as streaks only on beaches with two sediment populations which differ in colour and mobility.

3. Visible streaks will consist of sediment which is finer-grained, and has a higher proportion of dark-coloured minerals, than the intervening spaces.

4. Sediment transported by suspension and bedload traction in the swash zone will be similar in size, shape, and mineral composition to streak sediment.

5. Streaks will exhibit a quasi-regular, quantifiable spacing which will decrease with increasing wave height, swash velocity, and mean grain diameter, until at some point they merge and disappear.
Fig. 5: Model of sediment streaking.
5.0 Methodology

The aim of this study was to detect and measure sediment streaks in the swash zone, analyze their sedimentological characteristics, and relate their visibility and spacing to wave, swash, and grain characteristics. First, sediment samples, along with relevant wave and sediment streak measurements, were obtained in the field. Components of these data were then analyzed in the laboratory. Finally, by means of statistical analysis, any regularly observed patterns in the occurrence, morphology, or sedimentology of streaks were related to wave and swash conditions, and sedimentological parameters.

5.1 Field Methodology

The first step in this study was the collection of relevant data in the field. A wave staff, which uses an electric current to detect changes in water depth caused by the passage of waves, was used to measure wave height. The staff was placed in an upright position, with its bottom resting on the bed, in water approximately one metre deep. Wave heights were then read from the digital display on the instrument and recorded.

Wave period was measured using a stopwatch. The interval required for fifty successive wave crests to pass the wave staff was timed, and the period was calculated by dividing the total time by 50. Average swash velocity was determined using the "ping-pong ball method" outlined by Miller and Zeigler (1958). From the base of the swash zone, a distance of one metre was measured and demarcated, perpendicular to the uprush. A ping pong ball was then dropped into the water at the beginning of each uprush and timed over the measured distance. The average swash velocity was determined after 15 trials had been performed.
Unfortunately, the conclusiveness of this study is limited by the fact that the swash velocity, wave height, and wave period measurements were averages, calculated once during each visit to each beach. Although these averages are thought to have been very representative, it would have nonetheless been preferable to have obtained specific wave and swash measurements for each uprush when sediment streak data were collected. However, constraints on equipment and human power, as well as the concern that a large number of simultaneous measurements would significantly disrupt the swash zone, made the collection of such data impossible.

Four types of sediment sample were taken from each beach. First, a small trowel was used to scoop approximately one kilogram of sediment from the bed of the swash zone, down to a depth of one centimetre. Second, an attempt was made to detect swash zone sedimentary variations when streaks were visible, and when they were not. During uprushes, petroleum jelly-coated tapes, attached to a rigid board three metres in length, were pressed onto the bed in the swash zone, perpendicular to the uprush. Sediment was captured in the petroleum jelly on these tapes, which were retained for laboratory and statistical analysis.

A similar technique was used to measure the sedimentology of visible streaks and spaces. Five samples from streaks and five from adjacent spaces were collected on petroleum jelly-coated strips of duct tape which were affixed to the bottom of wooden, 3 x 3 centimetre boards. The boards were pressed onto the bed where either a streak or a space was observed, and the sediment-coated tapes were retained for analysis.

Sediment transported during uprushes by suspension or bedload traction was collected
to test whether it was similar to streak sediment. For the duration of an uprush, a small bucket was held on the bed with its opening pointing seawards. Following the bucket's removal, entrapped sediment was allowed to settle and dry in preparation for laboratory analysis.

Conventional photography was used to measure streak width and spacing, while written records were kept of streak visibility. On days when streaks were visible, a camera was placed on a tripod at the top of the swash zone and pointed downwards at the incoming swash. A series of photographic slides of the swash zone, the first of which included a measuring rod, was then taken. When no streaks were observed, only wave and swash conditions were recorded. In this way, a record of streak visibility, width, and spacing was compiled for each beach, every day it was visited.

5.2 Laboratory and Statistical Analysis

In the laboratory, sediment samples were analyzed to evaluate characteristics such as size, shape, and dark mineral content. First, 500 grams of sediment from each beach were sorted into size classes by being passed through a series of sieves with mesh openings of 4, 2, 1, 0.5, 0.25, 0.125, and 0.0625 millimetres. Following separation, five random samples of fifty grains from each size class were selected. These grains were inspected individually under a binocular microscope to determine whether they were composed of dark minerals. Statistical parameters including the mean, standard deviation, skewness, and kurtosis, were calculated based on the size distribution of each sample. These were subjected to a series of independent samples t-tests to determine whether the samples from the four beaches differed significantly from each other. A series of paired samples t-tests
was used to detect differences in the dark mineral component between the beaches. Finally, histograms and cumulative frequency curves were generated.

The size, shape, and mineralogy of the sediment collected from streak and space areas were evaluated under a microscope. Grains from each tape were randomly sampled using a transparent millimetre grid overlay on which fifty locations, whose coordinates corresponded to digits taken from a random numbers table, had been marked. The fifty grains which were directly below these marked locations when the square grid was overlain on the tape were sampled. The grid was then rotated 90 degrees for the succeeding tape. The lengths of the longest and second longest axes of the selected grains were measured using the millimetre scale on the ocular of the microscope, while shape was visually evaluated using the Power's scale (Lindholm, 1987). Since grains larger than 0.125 mm tend to be rock fragments consisting of several minerals, the dark mineral content of each grain was assessed visually using the ranks of "high", "medium" and "low". The size (length) and shape measurements of the streak and non-streak areas were then compared statistically using an independent samples t-test, while the dark mineral contents were compared using a Kolmogorov-Smirnov two sample test.

Laboratory analysis of both three metre long strips of tape was conducted using a procedure similar to that described above. First, each tape was divided into 100 quadrats, three centimetres in width. Using a transparent overlay, 19 grains were sampled from each of these quadrats, and their size, shape, colour, and orientation were measured under the microscope. Orientation, the only parameter whose measurement was not discussed in the previous paragraph, refers to the deviation in alignment of the long axis of the grain from
a hypothetical line drawn perpendicular to the tape's length. The mean size, shape, orientation, and percentage of dark-coloured mineral grain measurements for each section along the tape were then analyzed for periodic trends as a one-dimensional spatial series; specifically, autocorrelation, partial autocorrelation and spectral density function plots were generated and interpreted.

Mobile sediment collected from the swash zone was analyzed and compared to sediment collected from streaks. Forty grains were selected randomly from each of the five collection vessels from each beach, and their size, shape, and colour were determined using a microscope. The size and shape measurements were then compared to the corresponding ones for streak sediments using independent samples t-tests, while those for colour were compared using two-sample Kolmogorov-Smirnov tests.

The width and spacing of streaks were measured from the photographic slides taken in the field. The measurement scale was determined from the first slide in each series, which included a measuring rod laid down parallel to the waterline (Fig. 6). Projection of this slide allowed the measurement increments on the rod to be transferred onto a viewing screen. Streaks were then measured as each subsequent slide was projected onto the screen. Relationships between the measured dimensions of the streaks, their locations, and the conditions under which they formed, were tested statistically. For each beach, independent samples t-tests between each day's streak measurements and the grouped streak measurements for all other days on that beach were conducted. The same test was conducted to compare differences in streak width and spacing between the beaches for all days. In this way, significant differences between groups of measurements taken during
different conditions, and on different beaches, were detected.

Fig. 6: Photographic slide of measuring rod (spacing between tics is 2cm).
6.0 Analysis and Discussion

6.1 Beach Sedimentology

Analysis of sediment samples revealed grain size differences between the four beaches (Figs. 7-10). At least one of the statistical parameters (mean, standard deviation, skewness, and kurtosis) varied significantly between all pairs of beaches, except the pairing of the East and the Northwest Beaches (Table 1). Generally, Seacliff Beach had the finest-grained and best sorted sediment, as indicated by the mean and standard deviation. The West Beach had the coarsest sediment of the four beaches, while the sediment on the Northwest Beach was the most poorly sorted. The size distribution was highly skewed towards the fine-grained sediment in the case of the West Beach, slightly skewed towards the fine-grained sediment in the cases of Seacliff and the Northwest Beach, and symmetrical for the East Beach. The distributions for all beaches were slightly platykurtic, except the East Beach, which had a mesokurtic distribution. This indicates that the samples were not particularly bimodal with respect to size. The dark mineral component did not vary significantly between the four beaches (Table 2). In descending order, the percentage of sediment grains which consisted of dark-coloured minerals on each beach was: the East- 21.7%; the Northwest- 20.8%; the West- 19.6%; Seacliff-16.3%.
Mean: 1.25 mm (-0.32φ) Std. Dev: 0.51 mm (0.98φ)
Skewness: 0.74 mm (0.44φ)  Kurtosis: 0.40 mm (1.31φ)

Fig. 7: Grain-size and mineral colour on the Northwest Beach.
Mean: 0.37mm (1.39φ) Std. Dev: 0.62mm (0.68φ)
Skewness: 1.19mm (-0.26φ) Kurtosis: 0.59mm (0.75φ)

Fig. 8: Grain-size and mineral colour on Seacliff Beach.
Mean: 1.21mm (-0.27φ)  Std. Dev: 0.56mm (0.83φ)
Skewness: 0.92mm (0.11φ)  Kurtosis: 0.14mm (2.87φ)

Fig. 9: Grain-size and mineral colour on the East Beach.
Mean: 1.74mm (-0.8φ)  Std. Dev: 0.47mm (1.1φ)
Skewness: 0.46mm (1.13φ)  Kurtosis: 0.44mm (1.17φ)

Fig. 10: Grain-size and mineral colour on the West Beach.
<table>
<thead>
<tr>
<th>Paired Beaches</th>
<th>Attribute</th>
<th>Mean Diff.</th>
<th>t</th>
<th>Sig.</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW v. SC</td>
<td>Mean</td>
<td>1.957</td>
<td>8.3</td>
<td>.004</td>
<td>.236</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>-.548</td>
<td>-1.9</td>
<td>.166</td>
<td>.296</td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td>-.014</td>
<td>-.07</td>
<td>.946</td>
<td>.195</td>
</tr>
<tr>
<td></td>
<td>Kurtosis</td>
<td>0.0893</td>
<td>.64</td>
<td>.555</td>
<td>.139</td>
</tr>
<tr>
<td>NW v. East</td>
<td>Mean</td>
<td>-.107</td>
<td>-.42</td>
<td>.702</td>
<td>.258</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.1947</td>
<td>.67</td>
<td>.560</td>
<td>.292</td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td>-.1893</td>
<td>-2.0</td>
<td>.134</td>
<td>.094</td>
</tr>
<tr>
<td></td>
<td>Kurtosis</td>
<td>0.186</td>
<td>1.63</td>
<td>.180</td>
<td>.114</td>
</tr>
<tr>
<td>NW v. West</td>
<td>Mean</td>
<td>-.7733</td>
<td>-3.4</td>
<td>.052</td>
<td>.227</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>-.4643</td>
<td>-1.5</td>
<td>.227</td>
<td>.310</td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td>0.7540</td>
<td>6.10</td>
<td>.004</td>
<td>.124</td>
</tr>
<tr>
<td></td>
<td>Kurtosis</td>
<td>-.0327</td>
<td>-.34</td>
<td>.758</td>
<td>.097</td>
</tr>
<tr>
<td>SC v. East</td>
<td>Mean</td>
<td>-1.8497</td>
<td>-13.3</td>
<td>.001</td>
<td>.140</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.3533</td>
<td>4.90</td>
<td>.01</td>
<td>.072</td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td>-.2033</td>
<td>-1.15</td>
<td>.337</td>
<td>.176</td>
</tr>
<tr>
<td></td>
<td>Kurtosis</td>
<td>0.2753</td>
<td>2.17</td>
<td>.101</td>
<td>.127</td>
</tr>
<tr>
<td>SC v. West</td>
<td>Mean</td>
<td>-2.73</td>
<td>-41.0</td>
<td>.000</td>
<td>.067</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.0837</td>
<td>.67</td>
<td>.544</td>
<td>.125</td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td>-0.740</td>
<td>3.82</td>
<td>.026</td>
<td>.194</td>
</tr>
<tr>
<td></td>
<td>Kurtosis</td>
<td>0.0567</td>
<td>.51</td>
<td>.672</td>
<td>.112</td>
</tr>
<tr>
<td>East v. West</td>
<td>Mean</td>
<td>-0.8803</td>
<td>-7.11</td>
<td>.010</td>
<td>.124</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>-.2697</td>
<td>-2.31</td>
<td>.101</td>
<td>.117</td>
</tr>
<tr>
<td></td>
<td>Skewness</td>
<td>0.9433</td>
<td>10.22</td>
<td>.003</td>
<td>.092</td>
</tr>
<tr>
<td></td>
<td>Kurtosis</td>
<td>-.2187</td>
<td>-2.78</td>
<td>.059</td>
<td>.079</td>
</tr>
</tbody>
</table>

Table 1: Comparison of grain size distribution (in Phi units) for all possible pairs of the four study beaches.
<table>
<thead>
<tr>
<th>Paired Beaches</th>
<th>Mean Difference</th>
<th>t-value</th>
<th>2-tail sign.</th>
<th>SE of Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW v. SC</td>
<td>1.258</td>
<td>.76</td>
<td>.473</td>
<td>1.659</td>
</tr>
<tr>
<td>NW v. East</td>
<td>.1342</td>
<td>.23</td>
<td>.823</td>
<td>.579</td>
</tr>
<tr>
<td>NW v. West</td>
<td>-.2756</td>
<td>-.26</td>
<td>.806</td>
<td>1.080</td>
</tr>
<tr>
<td>SC v. East</td>
<td>-1.1238</td>
<td>-.8</td>
<td>.452</td>
<td>1.411</td>
</tr>
<tr>
<td>SC v. West</td>
<td>1.5335</td>
<td>.61</td>
<td>.558</td>
<td>2.495</td>
</tr>
<tr>
<td>East v. West</td>
<td>-.4098</td>
<td>-.27</td>
<td>.794</td>
<td>1.507</td>
</tr>
</tbody>
</table>

Table 2: Comparison of dark mineral components (by size class) for all pairs of beaches.

6.2 Measured Wave Conditions and Swash Velocities

Measurements were performed on the four beaches under a variety of swash and wave conditions (Table 3). Generally, the highest waves occurred on the West Beach, and the lowest on Seacliff Beach. Wave periods tended to be similar on all four beaches, although they were somewhat longer on the East Beach than on the other three. Average swash velocity for the beaches was also similar, with the Northwest Beach experiencing both the highest and lowest values.

The most important characteristic of the wave and swash data is the fact that the range of measured conditions for the four beaches overlap (Fig. 11). While measurement of streaks under identical conditions would clearly have been ideal, overlapping ranges allowed the effects of beach sedimentology to be isolated from those caused by changes in wave and swash characteristics.
<table>
<thead>
<tr>
<th>Beach</th>
<th>Date</th>
<th>Wave Height (cm)</th>
<th>Wave Period (s)</th>
<th>Swash Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>July 7</td>
<td>50</td>
<td>3.96</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>Aug 4</td>
<td>20</td>
<td>2.48</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>Aug 10</td>
<td>15</td>
<td>2.85</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Aug 25</td>
<td>7</td>
<td>4.40</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>Sept 1</td>
<td>14</td>
<td>2.56</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Sept 13</td>
<td>44</td>
<td>4.12</td>
<td>1.34</td>
</tr>
<tr>
<td>Seacliff</td>
<td>Aug 10</td>
<td>10</td>
<td>2.72</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>Aug 25</td>
<td>9</td>
<td>3.32</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>Sept 1</td>
<td>5</td>
<td>2.14</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Sept 13</td>
<td>22</td>
<td>4.18</td>
<td>1.30</td>
</tr>
<tr>
<td>East</td>
<td>July 14</td>
<td>7</td>
<td>3.12</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>Aug 10</td>
<td>10</td>
<td>2.47</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>Aug 25</td>
<td>46</td>
<td>4.92</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Sept 1</td>
<td>12</td>
<td>3.00</td>
<td>1.30</td>
</tr>
<tr>
<td>West</td>
<td>Aug 10</td>
<td>18</td>
<td>2.89</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>Sept 1</td>
<td>14</td>
<td>2.66</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>Sept 13</td>
<td>55</td>
<td>4.22</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table 3: Average wave and swash conditions measured during visits to the study beaches.
6.3 General Features of Sediment Streaks

Many general features of sediment streaks were noticed in the field. First, streaks are ephemeral features of the swash zone. Although they undergo partial or total destruction and re-formation between successive uprushes, their general form may remain similar over several swash cycles. They may completely disappear for a few swash cycles at a particular location, or shift along the beach. Streak morphology also changes slightly within individual swash cycles. During the uprush phase, sediment is sorted into quasi-regular streaks which propagate up the beach with the flow. As they lengthen, they widen and branch as the uprush fans out near the peak of its ascent up the beach. At this point, the streaks appear dendritic in form, although their width and spacing seem to remain fairly constant. On the downrush phase, the streaks maintain roughly the same position,
width, and spacing inherited from the uprush phase, although the dendritic pattern is soon replaced by more regular banding with streaks and spaces running parallel to the downrush direction.

Other sedimentary features were observed in and around the swash zone during this study, particularly during high waves (Table 4). On Seacliff Beach, dark, 10 to 20 cm wide, crescentic formations, whose "horns" pointed in the uprush direction, were visible. Dark-coloured "cross-hatchings" were noticed on both "streak beaches", particularly during high wave energy conditions, when uprushes occurred in rapid succession and interfered with each other in the swash zone. These nearly concurrent uprushes were often oriented at different angles, suggesting that cross-hatchings may consist of two superimposed sets of streaks. Occasionally, the superimposition of features of several varieties created confused patterns, making streaks difficult to discern (Fig. 9).

Flow-parallel features which differed in scale from streaks were observed under a variety of conditions. Parting lineations, a few grain diameters in width, were sometimes visible on beach ridges adjacent to the swash zone, while large-scale streaks with widths of 10 to 30 centimetres were noticed occasionally along sections of the Northwest Beach. In one instance, these large-scale features extended well seawards of the swash zone, which suggests that flow-parallel transport mechanisms may be important some distance offshore. The swash zone may therefore be characterized by a hierarchy of flow-parallel features apparently fractal in nature, in that they are similar in form, but different in scale.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Width (cm)</th>
<th>Orientation to Flow</th>
<th>Location</th>
<th>Conditions for Occurrence</th>
<th>Reason for Visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streaks</td>
<td>2-3</td>
<td>Parallel</td>
<td>Swash Zone</td>
<td>All</td>
<td>Dark Sediment</td>
</tr>
<tr>
<td>Crescents</td>
<td>10-15</td>
<td>Perpendicular</td>
<td>Swash Zone</td>
<td>High Waves</td>
<td>Dark Sediment</td>
</tr>
<tr>
<td>Cross-Hatchings</td>
<td>--</td>
<td>Varying</td>
<td>Swash Zone</td>
<td>High Waves</td>
<td>Dark Sediment</td>
</tr>
<tr>
<td>Parting Lineations</td>
<td>&lt;1</td>
<td>Parallel</td>
<td>Beach Ridge</td>
<td>All</td>
<td>Height Differences</td>
</tr>
<tr>
<td>Large &quot;Streaks&quot;</td>
<td>10-30</td>
<td>Parallel</td>
<td>Swash Zone &amp; Seaward</td>
<td>All</td>
<td>Dark Sediment</td>
</tr>
</tbody>
</table>

Table 4: Notable sedimentary features observed during the study and their characteristics.

Fig. 12: "Confused" pattern during high waves on Seacliff Beach (width of field of view is 160cm).
6.4 Streak Visibility

Sediment streaks were either visible on every visit, or never visible, on each beach. Streaks were never observed on either the East or the West Beach, but were observed during each visit to the Northwest and Se acliff Beaches (Figs. 10 & 11). Apparently, beaches are characteristically and unvaryingly "streak" or "non-streak" in nature.

The regular occurrence, or non-occurrence, of visible streaks on a beach was originally expected to be related to its sedimentary characteristics. However, statistical analysis of beach sediments did not support this assumption. Although there were sedimentary differences between the beaches visited in this study, the Northwest Beach, which is a "streak beach", and the East Beach, which is a "non-streak" beach, are nearly identical in composition. Perhaps the sampling methods or the sedimentary analysis were not sufficiently sophisticated to detect minute, but possibly important sedimentary differences between these beaches. Or perhaps the explanation partly lies in factors not considered in this study, including swash length, swash zone geometry (slope), position of the water table, and offshore slope, which would influence the dominant breaker type. Although there appear to be factors aside from beach sedimentology which affect streak visibility, sedimentology is nevertheless important. For streaking to occur, beach sediment must consist of two distinct classes which differ in grain size or mineralogy. This condition was met on both "streak" and "non-streak" study beaches, however, and is thus not the only requirement for streak occurrence. Furthermore, as streaks are probably generated by a mechanism that is limited in strength, it is reasonable to assume that the mean grain size of certain beaches, such as the West, may be too large for streak formation.
Fig 13: Streaks on the Northwest Beach (width of field of view is 150cm).

Fig. 14: Streaks on Seacliff Beach (width of field of view is 165cm).
6.5 Streak Sedimentology - Part I

Spatial-series analysis of the three-metre long tapes failed to reveal periodic trends in sediment size, shape, colour, or orientation on either the streak beach (the Northwest), or the non-streak beach (the East). The sequence plots for the beaches show no clear regularities; they appear instead to indicate that there is considerable noise in these variables (Figs. 12-16). Autocorrelation and partial autocorrelation plots reveal autocorrelation outside the confidence limits at Lag 1 for all variables except mineralogy (colour) on the streak beach, and shape, on the non-streak beach (Figs. 17-26). This is an indication of non-stationarity, or a change in the mean value of the measured variable over the length of the series. While non-stationarity may be expected in some systems, it is both unexpected and undesirable in this instance, as the only available explanations for it seem to be measurement or sampling error.

The lack of periodic behaviour along the tapes is supported further by the spectral density plots (Figs. 27-31). In these plots, periodic trends appear as well defined peaks or spikes. In all cases, however, the generated plots indicate only small, irregular spikes in the first few lags, followed by rapidly increasing spectral densities beyond Lag 10. Such behaviour is indicative of a non-stationary and non-periodic series.

Several explanations can be suggested for the lack of periodicity along the tapes. First, the regular variation in grain characteristics that was hypothesized may simply not have existed at the particular times and locations the samples were taken. While this is a cogent argument in the case of the East beach, it is much less convincing for the Northwest
Beach, where streaks of dark sediment were visible when samples were collected. Another possibility is that the laboratory analysis was inappropriate. Specifically, three centimetres may not have been the best interval by which to subdivide the tape. Cycles in which streaks and spaces repeatedly shared the same quadrat would not be easily detected using such a method.

The most likely weakness appears to be related to the sampling procedures. Inspection revealed that the sample tapes were not coated uniformly with sediment but were instead characterized by dense, sandy clusters separated by areas in which sediment was scarce. This suggests that each section of tape may not have provided an equally accurate representation of the swash zone sediment. There are several reasons why this may have occurred: first, unequal pressure may have been applied to different areas of the board as it was laid down; second, petroleum jelly may not have been spread uniformly over the length of tape; third, slight irregularities in the elevation of the bed of the swash zone may have facilitated greater contact between the tape and higher areas than occurred in lower areas; finally, sediment of certain shapes and sizes may be more easily captured by the petroleum jelly than others. The latter two possibilities are considered to be the most likely.

Unfortunately, then, these results reveal little with respect to flow-perpendicular sedimentary variations in the swash zone. Although sedimentological differences between visible streaks and spaces are discussed in subsequent sections of this thesis, it remains unclear as to whether similar variations also occur when streaks are not visible.
Fig. 15: Sequence plots for grain parameters [long and short axis length (size), density (colour), shape, and orientation] along the 3 metre tape from the Northwest Beach.
Fig. 16: Sequence plots for grain parameters [long and short axis length (size), density (colour), shape, and orientation] along the 3 metre tape from the East Beach.
Fig. 17: Autocorrelation and Partial Autocorrelation Plots for long-axis length (lasize) from the Northwest Beach Sequence.
Fig. 18: Autocorrelation and Partial Autocorrelation Plots for second-longest axis length (sasize) from the Northwest Beach Sequence.
Fig. 19: Autocorrelation and Partial Autocorrelation Plots for colour (density) from the Northwest Beach Sequence.
Fig. 20: Autocorrelation and Partial Autocorrelation Plots for shape from the Northwest Beach Sequence.
Fig. 21: Autocorrelation and Partial Autocorrelation Plots for orientation (orient) from the Northwest Beach Sequence.
Fig. 22: Autocorrelation and Partial Autocorrelation Plots for long axis length (lasize) from the East Beach Sequence.
Fig. 23: Autocorrelation and Partial Autocorrelation Plots for second-longest axis length (sasize) from the East Beach Sequence.
Fig. 24: Autocorrelation and Partial Autocorrelation Plots for colour (density) from the East Beach Sequence.
Fig. 25: Autocorrelation and Partial Autocorrelation Plots for shape from the East Beach Sequence.
Fig. 26: Autocorrelation and Partial Autocorrelation Plots for orientation (orient) from the East Beach Sequence.
Figs. 27 A-E: Spectral density plots for grain parameters from the Northwest Beach Sequence - A: Long Axis Length B: Second-Longest Axis Length C: Colour (Density) D: Shape E: Orientation.
Figs. 28 A-E: Spectral density plots of grain parameters from the East Beach Sequence-
A: Long Axis Length B: Second-Longest Axis Length C: Colour (Density) D: Shape
E: Orientation
6.6 Streak Sedimentology - Part II

Statistical analysis of the sediment collected from adjacent streaks and spaces revealed significant sedimentological differences between the two (Table 5). Specifically, the mean

<table>
<thead>
<tr>
<th>Beach</th>
<th>Variable</th>
<th>Mean-Streaks</th>
<th>Mean-Spaces</th>
<th>t / K-S Z</th>
<th>Sig</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>Size(LA)</td>
<td>1.42</td>
<td>0.41</td>
<td>21.3</td>
<td>.000</td>
<td>.047</td>
</tr>
<tr>
<td></td>
<td>Size(SA)</td>
<td>0.97</td>
<td>0.28</td>
<td>21.7</td>
<td>.000</td>
<td>.032</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>0.58</td>
<td>0.53</td>
<td>3.11</td>
<td>.002</td>
<td>.018</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>-</td>
<td>-</td>
<td>3.64 *</td>
<td>.000</td>
<td>-</td>
</tr>
<tr>
<td>SC</td>
<td>Size(LA)</td>
<td>0.75</td>
<td>0.45</td>
<td>5.48</td>
<td>.000</td>
<td>.055</td>
</tr>
<tr>
<td></td>
<td>Size(SA)</td>
<td>0.45</td>
<td>0.30</td>
<td>9.66</td>
<td>.000</td>
<td>.015</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>0.52</td>
<td>0.51</td>
<td>.69</td>
<td>.459</td>
<td>.014</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>0.74</td>
<td>-</td>
<td>2.08 *</td>
<td>.000</td>
<td>-</td>
</tr>
</tbody>
</table>

* denotes a Kolmogorov-Smirnov Z, rather than a "t" value.

Table 5: Comparison of streak sediment to sediment from spaces.

grain size was larger and dark mineral concentrations were higher in streak areas than in the intervening spaces (within streaks, dark mineral grains did not differ in size from lighter grains). Grains were also significantly more rounded in the streaks of the Northwest Beach than in the spaces; however, on Seacliff Beach, grain roundness did not differ significantly between the streaks and the spaces. Thus, it would appear that streaks consist of sediment that is larger in size, and richer in dark minerals than the sediment in adjacent spaces.
6.7 Streak Sedimentology - Part III

Sediment grains transported through suspension or bedload traction exhibited both similarities and differences compared to streak sediment (Table 6). On both beaches.

<table>
<thead>
<tr>
<th>Beach</th>
<th>Variable</th>
<th>Mean-Streaks</th>
<th>Mean-Mobile</th>
<th>t/K-S Z*</th>
<th>Sig</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>Size(LA)</td>
<td>1.42</td>
<td>2.08</td>
<td>-8.1</td>
<td>.000</td>
<td>.082</td>
</tr>
<tr>
<td></td>
<td>Size(SA)</td>
<td>0.97</td>
<td>1.46</td>
<td>-8.3</td>
<td>.000</td>
<td>.059</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>0.58</td>
<td>0.53</td>
<td>2.81</td>
<td>.005</td>
<td>.018</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>-</td>
<td>-</td>
<td>1.00 *</td>
<td>.267</td>
<td>-</td>
</tr>
<tr>
<td>SC</td>
<td>Size(LA)</td>
<td>0.75</td>
<td>0.45</td>
<td>1.16</td>
<td>.247</td>
<td>.055</td>
</tr>
<tr>
<td></td>
<td>Size(SA)</td>
<td>0.45</td>
<td>0.472</td>
<td>-.98</td>
<td>.330</td>
<td>.018</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>0.52</td>
<td>0.45</td>
<td>5.30</td>
<td>.000</td>
<td>.012</td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>-</td>
<td>-</td>
<td>.509 *</td>
<td>.954</td>
<td>-</td>
</tr>
</tbody>
</table>

* denotes a Kolmogorov-Smirnov Z, rather than a "t" value.

Table 6: Comparison of streak sediment to mobile swash zone sediment.

the proportion of heavy minerals in the transported sedimentary material was statistically similar to that in the streaks. On the other hand, the transported sediment on both beaches was significantly more angular than streak sediment. While transported sediment on the Northwest Beach was significantly coarser than that found in the streaks, the sediments on Seacliff Beach were statistically similar in size.

Although streak sediment appears to be similar in colour to mobile material in the swash zone, any broad inferences regarding similarities between the composition of these sediment populations would be unfounded at this point. While some beaches, including perhaps Seacliff, may have streaks which consist of material which is constantly in
transport, this is apparently not the case for all beaches.

6.8 Streak Morphology

On the Northwest Beach, mean streak width was 2.39 centimetres and spacing was 1.48 centimetres. On Seacliff Beach, streak width averaged 2.81 centimetres while spacing averaged 1.70 centimetres (Tables 7-10). Aside from a few exceptions (one day on the Northwest Beach, and two days on Seacliff Beach), the day to day differences in streak dimensions on a particular beach were statistically insignificant (Tables 11-14). In general, therefore, changes in wave height, wave period and swash velocity did not affect significantly the width and spacing of streaks in the swash zone. The author suspects, however, that wave height, wave period, and swash velocity are probably factors in determining streak morphology, but were not shown to be important in this study, owing to the use of average, rather than specific, wave and swash measurements.

Streak width and spacing were significantly larger on Seacliff than on the Northwest Beach (Table 14), likely as a result of the differing sedimentary characteristics of these beaches. The Northwest Beach, with a modal grain size of one to two millimetres, consists of significantly coarser sediment than does Seacliff Beach, which has a modal grain size of 0.125 to 0.25 millimetres. This suggests that coarse-grained beaches may exhibit narrower, and more narrowly spaced streaks than fine-grained beaches.
<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Observations</th>
<th>Mean (cm)</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>102</td>
<td>2.31</td>
<td>0.93</td>
<td>0.7</td>
<td>5.8</td>
</tr>
<tr>
<td>Aug 10</td>
<td>35</td>
<td>2.46</td>
<td>1.1</td>
<td>1.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Aug 25</td>
<td>89</td>
<td>2.31</td>
<td>0.74</td>
<td>1.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Sept 1</td>
<td>68</td>
<td>2.24</td>
<td>0.96</td>
<td>0.6</td>
<td>6.7</td>
</tr>
<tr>
<td>Sept 13</td>
<td>103</td>
<td>2.6</td>
<td>0.9</td>
<td>1.0</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Table 7: Statistics for streak width on the Northwest Beach

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Observations</th>
<th>Mean (cm)</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>100</td>
<td>1.41</td>
<td>0.73</td>
<td>0.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Aug 10</td>
<td>33</td>
<td>1.46</td>
<td>0.82</td>
<td>0.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Aug 25</td>
<td>85</td>
<td>1.53</td>
<td>0.64</td>
<td>0.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Sept 1</td>
<td>68</td>
<td>1.39</td>
<td>0.79</td>
<td>0.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Sept 13</td>
<td>102</td>
<td>1.58</td>
<td>0.86</td>
<td>0.5</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 8: Statistics for streak spacing on the Northwest Beach
<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Observations</th>
<th>Mean (cm)</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug 10</td>
<td>42</td>
<td>3.19</td>
<td>1.22</td>
<td>1.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Aug 25</td>
<td>86</td>
<td>2.98</td>
<td>1.07</td>
<td>0.8</td>
<td>5.5</td>
</tr>
<tr>
<td>Sept 1</td>
<td>140</td>
<td>2.72</td>
<td>1.03</td>
<td>0.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Sept 13</td>
<td>92</td>
<td>2.63</td>
<td>0.7</td>
<td>1.1</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 9: Statistics for streak width on Seacliff Beach.

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Observations</th>
<th>Mean (cm)</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug 10</td>
<td>40</td>
<td>2.03</td>
<td>1.03</td>
<td>0.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Aug 25</td>
<td>79</td>
<td>1.88</td>
<td>1.03</td>
<td>0.4</td>
<td>4.8</td>
</tr>
<tr>
<td>Sept 1</td>
<td>134</td>
<td>1.74</td>
<td>1.03</td>
<td>0.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Sept 13</td>
<td>90</td>
<td>1.34</td>
<td>0.63</td>
<td>0.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 10: Statistics for streak spacing on Seacliff Beach
<table>
<thead>
<tr>
<th>Date</th>
<th>Mean Difference</th>
<th>t-value</th>
<th>2-tail significance</th>
<th>SE of Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>0.0806</td>
<td>0.77</td>
<td>0.445</td>
<td>0.105</td>
</tr>
<tr>
<td>Aug 10</td>
<td>0.0770</td>
<td>0.44</td>
<td>0.662</td>
<td>0.176</td>
</tr>
<tr>
<td>Aug 25</td>
<td>-0.0946</td>
<td>-0.93</td>
<td>0.353</td>
<td>0.103</td>
</tr>
<tr>
<td>Sep 1</td>
<td>-0.1812</td>
<td>-1.46</td>
<td>0.135</td>
<td>0.123</td>
</tr>
<tr>
<td>Sep 13</td>
<td>0.2878</td>
<td>2.79</td>
<td>0.006</td>
<td>0.103</td>
</tr>
</tbody>
</table>

Table 11: Comparison of streak widths (cm) for each day on the Northwest Beach to widths for all other days on the Northwest Beach.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean Difference</th>
<th>t-value</th>
<th>2-tail significance</th>
<th>SE of Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>0.1100</td>
<td>1.24</td>
<td>0.213</td>
<td>0.87</td>
</tr>
<tr>
<td>Aug 10</td>
<td>-0.0250</td>
<td>-0.17</td>
<td>0.863</td>
<td>0.144</td>
</tr>
<tr>
<td>Aug 25</td>
<td>0.0643</td>
<td>0.73</td>
<td>0.470</td>
<td>0.89</td>
</tr>
<tr>
<td>Sep 1</td>
<td>-0.1153</td>
<td>-1.11</td>
<td>0.267</td>
<td>0.104</td>
</tr>
<tr>
<td>Sep 13</td>
<td>0.1383</td>
<td>1.50</td>
<td>0.135</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 12: Comparison of streak spacings (cm) for each day on the Northwest Beach to spacings for all other days on the Northwest Beach.
<table>
<thead>
<tr>
<th>Date</th>
<th>Mean Difference</th>
<th>t-value</th>
<th>2-tail significance</th>
<th>SE of Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug 10</td>
<td>-0.4236</td>
<td>-2.38</td>
<td>0.018</td>
<td>0.180</td>
</tr>
<tr>
<td>Aug 25</td>
<td>0.2231</td>
<td>1.76</td>
<td>0.080</td>
<td>0.127</td>
</tr>
<tr>
<td>Sep 1</td>
<td>-0.1536</td>
<td>-1.41</td>
<td>0.160</td>
<td>0.108</td>
</tr>
<tr>
<td>Sep 13</td>
<td>-0.2508</td>
<td>-2.32</td>
<td>0.025</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Table 13: Comparison of streak widths (cm) for each day on Seacliff Beach to widths for all other days on Seacliff Beach.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean Difference</th>
<th>t-value</th>
<th>2-tail significance</th>
<th>SE of Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug 10</td>
<td>-0.3716</td>
<td>-2.22</td>
<td>0.290</td>
<td>0.167</td>
</tr>
<tr>
<td>Aug 25</td>
<td>0.2395</td>
<td>1.89</td>
<td>0.06</td>
<td>0.126</td>
</tr>
<tr>
<td>Sep 1</td>
<td>0.0589</td>
<td>0.55</td>
<td>0.588</td>
<td>0.109</td>
</tr>
<tr>
<td>Sep 13</td>
<td>-0.4896</td>
<td>-4.74</td>
<td>0.000</td>
<td>0.105</td>
</tr>
</tbody>
</table>

Table 14: Comparison of streak spacings (cm) for each day on Seacliff Beach to spacings for all other days on Seacliff Beach.
7.0 Conclusions

Three major conclusions are suggested by this study. First, quasi-regular streaks of sorted sediment, which consist of coarser grains, and higher concentrations of dark minerals than the adjacent spaces, are a regular feature of swash zones on many sandy beaches. Second, whether visible streaks occur on a particular beach appears to be determined by the sedimentary and morphological characteristics of that beach, rather than by wave conditions or swash velocity. While a significant component of dark mineral grains seems to be necessary for streaking to occur, other factors appear to be important. Finally, the width and spacing of streaks seem to be largely determined by the sedimentary characteristics of the beach. Specifically, streaks on fine-grained beaches may be wider and more widely spaced than those on coarse-grained beaches.

Sediment streaks are important both because of their potential for geological preservation, and as evidence of possible secondary flows in the swash zone. Future research on streaking is therefore needed, both in the field, where the use of video cameras and sediment dye tracers might prove useful, and in the laboratory, where a wave flume would allow researchers greater control over relevant physical parameters. As yet, however, the nature of sediment streaks in the swash zone remains poorly understood, particularly with respect to formative process.
References


Karcz, I. 1973, "Reflection on the origin of some small-scale longitudinal streambed scour.". In Fluvial Geomorphology (M. Morisawa, Ed.): 149-73, Binghamton, N.Y: SUNY.


Vita Auctoris

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