Magnetic mineral transport and sorting in the swash-zone: Northern Lake Erie

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Magnetic mineral transport and sorting in the swash-zone: Northern Lake Erie

by

Eric Gallaway

A Thesis
Submitted to the Faculty of Graduate Studies through the
Department of Earth and Environmental Science
in Partial Fulfillment of the Requirements for
the Degree of Master of Science at the
University of Windsor

Windsor, Ontario, Canada

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Magnetic mineral transport and sorting in the swash-zone: Northern Lake Erie

By

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17 August 2011
Declaration of Co-Authorship / Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

The collaboration occurs in Chapter 2 of the thesis. This chapter contains material that has been submitted for publication. It was coauthored by A.S. Trenhaile, M.T. Cioppa and R. Hatfield who provided advice with the writing, design and analysis for the publication. The key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author of this thesis.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-authors to include the above material in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Declaration of Previous Publication

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<thead>
<tr>
<th>Thesis Chapter</th>
<th>Publication title</th>
<th>Publication status</th>
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<tr>
<td>Chapter 2</td>
<td>Magnetic mineral transport and sorting in the swash zone: Northern Lake Erie, Canada (Manuscript ID SED-2011-OM-113)</td>
<td>Submitted (July 26, 2011) to the journal Sedimentology</td>
</tr>
</tbody>
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ABSTRACT

A study was conducted along the coast of Point Pelee National Park in northern Lake Erie to address uncertainties over the sediment transport of fine magnetic minerals (< 250 μm) in the swash zone. Magnetic tracers (magnetite) were tracked with a magnetic susceptibility meter, and for comparative purposes, fluorescent tracers were also used to track the movement of two sizes (< 250 μm and > 250 μm) of non-magnetic grains (quartz and calcite). Despite higher threshold shear stresses and settling velocities than for the coarse non-magnetic tracers, movement of the magnetic tracers was much slower and less prolonged, with the magnetic tracers eventually being buried and deposited into the upper foreshore. The results suggest, under low to moderate wave energy conditions, magnetic grains remain below the surface in the swash zone and do not contribute to the net sediment transport, and only move during high energy wave conditions.
ACKNOWLEDGEMENTS

This project could not have been completed without the help from a number of individuals.

I would like to thank Dr. Alan Trenhaile and Dr. Maria Cioppa for not only advising and providing their knowledge to this research project but also for providing me with the funding to complete it. A special thanks also goes to Dr. Robert Hatfield for his ideas and assistance on how to conduct the experiments. I also would like to acknowledge Karly Soulliere, Nicholas Falk and Birendra Sapkota for helping me with the field work. A big thank you also goes to Tammy Dobbie for allowing Point Pelee National Park to be the study area and to Melissa Price for assisting me with the use of laboratory equipment. And finally I would like to thank my Fiancée Jennifer Anthony, for inspiring me to obtain a better education.
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CSF = Corey shape factor
D = Diameter of a grain
\( g \) = Acceleration due to gravity
\( H \) = Inductive magnetic field
\( H_b \) = Breaker height
\( M \) = Magnetisation
N = Tracer concentration
\( R \) = Submerged specific gravity of a grain
\( t \) = Elapsed time that the tracer had been in the swash zone at time of sample
T = Wave period
\( V \) = Tracer velocity alongshore
\( \nu \) = Viscosity of water
\( w_s \) = Settling velocity for a spherical grain
\( w_n \) = Settling velocity for a non-spherical grain
\( x \) = Distance of tracer in the longshore direction
\( Y \) = Cross-shore centroid of tracer
\( y \) = Distance of the tracer in the cross-shore direction
\( z \) = Depth of tracer within core
\( \beta \) = Beach slope
\( \varepsilon \) = Surf scaling parameter
\( \kappa \) = Magnetic Susceptibility
\( \rho_g \) = Density of a grain
\( \rho_w \) = Density of water
\( \tau_{cr} \) = Threshold shear stress
\( \omega \) = Wave radian frequency
Chapter I

An Introduction to Sediment Transport, Sorting, Tracing

and Magnetic Susceptibility
1.1 Introduction

The need to better understand coastal processes is driven in part by growing human populations living near the coast, which places increasing demands on the use and management of coastal resources. Among the most important processes are those responsible for sediment transport in the littoral zone. Transport may occur in the longshore direction, which supplies sediment to areas downdrift, and in the cross-shore direction, which is responsible for beach erosion or build-up, and corresponding changes in the slope and other attributes of the beach profile. The direction and amount of sediment transport is the most important component of many coastal systems, contributing to beach morphodynamics, coastal budgets, and to the formation of barrier spits and other coastal features (Trenhaile, 1997; Woodroffe, 2008).

Sediment transport occurs in two zones (Horikama, 1988) - the surf zone and the swash zone (Fig. 1.1). Waves approaching the coast at an oblique angle generate a current, the longshore current, parallel to the shore. The current occurs in the surf zone but is usually strongest on the landward side of the breakpoint (location waves begin to break), and it is absent on the beach face. Mobile sediment is thrown into suspension by the breaking waves and then carried downdrift by this current. Sediment may also be transported along the beach face in a saw tooth pattern within the swash zone. Waves breaking at an angle to the shoreline generate uprush which carries sediment at an angle up the beach. This sediment is then returned back down the beach by the backrush, assisted by the force of gravity, along a path almost perpendicular to the
shoreline. The alternating swash-backwash of the waves therefore causes sediment to migrate alongshore. Sediment transport in the swash zone is more important than the longshore current when the waves approach at high angles, close to perpendicular, to the shore and on beaches of low gradients. However, swash zone transport is particularly important because this is the main location where erosion and accretion occurs, and it can contribute to a large portion of the longshore transport sediment budget (Masselink and Puleo, 2006).

**Figure 1.1** – Sediment transport in the nearshore (Trenhaile 2010).

The effect of grain size and shape on sediment transport has been considered by a number of workers (Komar, 1977; Guillien and Jimenez, 1995; Trenhaile et al., 1996),
but the effect of grain density on sediment transport is usually overlooked (Singerland, 1977; Trenhaile, 1997). Variations in grain density are largely responsible for the separation of heavy minerals (defined as minerals with densities >= to 2900 kg m⁻³) from less dense minerals. Heavy minerals often accumulate in the swash zone (Frihy et al., 1995) and, through selective entrainment and deposition, they form bands or streaks near the high tidal or upper swash zone (Li and Komar, 1992 a,b). Frihy et al. (1995) observed deposits of heavy minerals in areas of erosion and light minerals in areas of accretion along the coast of the Nile Delta. It was concluded that the lighter minerals were selectively removed from the areas of erosion and transported to areas of accretion. Hatfield et al. (2010) have recently identified a similar pattern along the eastern beach of Point Pelee National Park.

In highly transient coastal systems, sediment sorting occurs in conjunction with transport, separating grains of different mineralogy and density. Sorting is the result of many variables, including the rate of sediment accumulation, nature of the sediment surface, mode of grain movement, flow depth and velocity, and the size, shape, and density of the grains (Steidtmann, 1982). The size and weight of heavy minerals often cause the small grains to sink into the spaces between larger grains during sediment transport, thereby displacing coarser grains towards the surface (Clifton, 1969; Sallenger, 1979; Hughes et al., 2000; Komar and Wang, 1984).

There are considerable uncertainties over the modes and the absolute and relative transport rates of heavy minerals on beaches, largely reflecting the difficulty in tracking and modeling sand grain movement. Tracers have been used to model
sediment transport and to avoid the inherent uncertainties of numerical expressions.

Tracers are sediments, with some distinctive characteristic, that are placed into a larger mass of grains in order to measure its movement (Ciavola, 2005). A variety of tracing mechanisms have been used to study the movement of sand in the cross-shore and longshore directions (Yasso, 1966; Teliki, 1966; Trenhaile et al., 1996; Ciavola et al., 1997; Voulgaris, 1998; Nordstron et al., 2003; Baolin et al., 2005). Many of the early tracers were radioactive. This technique involved placing irradiative sand grains along the shoreline and then tracking their movement with a Geiger Counter (White, 1998). Radioactive tracers are no longer generally in use because of strict nuclear laws and their potential, albeit small, effect on the environment (White, 1998).

Fluorescent tracers were introduced in the 1960’s (Yasso, 1966; Teliki, 1966), and they continue to be employed today (Trenhaile et al., 1996; Ciavola et al., 1997; Voulgaris, 1998; Nordstron et al., 2003; Baolin et al., 2005). Tagging fluorescent sand is fairly easy and inexpensive (Ciavola, 2005) but it is time-consuming, as the distributed grains must be counted to determine tracer distribution (White, 1998). Fluorescent tracing uses sand grains coated with a thin coat of fluorescent paint/dye. The fluorescent sediments can then be tracked because they are luminous in the presence of ultra-violet (UV) light. Early studies used products such as beetle resin or acrylic lacquer (thinned with toluene resin) (Yasso, 1966), but more recent applications have employed water-based products such as acrylic dyes (Voulgaris, 1998), which are resistant to abrasion and are non-toxic. Histograms of the grain size distribution for both before and after dying are generally used to determine whether the mean and median
grain size distribution of the sample has been altered by the application of the dye, which would affect its mobility on the beach (White, 1998).

Magnetic properties such as magnetic susceptibility allow for rapid and high resolution tracking of magnetic materials (Thompson and Oldfield, 1986). Magnetic susceptibility is a measure of the ease of magnetization of a material. It is defined by the relationship

\[ M = \kappa H, \]

which can then be reformatted as

\[ \kappa = M / H \]

where \( M \) is the magnetization produced from the application of a specific inductive field \( H \) and the inherent susceptibility \( \kappa \) of a material (Thompson and Oldfield, 1986). Susceptibility values are often used as a proxy for the amount of magnetite in a sedimentary body (Thompson and Oldfield, 1986). Magnetic measurement and analysis are no longer used solely by paleomagnetists, but have become an attractive technique for a variety of Earth Scientists (Thompson and Oldfield, 1986). Magnetically enhanced sand for example has been used to study longshore processes (Van der Post et al., 1995).

Ferrimagnetic behavior in a mineral occurs when unpaired electrons within the mineral align with the rotation of an applied magnetic field, resulting in very high magnetic susceptibility. More prominent minerals present on most beaches, such as quartz, feldspar and calcite (less dense minerals), illustrate diamagnetic behavior,
defined as a negative response to an applied magnetic field. Diamagnetic minerals are not remnant i.e. the magnetization disappears when the magnetic field is removed. Magnetite is a dense ferrimagnetic mineral with a magnetic susceptibility that can be up to 1000 times greater than quartz, feldspar, and calcite (Thompson and Oldfield, 1986). Heavy mineral deposits often contain significant concentrations of magnetite, and magnetic techniques therefore offer the possibility of rapid and high resolution investigation of sediment transport and the effect of hydrological sorting on the composition of natural sediments.

1.2 Purpose of the Research

This thesis presents the results of a research project that used magnetic tracers to characterize the sediment transport and sorting properties of heavy magnetic minerals along the coast of northern Lake Erie. The study was conducted as a follow up to previous work in this area which used magnetic properties to identify sediment sources and transport paths and to identify areas of accelerated beach erosion (Cioppa et al., 2010; Hatfield et al., 2010). Those investigations raised questions regarding modes and rates of magnetic mineral transport in this area. The main chapter of this thesis, chapter 2, is a manuscript that was been submitted to the journal Sedimentology on the 26th of July, 2011 (Manuscript ID SED-2011-OM-113).
1.3 Hypotheses

The main hypotheses of this work were:

a) The longshore and cross-shore transport of heavy magnetic minerals is significantly slower than that of the more dominant non-magnetic minerals present on the beach. This is a result of the sinking of the heavy minerals due to their smaller grain size and greater weight.

b) Placer deposits or concentrations of heavy magnetic minerals are the result of erosion and removal of lighter non-magnetic minerals during storms, leaving behind the magnetic minerals.
Bibliography


Chapter II

Magnetic Mineral Transport and Sorting

This chapter has been submitted, in a slightly modified form, to the journal *Sedimentology* as a manuscript entitled, “Magnetic mineral transport and sorting in the swash-zone: Northern Lake Erie, Canada”
2.1 Introduction

Beach sediment sorting is the result of a number of variables working together, or independently, to separate grains with different characteristics. These variables include the rate of sediment accumulation, nature of the sediment surface, mode of grain movement, flow depth, velocity and other characteristics, and the size, shape, and density of the grains (Steidtmann, 1982). Sediment sorting is sensitive to variations in grain density and particularly to the abundance and mineralogy of the heavy mineral component. Consequently, heavy minerals, which are often magnetic, are frequently concentrated in beach placers, sand dunes, and beach ridges (Komar and Wang, 1984; Peterson et al., 1986; Li and Komar, 1992a,b; Frihy et al., 1995; McCubbin et al., 2000; Hughes et al., 2000; Hou et al., 2003; Bryan et al., 2007). Heavy minerals accumulate on beaches in bands or streaks near the high tidal level or in the upper swash zone, as well as in the troughs of ripples and where there are shells, coarse clasts, or other flow obstructions (Li and Komar, 1992a; Frihy et al., 1995). Viewed in cross section, the upper swash zone frequently consists of layers of fine, heavy minerals, grading upwards into layers of coarser sediment. These alternating layers are between about 1 and 25 mm in thickness, and they typically extend along the beach for a few tens of meters (Clifton, 1969).

It is has been assumed that because small, heavy mineral grains are shielded from the flow by larger quartz and other grains, they are less easily entrained and are therefore carried alongshore less rapidly than the larger, less dense grains, even when they have the same settling velocity (Slingerland, 1977; Trask and Hand, 1985). Heavy
mineral concentrations in the cross-shore direction have been attributed to heavy minerals being carried onshore by higher current velocities, but not by the weaker offshore flows (wave current asymmetry), or to beach erosion and offshore transport of the lighter, more easily mobilized grains (Komar and Wang, 1984). In the swash zone, it has been proposed that shear sorting by swash and backwash causes the coarser, or lighter, grains to migrate upwards into the zone of lower shear, while the finer, or heavier, grains move downwards, into the zone of maximum shear at the bed. Alternately, smaller particles may tend to fall into the spaces between the larger grains, thereby displacing coarser grains towards the surface (Clifton, 1969; Sallenger, 1979; Hughes et al., 2000; Komar and Wang, 1984).

The analysis of heavy magnetic minerals has been used in coastal environments to determine the chronology of pollution and deposition in estuaries, salt marshes, and tidal flats, and to investigate sediment provenance, transport paths, and depositional processes (Foster et al., 1991; Razjigaeva and Naumova, 1992; Oldfield and Yu, 1994; Lees and Pethick, 1995; Wheeler et al., 1999; Lario et al., 2001; Kean, 2004; Plater and Appleby, 2004; Booth et al., 2005; Zhang et al., 2007; Maher et al., 2008; Rotman et al., 2008; Cioppa et al., 2010). Along the Nile Delta, Frihy et al. (1995) and Frihy and Dewidar (2003) distinguished areas of erosion with a concentration of heavier and denser minerals and areas of deposition with a higher proportion of lighter minerals. More recently, Hatfield et al. (2010) conducted a similar study based on the distribution of heavy magnetic minerals along the beaches of eastern Point Pelee, in northwestern Lake Erie, Canada.
Heavy mineral deposits often contain significant concentrations of magnetite and other ferromagnetic oxides (Hatfield et al., 2010). Although magnetic techniques are therefore potentially useful tools for coastal investigations, we presently lack sufficient understanding of the mechanisms responsible for magnetic mineral sorting, concentration, and transportation on the foreshore. To advance the understanding of the behavior of magnetic material on beaches dominated by non-magnetic grains, a study was conducted to examine the movement of magnetic sediment in the swash zone along the northwestern coast of Lake Erie. This study built on previous work in this area which used magnetic properties to trace sand sources and transport paths and to identify areas of accelerated beach erosion (Cioppa et al., 2010; Hatfield et al., 2010). Those investigations raised questions regarding modes and rates of magnetic mineral transport in this area, and whether the relationship between magnetic and non-magnetic grain transport could be used to determine rates of longshore transport along a quartz-dominated coast.

2.1.1 Study Area

The study was conducted at Point Pelee National Park (PPNP), a long cuspate foreland on the north-eastern shore of Lake Erie. Point Pelee extends approximately 15 km into Lake Erie, with the southern 9 km forming PPNP (Fig. 2.1). Work was conducted on a fairly secluded section of the beach on the eastern side, at sites ranging
approximately 1 to 5 km north of the tip. Beach widths range from 3-40 m along the eastern coast (Hatfield et al., 2010). It has been estimated that the erosion rates between 1918 and 1973 were 0.4 to 2.8 m (Coakley, 1980). Alongshore transport rates were estimated to be between 6000 m$^3$ year$^{-1}$ and 19 000 m$^3$ year$^{-1}$ (Kamphuis, 1972; Skafel et al., 1985; Trenhaile et al., 2000), although because of the construction of permanent structures northeast of the Point, these rates are likely to be lower at present.

There are thick and extensive deposits of heavy magnetic minerals on the eastern beach (Fig. 2.2). These deposits, which extend for a total distance of 2.4 km, are most prominent in areas that are experiencing accelerated erosion (Hatfield et al., 2010). Magnetic remanence measurements demonstrated that the magnetic properties are dominated by multidomain ferrimagnetic grains, most certainly magnetite and/or maghemite. Particle size-specific measurements also showed that the <250 μm fraction of the beach sands was responsible for the majority of the bulk magnetic signal. X-ray diffraction analysis indicated that the non-magnetic grains on the beach are primarily quartz and calcite grains (Hatfield et al., 2010). Understanding how and when heavy minerals are transported along this coast may help us to understand and predict how the form and existence of the East Beach may alter in the future.
Figure 2.1 – Study area of this project is located at Point Pelee National Park which is located on the north shore of Lake Erie.
Figure 2.2 – Heavy magnetic minerals are present along the beach of Point Pelee. Deposits can be seen exposed on the beach surface (a) or by digging down into the beach, where they are often seen layered among non-magnetic sand (b).
2.2 Methodology

Although this study was concerned primarily with the transport of heavy magnetic minerals in the swash zone, some experiments were also run, for comparative purposes, to investigate the movement of lighter, non-magnetic minerals. Heavy magnetic tracers were tracked by recording changes in magnetic susceptibility and non-magnetic tracers using fluorescent paint and sediment coring. Twenty-one magnetic and two concurrent non-magnetic tracing experiments were conducted between July and November 2010. However, because of equipment malfunctions and beach conditions, the final analysis used data from 19 tracing experiments. Another six non-magnetic experiments were conducted without simultaneous magnetic tracing to provide additional information on the movement of non-magnetic grains under conditions similar to those conducted with the magnetic tracers. Accompanying laboratory measurements were also undertaken to investigate grain sorting and heavy magnetic mineral burial under controlled conditions.

2.2.1 Tracer Preparation

Sand was removed from the beaches in the study area and dried. A rare-earth magnet was used to separate the grains into its magnetic and non-magnetic components. The term ‘non-magnetic’ is used in this paper to refer to the residual sand that had a weak magnetic moment and could not be extracted with the rare-earth
magnet, and ‘magnetic’ for sand with a strong positive susceptibility that was extracted by the magnet.

The magnetic properties of the magnetic grains were used to identify these grains, but fluorescent paints were used for the non-magnetic tracers. Two types of paint were considered for this study, an acrylic ‘screen printing ink’ manufactured by Speedball Art Products (Statesville, North Carolina), and an alkyd enamel (oil paint) manufactured by Macdonald and White Varnish and Paint Company (Windsor, Ontario). Before any paint was applied, the non-magnetic sand was sieved to determine the grain size distribution. The paints were thinned, using water for the acrylic paint and mineral spirits for the enamel paint, and then hand mixed with the sand. An equal volume of water and paint produced a dye with a consistency a little thicker than water, and a ratio of 200 ml of thinned paint to 900 g of sand produced just enough thinned paint to coat all the grains without leaving any excess within the mixture.

Tests were then conducted to determine whether these paint applications satisfied the fluorescent tracer criteria of Yasso (1966). These include the requirements that the coat of paint on the sand grains should be thin, so that it does not markedly alter the hydrodynamic behaviour of the grains, and be resistant to abrasion and dissolution in water. The painted sand was air dried for 16 hours and then oven-dried for 2 hours at 70°C. After drying, the sand was placed in a sieve-shaker for 1 hour, to determine the modified grain size distribution and to break up any clumps that may have developed. The mean and median grain size, skewness, and kurtosis were then compared to the same parameters for the original, pre-painted grain size distribution.
Figure 2.3 – Grain size distributions of sand before and after the application of paint are displayed in the below graphs. The table shows the resulting mean, median, skewness, kurtosis and sorting before and after the paint was applied.

<table>
<thead>
<tr>
<th></th>
<th>Acrylic (1)</th>
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<th>Acrylic (3)</th>
<th>Enamel</th>
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<td>After</td>
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<tr>
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<td>1.00</td>
</tr>
<tr>
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<td>0.75</td>
<td>0.69</td>
<td>0.76</td>
</tr>
</tbody>
</table>

■ Before Paint   □ After Paint
(Fig. 2.3). Initial tests showed the acrylic paint changed the mean grain size by 0.13 phi while the enamel paint changed the mean grain size by 0.88 phi (Fig. 2.3). Because the acrylic coat showed limited change in grain size compared with the oil paint, the acrylic paint was retested an additional two times in order to confirm that changes in tracer grain size were minimal. To ensure that this acrylic coat was also resistant to abrasion and dissolution, the sand was placed in a pan with water and shaken for 1 hour. After drying, the sand was mixed with non-dyed sand then placed under UV light to ensure that the grains still fluoresced and thus could be distinguished from the non-dyed grains in cores. Different acrylic colours were used for the non-magnetic tracers, according to the grain size. A green paint was used for grains of < 250 μm (mean grain size of 209 μm), and pink for grains >250 μm (mean grain size of 483 μm). This distinction allowed a direct comparison to be made between magnetic grains and non-magnetic grains (< 250 μm) of roughly the same size, based on the observation that heavy magnetic grains in the study area are primarily < 250 μm in size (Hatfield et al., 2010). The magnetic tracer had a mean grain size of 178 μm.

2.2.2 Tracer Tracking

Tracer movement in the swash zone was measured with reference to markers placed at 0.2 m intervals along the beach, landwards of the maximum swash uprush, for 7 m in the downdrift direction and 2 m in the updrift direction (Fig. 2.4). The length of this experimental track was based on preliminary experiments that showed that the
tracers did not move beyond these boundaries during the several hours of each experiment. The location where the tracer was released was labelled as 0 m alongshore. The magnetic and non-magnetic tracers were saturated with water in a bag before being released into the swash zone at the 0 m longshore location. The width of the swash zone determined the amount of tracer that was used; 750 g when less than 3 m, 1500 g when 3-5 m, and 3000 g when > 5 m for the magnetic tracer. For the non-magnetic experiments, 750 g of the green and 750 g of the pink tracer were used when the swash zone was less than 3 m wide, and 1500 g when greater than 3 m.

Longshore and cross-shore magnetic susceptibility measurements were made with a Bartington MS2 susceptibility meter with a 0.2 m diameter D probe. Consequently, all measurements, which covered the entire swash zone, were made within 0.2 m square cells (Fig. 2.4), the cross-shore measurements being taken by carefully reaching over the swash zone to avoid trampling on it and disturbing the grain distributions. The one exception to this procedure was in magnetic tracer run 18, which had a 6 m – wide swash zone. Because the researcher would have had to enter, and therefore disturb, this wide swash zone during the experiment to take sample readings, the distribution of the tracer was recorded only at the end of this experiment.

The background magnetic susceptibility was recorded in each of the cells before each magnetic tracing experiment. This was done because though the bulk of Point Pelee sand is largely non-magnetic grains, there is a low magnetic susceptibility signal in the swash zone that is likely due to the presence of a small amount of magnetic grains. Magnetic tracer was then distributed evenly along the 0 m marker, extending from the
minimum extent of the uprush to approximately 0.4 - 1 m lakewards, depending on the 
breaker height and swash zone width. Magnetic susceptibility measurements were 
made in each cell, moving downdrift until the magnetic susceptibility values returned to 
the background values, at intervals ranging from 5-30 minutes, for up to 3.5 hours, 
depending on rates of movement and grain burial.

**Figure 2.4** – Set up of the sampling grid for both magnetic tracing experiments and non-
magnetic experiments. The magnetic experiments had magnetic susceptibility readings taken 
every 0.2 m in both the longshore and cross-shore direction (sample locations represented by 
the squares). The non-magnetic experiments had cores taken every 0.2 m in the longshore 
direction and 0.5 m in the cross-shore direction (sample locations represented by the crosses).

Movement of the non-magnetic tracer was recorded by extracting sediment 
cores in glass containers, 15 mm in diameter, and 50 mm in depth, at 0.2 m intervals 
alongshore and at 0.5 m intervals cross-shore, across the entire width of the swash 
zone. Because of its invasive nature and inevitable disturbance of the sand, core 
collection was conducted only at the end of each experiment, after 1-2 hours. The cores 
were taken and examined under UV light in the laboratory to determine the number of 
grains in each core. Additionally the depths of the grains were recorded within 2 mm 
increments. To minimize disturbance, including changes in tracer depth which might
have arisen from drying, the number of fluorescent grains of each colour were counted only through the glass container, from the outer perimeter of the cores.

Breaker height, period and swash direction were recorded to relate tracer movement to the prevailing wave conditions during each experiment. Measurements were also made of the beach gradient, swash zone grain size, swash velocity and swash zone width. The breaker height and swash width were measured with a tape measure and the wave angle with a compass. Wave period was recorded by counting the number of breaking waves during a 90 second period. Swash velocity was found by dividing the average swash width by the time required to move from its breaking position to its maximum up rush; this procedure was repeated 10 times and the velocities were then averaged. The beach gradient was determined from the length of the vertical rise and the corresponding horizontal length. All these parameters were recorded every 1-1.5 hrs during both the magnetic and non-magnetic tracer experiments, and then averaged. The swash zone grain size distribution was obtained by sieving 0.5-1 kg samples taken from the swash zone before and after the tracing experiments. The samples were taken just outside of the sampling grid to avoid disturbance to the bed in the experimental tract.

2.2.3 Tracer Centroid Calculation

A spatial integration method was applied to each of the longshore tracer distributions (Crickmore and Lean, 1962; Komar and Inman, 1970; White and Inman,
1989; Ciavola et al., 1997; Nordstrom et al., 2003; Tonk et al., 2005). The longshore velocity of the tracers, which is considered to be represented by the movement of the centroid of the tracer cloud, was determined using the expression:

\[ V = \frac{\sum_{(x,y)}^{N} N(x, y, t') \frac{x}{t}}{\sum_{(x,y)}^{N} N(x, y, t')} \]

Where \( V \) is the tracer velocity, \( N \) is the tracer concentration, \( x \) is the longshore distance from the location of tracer injection, \( y \) is the distance up the swash zone, and \( t \) is the elapsed time since the tracer sample was released. For the cross-shore centroid:

\[ Y = \frac{\sum_{(x,y)}^{N} N(x, y) y}{\sum_{(x,y)}^{N} N(x, y)} \]

Tracer depth (\( z \)) rather than cross-shore location was used to locate the centroid depth of the non-magnetic fluorescent tracers within the cores. Magnetic tracer concentrations were represented by the magnetic susceptibility values, using only values that were greater than the background values in the swash zone. For the non-magnetic tracers, the concentrations were represented by the number of grains of each colour that were counted along the perimeter of each core as a percentage of the total number of grains of that colour counted in all the cores.

### 2.2.4 Laboratory Experiments

To investigate the effect of small, heavy mineral grain burial on magnetic susceptibility measurements, 300 g of magnetic tracer were distributed in a layer, about 1 mm thick, on top of non-magnetic sand in a 400 x 500 mm plastic box. The
magnetic susceptibility of the surface was recorded at 6 points on the surface to
determine the mean value. A fixed volume of non-magnetic sand, equivalent to a 2 mm
layer, was then laid evenly on top of the magnetic grains and the magnetic susceptibility
of the surface was recorded again at the same 6 locations. This procedure was repeated
as additional 2 mm thick layers of non-magnetic sand were added to the container. The
experiment concluded when the magnetic layer had been buried under 84 mm of non-
magnetic sand.

A second experiment was conducted in the laboratory to investigate the effect of
non-magnetic grain size on magnetic sand burial rates. Non-magnetic sand from Point
Pelee was sieved and separated into grain size ranges of 2.83 – 2.00 mm (-1.5 to -1 φ), 1
– 0.71 mm (0 to 0.5 φ), 0.71 – 0.50 mm (0.5 to 1 φ), and 0.50 – 0.35 mm (1 to 1.5 φ)
grain sizes. Each size fraction was put into separate cylindrical plastic containers
(diameter 300 mm) to a depth of 100 mm. Water was then added to each container
until it was 10 mm above the top of the sand, and 100 g of magnetic tracer was then
spread out evenly over the surface. The magnetic susceptibility was measured on the
surface of each container at four locations around the perimeter and at one point in the
centre to obtain an average. The containers were then shaken at a speed of 50 rotations
per minute using an electric agitator for 1 minute. The magnetic susceptibility was then
recorded at the same points on the sand surface. This was repeated 22 times, recording
the susceptibility every 1 minute for a total agitation time of 22 minutes. The same
experimental procedure was also conducted using a faster agitation speed of 70
rotations per minute.
2.3 Results

2.3.1 Field results

Longshore rates of transport of the magnetic tracers decreased through time in almost all the experiments. Rates of movement were usually between 0.51 and 2.87 m hr\(^{-1}\) in the first 10 minutes and less than 0.1 m hr\(^{-1}\) after being in the swash zone for 1 to 2 hours. Tracer movement had stopped completely after a few hours in about half the runs, and by the next morning in most others (Fig. 2.5). For example during run 5, after 87 minutes of movement the tracer centroid was located 0.09 m from the initial location (point of release), and all of the tracer was within 0.6 m of the release point. After another hour, the tracer was still entirely within the 0.6 m distance, with the centroid between 0.07-0.08 m. Movement was similar in runs 1, 2, 5, 6, 9, 11, 12, 14 and 19, but it was generally more prolonged in runs with higher breakers. For instance, during Run 5 the tracer centroid continued to move for approximately 87 minutes, whereas in Run 14, which had maximum breakers heights that were twice as high, the centroid moved for 167 minutes (Table 2.1). In the cross-shore direction, the magnetic tracers moved landwards during all the experiments generally into the upper 60 to 80 % of the swash zone (Table 2.1).

The longshore velocity of the finer non-magnetic tracers (diameter < 250 µm) was between 0.70 m hr\(^{-1}\) and 2.67 m hr\(^{-1}\), and for the larger non-magnetic tracers (diameter > 250 µm) between 1.00 m hr\(^{-1}\) and 2.58 m hr\(^{-1}\). In combined experiments Run
Figure 2.5 – The magnetic tracers velocity are displayed vs. the time it had been in the swash zone. The coincident percent of initial magnetic susceptibility of the tracer is also displayed vs time.
Table 2.1 – Wave conditions during the experiments. Runs that are numbered represent magnetic tracer runs and lettered represent non-magnetic runs. Runs 20 and G were concurrent, as were runs 21 and H. The values for the coarser non-magnetic grains velocities and cross-shore positions are the first values followed by the finer non-magnetic values. ε represents the surf scaling parameter.

<table>
<thead>
<tr>
<th>Run</th>
<th>Tracer Velocity at 60 mins (m hr$^{-1}$)</th>
<th>% up cross-shore</th>
<th>Swash Grain Size (μ)</th>
<th>Wave Angle (°)</th>
<th>Swash Width (m)</th>
<th>Period T (s)</th>
<th>Breaker Height (m)</th>
<th>Gradient (°)</th>
<th>Swash Velocity (m/s)</th>
<th>ε</th>
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<td>1</td>
<td>0.01</td>
<td>76</td>
<td>-0.32</td>
<td>0.0</td>
<td>1.20 to 1.55</td>
<td>1.80</td>
<td>0.17 to 0.23</td>
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<td>0.55</td>
<td>5.6</td>
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<tr>
<td>2</td>
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<td>73</td>
<td>0.61</td>
<td>2.0</td>
<td>1.33 to 2.00</td>
<td>3.71</td>
<td>0.23 to 0.37</td>
<td>7.8</td>
<td>0.59</td>
<td>2.9</td>
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<tr>
<td>3</td>
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<td>64</td>
<td>-1.52</td>
<td>8.0</td>
<td>1.33 to 1.80</td>
<td>4.54</td>
<td>0.13 t 0.20</td>
<td>4.7</td>
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<td>86</td>
<td>0.90</td>
<td>4.0</td>
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<td>2.38</td>
<td>0.08 to 0.11</td>
<td>6.4</td>
<td>0.53</td>
<td>3.0</td>
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<td>71</td>
<td>-0.11</td>
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<td>1.13 to 1.80</td>
<td>2.31</td>
<td>0.15 to 0.22</td>
<td>6.4</td>
<td>0.69</td>
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<td>0.80 to 1.20</td>
<td>4.59</td>
<td>0.06 to 0.09</td>
<td>9.0</td>
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<td>4.51</td>
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<td>6.9</td>
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<td>2.60 to 3.53</td>
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<td>0.42</td>
<td>8.0</td>
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<td>3.33</td>
<td>0.30 to 0.80</td>
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<td>6.6</td>
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<td>16</td>
<td>0.72</td>
<td>74</td>
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<td>10.0</td>
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<td>3.46</td>
<td>0.25 to 0.54</td>
<td>7.1</td>
<td>1.14</td>
<td>5.8</td>
</tr>
<tr>
<td>17</td>
<td>0.18</td>
<td>83</td>
<td>1.10</td>
<td>2.7</td>
<td>1.60 to 2.73</td>
<td>2.21</td>
<td>0.21 to 0.32</td>
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<td>5.7</td>
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<td>18</td>
<td>1.25</td>
<td>78</td>
<td>0.95</td>
<td>2.0</td>
<td>4.00 to 6.00</td>
<td>3.46</td>
<td>0.50 to 1.00</td>
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<td>1.47</td>
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<td>0.79</td>
<td>75</td>
<td>1.02</td>
<td>3.3</td>
<td>2.00 to 2.68</td>
<td>2.68</td>
<td>0.25 to 0.49</td>
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<td>8.4</td>
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<tr>
<td>20</td>
<td>0.31</td>
<td>61</td>
<td>1.43</td>
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<td>0.40 to 0.60</td>
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<td>21</td>
<td>0.30</td>
<td>46</td>
<td>1.41</td>
<td>6.0</td>
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<td>3.46</td>
<td>0.20 to 0.32</td>
<td>6.9</td>
<td>0.74</td>
<td>3.6</td>
</tr>
</tbody>
</table>

| A   | 2.33/1.61                             | 53/58            | 1.46                 | 6             | 1.30 to 1.55    | 3.21        | 0.18 to 0.30        | 6.5         | 0.56                | 4.6 |
| B   | 2.58/2.67                             | 60/69            | 0.42                 | 10            | 1.50 to 2.50    | 3.05        | 0.20 to 0.43        | 6.1         | 0.70                | 8.2 |
| C   | 2.17/1.73                             | 74/62            | 0.87                 | 8             | 1.65 to 2.25    | 2.96        | 0.18 to 0.31        | 6.6         | 0.71                | 5.3 |
| D   | 2.31/2.63                             | 68/71            | 0.93                 | 9             | 1.50 to 1.95    | 2.81        | 0.13 to 0.24        | 7.3         | 0.75                | 3.7 |
| E   | 1.00/0.70                             | 72/67            | -0.02                | 6             | 0.90 to 1.50    | 3.53        | 0.12 to 0.15        | 7.3         | 0.53                | 1.3 |
| F   | 1.43/1.07                             | 76/69            | 0.31                 | 6             | 1.50 to 2.20    | 3.18        | 0.12 to 0.15        | 7.1         | 0.62                | 1.9 |
| G   | 2.33/2.13                             | 57/61            | 1.43                 | 2             | 1.80 to 3.00    | 2.43        | 0.40 to 0.60        | 7.7         | 0.90                | 11.2 |
| H   | 2.56/2.59                             | 66/65            | 1.41                 | 6             | 1.40 to 2.00    | 3.46        | 0.20 to 0.32        | 6.9         | 0.74                | 3.6 |
Figure 2.6 – Distribution of the magnetic and non-magnetic grains during simultaneous runs after 60 mins. The distribution was interpolated using an inverse distance weighted algorithm.

a) Runs 20 and G

Distance alongshore (m)

% Tracer
0 1.321 - 1.65
0.331 - 0.66 1.651 - 2.05
0.661 - 0.99 2.051 - 2.5
0.991 - 1.32

Tracer release point
Sample points

Magnetic

Finer non-magnetic

Coarser non-magnetic

b) Runs 21 and H

Distance alongshore (m)

% Tracer
0 3.01 - 3.75
0.51 - 1.5 3.76 - 4.5
1.51 - 2.25 5.01 - 7
2.26 - 3 7.01 - 14

Tracer release point
Sample points

Magnetic

Finer non-magnetic

Coarser non-magnetic
20 and Run G, which employed both magnetic and non-magnetic tracers, the magnetic tracer had a mean longshore velocity over the first hour of 0.31 m hr⁻¹, compared with 2.13 m hr⁻¹ and 2.33 m hr⁻¹ for the finer and coarser non-magnetic tracers respectively (Table 2.1; Fig. 2.6 a). The corresponding figures in Run 21 and Run H, which also used magnetic and non-magnetic tracers, were 0.30, 2.56, and 2.59 m hr⁻¹, respectively (Table 2.1; Fig. 2.6 b). There was typically a small amount of tracer seen at the 7 m marker. This means that the longshore centroid could be further downdrift than calculated, indicating that the longshore velocities may be somewhat faster than those given herein.

There was one clear exception to the general decrease in alongshore velocity. In Run 3, once the longshore movement of the magnetic tracer centroid had fallen to about 0.12 m hr⁻¹, which occurred after about 37 minutes, it continued to move alongshore at this velocity for the next 113 minutes (Fig. 2.5); it is not known whether the magnetic tracers continued to move alongshore after that time. The reason for protracted longshore transport in this run is unclear, particularly as its only distinguishing characteristics were the particularly coarse surface sediment in the swash zone (-1.52 Φ, 2.87 mm), which should have promoted magnetic grain shielding, and burial, and the gentle swash zone gradient (Table 2.1).

Because higher energy conditions were less frequent than lower energy conditions over the experimental period, the distributions of such variables as breaker height, swash velocity, and rates of transport had a positive skew. To produce more normal distributions for correlation and regression analyses, log-log and log-linear
transformations were made to the data. Additionally, because rates of movement of the magnetic tracers decreased through time, movement over the first hour of the experiments was used to analyze relationships with various experimental conditions. As coring was only conducted at the end of the experiments, correlations were made between the movement of the non-magnetic tracers and prevailing conditions over the entire experimental periods.

The tracer velocities showed significant correlations to two of the wave parameters. At a 95% confidence level the log of the breaker height was correlated to the log of the velocities of all three tracers (Table 2.2 a; Fig. 2.7). The log of the swash velocity was also correlated to the velocities of the magnetic and finer non-magnetic velocities at the 95 % confidence level. The coarser non-magnetic grains showed a correlation but only at a 90% confidence level. There were no correlations found to the log of the wave period or wave angle for any of the tracers (Table 2.2 a).

There were also high significant correlations between the cross-shore position (% distance of the centroid up the swash zone) and the log of the breaker height for the coarser non-magnetic tracer, but the correlation was insignificant for the magnetic and the finer non-magnetic tracers (Table 2.2 b; Fig. 2.7). This was the only correlation observed between any of the tracer cross-shore positions with the wave parameters (Table 2.2 b).

Several dimensionless parameters have been used to analyze relationships between beach morphology and processes and breaker type, wave run-up, and wave reflection and dissipation (Galvin, 1972; Battjes, 1974). The surf scaling parameter (Guza
and Inman, 1975; Guza and Bowen, 1975) combines variables describing wave conditions and beach morphology:

\[ \epsilon = \frac{H_b \omega^2}{2g \tan^2 \beta} \]

where \( \epsilon \) is the surf scaling parameter, \( H_b \) is the breaking wave height, \( g \) is the acceleration due to gravity, \( \beta \) is the beach slope, and \( \omega \), the wave radian frequency, is equal to \( 2\pi/T \), where \( T \) is the wave period. There were significant correlations between the log of the longshore velocities and log of the surf scaling parameter for all three of the tracers, but the correlations were much lower for the magnetic tracer (Table 2.2 a; Fig. 2.7). There was also a small correlation between the cross-shore position of the coarser non-magnetic tracer to the log of the surf scaling parameter, but only at a 90% confidence level (Table 2.2 b).

The difference in the initial magnetic susceptibility measured at the sample release point and the total of the susceptibility recorded in each of the grid cells at the end of the experiments is a measure of the degree to which the small, heavy magnetic minerals sank below, and were buried by, the larger and lighter non-magnetic minerals. There was generally a decrease in the total magnetic susceptibility as the experiments progressed. Sudden increases in the magnetic susceptibility did occur in some runs, however, when a single wave or a series of waves washed away the lighter grains, re-exposing the magnetic grains below (Fig. 2.5). For example, run 2 showed a decrease in magnetic susceptibility as well as a decrease in velocity in the first 20 minutes. Continuous sampling indicated that the magnetic susceptibility along with the velocity then increased, allowing the tracer to continue moving until the 75 minute mark when
Table 2.2 – Regression analysis of the dependent variables a) tracer velocity at 60 minutes b) the cross-shore position of the tracer c) the magnetic tracers’ % of initial magnetic susceptibility at 60 minutes. Relationships denoted with the symbol * are significant at the 95% confidence level while relationships with the symbol + are significant at the 90 % confidence level. Df signifies degrees of freedom, Sigf the significant f values, b0 signifies the y intercept and b1 signifies the slope of the relationship. ε signifies surf scaling parameter.

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<thead>
<tr>
<th>a) Dependent</th>
<th>Tracer Velocity (log)</th>
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<tbody>
<tr>
<td>Tracer</td>
<td>Independent</td>
</tr>
<tr>
<td>*Magnetic</td>
<td>Hb (log)</td>
</tr>
<tr>
<td>*Non-mag. (coarse)</td>
<td>Hb (log)</td>
</tr>
<tr>
<td>*Non-mag. (fine)</td>
<td>Hb (log)</td>
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<tr>
<td>*Magnetic</td>
<td>ε (log)</td>
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<td>*Non-mag. (coarse)</td>
<td>ε (log)</td>
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<tr>
<td>*Non-mag. (fine)</td>
<td>ε (log)</td>
</tr>
<tr>
<td>*Magnetic</td>
<td>Swash Velocity (log)</td>
</tr>
<tr>
<td>+Non-mag. (coarse)</td>
<td>Swash Velocity (log)</td>
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<tr>
<td>*Non-mag. (fine)</td>
<td>Swash Velocity (log)</td>
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<tr>
<td>Magnetic</td>
<td>Period (log)</td>
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<tr>
<td>Non-mag. (coarse)</td>
<td>Period (log)</td>
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<tr>
<td>Non-mag. (fine)</td>
<td>Period (log)</td>
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<tr>
<td>Magnetic</td>
<td>Wave angle</td>
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<tr>
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<td>Wave angle</td>
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<td>Non-mag. (fine)</td>
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</tr>
<tr>
<td>Magnetic</td>
<td>Angle (log)</td>
</tr>
<tr>
<td>+Magnetic</td>
<td>Swash Grain size (log)</td>
</tr>
</tbody>
</table>
Table 2.2 d – Regression results of the relationships between the centroid of the non-magnetic grains (coarse and fine), vs. wave and beach parameters. Df signifies degrees of freedom, Sigf signifies the significant f values, b0 signifies the y intercept and b1 signifies the slope of the relationship.

<table>
<thead>
<tr>
<th>d) Dependent</th>
<th>Tracer depth</th>
<th>R²</th>
<th>Df</th>
<th>F</th>
<th>Sigf</th>
<th>b0</th>
<th>b1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-mag. (coarse)</td>
<td>Hb</td>
<td>0.001</td>
<td>6</td>
<td>0.009</td>
<td>0.928</td>
<td>0.6814</td>
<td>-0.0768</td>
</tr>
<tr>
<td>Non-mag. (fine)</td>
<td>Hb</td>
<td>0</td>
<td>6</td>
<td>0.001</td>
<td>0.971</td>
<td>0.8486</td>
<td>0.0283</td>
</tr>
<tr>
<td>Non-mag. (coarse)</td>
<td>∊</td>
<td>0.014</td>
<td>6</td>
<td>0.080</td>
<td>0.783</td>
<td>0.6053</td>
<td>0.0105</td>
</tr>
<tr>
<td>Non-mag. (fine)</td>
<td>∊</td>
<td>0.007</td>
<td>6</td>
<td>0.040</td>
<td>0.849</td>
<td>0.8067</td>
<td>0.0066</td>
</tr>
<tr>
<td>Non-mag. (coarse)</td>
<td>Swash Velocity</td>
<td>0.130</td>
<td>6</td>
<td>0.130</td>
<td>0.731</td>
<td>0.4059</td>
<td>0.3651</td>
</tr>
<tr>
<td>Non-mag. (fine)</td>
<td>Swash Velocity</td>
<td>0.070</td>
<td>6</td>
<td>0.700</td>
<td>0.434</td>
<td>0.3287</td>
<td>0.7415</td>
</tr>
<tr>
<td>Non-mag. (coarse)</td>
<td>Period</td>
<td>0.062</td>
<td>6</td>
<td>0.390</td>
<td>0.533</td>
<td>1.2926</td>
<td>-0.2063</td>
</tr>
<tr>
<td>Non-mag. (fine)</td>
<td>Period</td>
<td>0.037</td>
<td>6</td>
<td>0.230</td>
<td>0.646</td>
<td>1.2921</td>
<td>-0.1469</td>
</tr>
<tr>
<td>Non-mag. (coarse)</td>
<td>Swash Grain size</td>
<td>0.261</td>
<td>6</td>
<td>2.210</td>
<td>0.195</td>
<td>0.8830</td>
<td>-0.2649</td>
</tr>
<tr>
<td>Non-mag. (fine)</td>
<td>Swash Grain size</td>
<td>0.182</td>
<td>6</td>
<td>1.330</td>
<td>0.292</td>
<td>1.0115</td>
<td>-0.2018</td>
</tr>
</tbody>
</table>

Figure 2.7 - Regression analysis showing relationships significant at the 95% confidence level between the tracer distributions and wave and beach parameters.
longshore movement stopped and there was a decrease in magnetic susceptibility. There was a fairly low but significant correlation at the 90% confidence level between the reduction in total magnetic susceptibility over the first hour of the experiments and the log of the swash zone grain size, but all other correlations with wave and swash zone conditions were insignificant (Table 2.2 c).

Seven of the experiments were revisited 24 hours after the tracer release to examine the long term distribution. Run 8 had 65 % of the tracers’ original magnetic susceptibility signal located within 0.8 m of the release point. Run 4, 10 and 12 had 38%, 41%, and 26% of the initial magnetic susceptibility within 0.8 m of the release point, respectively, and runs 5, 9 and 16 between 7 and 14% the initial magnetic susceptibility within 1.2 m of the release point. The centroid of the tracer during all the experiments was on average 0.32 m from the location it was located at the previous day. The close proximity of the magnetic susceptibility signal to the release point suggests after the tracer stopped moving they then remained at the same location within the swash zone and continued being buried by the non-magnetic material.

At the end of each experiment, the finer non-magnetic tracer grains were located deeper within the cores than the coarser non-magnetic tracers (Fig 2.8). The centroid of the finer tracer ranged from depths of 3.2 to 12 mm and the centroid of the coarser tracer from 2.4 to 10 mm. There were no significant correlations between the depth of the tracers within the cores and any wave or swash parameters (Table 2.2 d).
2.3.2 Laboratory Results

Laboratory experiments showed that magnetic susceptibility decreases exponentially with the depth of burial beneath non-magnetic grains (Fig. 2.9 a). There were rapid decreases in magnetic susceptibility when magnetic grains were buried under up to a few millimeters of non-magnetic material and slower decreases thereafter, particularly once the magnetic grains were more than about 25 to 40 mm below the surface. The laboratory experiments demonstrated that rates and depths of burial of the magnetic minerals were much greater when the grain size of the non-magnetic grains was 2.00 - 2.83 mm (-1.5 to -1Φ), about 11 times larger than the magnetic grains, than when the grain size of the host material was between 0.71 (0.5 Φ) and 0.35 mm (1.5 Φ), from about 4 to 2 times larger than the magnetic grains. The
experiments also showed that burial of the magnetic grains was unaffected by the
degree of agitation of the coarsest non-magnetic sand, and that burial was less effective
in finer non-magnetic sand as the degree of agitation increased (Fig. 2.9 b and c). This
conclusion is consistent with field experiments in which the magnetic tracers continued
to move for a longer period when the breakers were high (equivalent to high agitation)
than when they were low.

Figure 2.9 – Results of laboratory experiments, a) shows the decrease in the magnetic
susceptibility signal when buried with non-magnetic sand at 2mm increments. Figure b) and c)
illustrates the sinking of magnetic grains within different grain size fractions at two speeds of
agitation, 50 rotations per minute and 70 rotations per minute.

a)

![Graph showing magnetic susceptibility signal decrease with depth of burial.]

b)

![Graph showing magnetic grains sinking at 50 rotations per minute.]

c)

![Graph showing magnetic grains sinking at 70 rotations per minute.]

- -1.5 to -1 (Φ)  - - 0 to 0.5(Φ)  - - - - 0.5 to 1(Φ)  - - - - 1 to 1.5(Φ)
2.4. Discussion

The experiments showed that small, heavy magnetic minerals are buried rapidly in the swash zone. The magnetic tracers not only travelled less rapidly alongshore in the experiments under low to moderate wave conditions, but there was usually little movement at all after an initial period, generally lasting up to a few hours. In a similar way, magnetic grains tended to move into the upper swash zone before being buried and becoming immobile beneath non-magnetic grains.

Grains with higher settling velocities are less easily transported than grains with lower settling velocities because they do not remain in suspension as long; this may result in suspension sorting. A universal equation for grain settling velocities \( w_s \) has been developed by Ferguson and Church (2004):

\[
  w_s = \frac{RgD^2}{C_1v + \sqrt{0.75C_2RgD^3}}
\]

where \( g \) is the acceleration due to gravity, \( D \) is the grain diameter, \( C_1 \) and \( C_2 \) constants equal respectively, to 18 and 0.4 for smooth spheres, \( v \) is the kinematic viscosity of the water \( (1 \times 10^{-6} \text{ kg m}^{-1} \text{ s}^{-1} \) for water at \( 20^\circ\text{C} \)), and \( R \) is the submerged specific gravity of the grain, equal to \( (\rho_g - \rho_w)/\rho_w \), where \( \rho_g \) is the density of the grain and \( \rho_w \) is the density of the water. Substituting the density \( (5200 \text{ kg m}^{-3}) \) and the mean diameter of the magnetic tracer \( (178 \mu\text{m}) \), and the corresponding values of the finer \( (\text{density } 2650 \text{ kg m}^{-3}, \text{mean diameter } 209 \mu\text{m}) \) and coarser \( (\text{density } 2650 \text{ kg m}^{-3}, \text{mean diameter } 483 \mu\text{m}) \) non-magnetic tracers, suggests that the finer and coarser non-magnetic grains have
settling velocities of respectively, about 0.58 and 1.82 times that of the magnetic grains (Table 2.3).

Natural, non-spherical grains settle at different rates than perfectly spherical grains of the same mineralogy. There have been several equations developed to modify the settling velocity based on the actual shape of the grain. Van Rijn (1989) proposed that:

\[
\frac{w_n}{w_s} = 0.808 \ (CSF) + 0.192
\]

Where \(w_n\) is the fall velocity of a natural, non-spherical grain, \(w_s\) is the fall velocity of a sphere of the same volume and weight, and CSF is the Corey Shape Factor. The CSF is based on the length of the three primary axes, the short (\(D_s\)), intermediate (\(D_i\)), and long axes (\(D_l\)) of the grain:

\[
CSF = \frac{D_s}{\sqrt{D_iD_l}}
\]

The CSF is a measure of the degree of divergence of a natural grain from a perfect sphere, which has a value of 1. To address the effect of grain shape on fall velocities, grains were measured under a microscope to determine the length of their three axes. The mean CSF value was 0.78, 0.88 and 0.86 for the magnetic, and the finer and coarser non-magnetic tracers (refer to Hatfield et al. (2010) for optical micrographs of the magnetic grains). Adjusting for particle shape, the actual fall velocities of the finer and coarser non-magnetic tracer grains were respectively, about 0.63 and 1.99 times that of the magnetic grains.
Heavy magnetic minerals may also be separated from non-magnetic minerals according to different thresholds for grain movement (entrainment sorting), which is often expressed as the minimum shear stress necessary to move a grain across a solid base. The critical threshold for sediment entrainment is dependent on the grain size and density, although it is also affected by grain shape and bed topography (Madsen and Grant, 1976; Larsen et al., 1981; Sleath, 1984; Hardisty, 1990). The magnetic grains could therefore move at different rates than the non-magnetic grains if their critical threshold was different. Chepil’s (1959) equation was used to calculate the critical or threshold shear stress of the tracers:

$$\tau_{cr} = \frac{0.66 \, D \, g \left( \rho_g - \rho_w \right) \, 0.3 \, \tan \alpha}{1 + 0.85 \, \tan \alpha}$$

Where $\tau_{cr}$ is the critical or threshold shear stress and $\alpha$ is the angle made with the vertical by a line drawn from the point in the grain through which the drag operates, to the centre of the grains below. Using Chepil’s value of $\alpha=24^\circ$, the equation suggests that the critical shear stress needed to initiate movement of the finer and coarser non-magnetic grain tracers is respectively, 0.46 and 1.07 times that for the magnetic grains (Table 2.3). Similar values were obtained using the Shields parameter (Table 2.3) which, for a unidirectional flow, such as the uprush or downrush, over a hydrodynamically rough bed, reduces to:

$$\tau_{cr} = 0.06 \, D \, g \left( \rho_g - \rho \right)$$

Dispersal of the initial magnetic tracer deposit caused the grains to mix with more abundant non-magnetic sand in the swash zone. This sand had a mean diameter in the various experiments ranging from about 330 to 2870 μm, with corresponding
threshold shear stresses of 0.73 and 6.19 times, and fall velocities of 1.25 and 8.02 times that of the magnetic grain tracers, respectively (Table 2.3). Despite generally much lower threshold shear stresses and settling velocities, which would suggest that movement of the magnetic grains should be easier than the non-magnetic grains, the alongshore movement of the magnetic grains declined through the experiments, possibly in part as a result of the larger non-magnetic grains shielding the smaller magnetic grains (Li and Komar, 1986), and because of the magnetic grains sinking between, and being buried by, the non-magnetic grains. This conclusion is consistent with the laboratory experiments (Fig. 2.9) and with the progressive decline in total susceptibility (the sum of the susceptibility at all the points) (Fig. 2.5). The laboratory experiments suggest that, based on typical decreases of 40 to 60% in the original magnetic susceptibility, the magnetic grains had usually been buried under 4 to 10 mm of non-magnetic grains by the end of each experiment (Fig. 2.9 b and c). Once the grains were buried they may remain in place while the non-magnetic grains moved over them. This was manifested by the continuing presence of the magnetic tracers within the sampling grid, even 24 hours after being added to the swash zone.

Both the fine and coarser non-magnetic tracers moved further along the foreshore than the magnetic tracers. The greater movement of the finer non-magnetic tracer is consistent with its lower settling velocity and threshold shear stress than the magnetic tracer. However the movement of the coarser non-magnetic tracer was similar to that of the finer non-magnetic tracer, despite having higher shear stress thresholds and fall velocities, and displayed much greater movement than the magnetic minerals.
despite similar shear stress thresholds and higher fall velocities (Table 2.1, Fig. 2.6). The most plausible explanation for the relative transport efficacy of the three tracers is related to the effect of variable grain size and density on the tendency for grain sinking and burial in the swash zone.

<table>
<thead>
<tr>
<th>Table 2.3 – Settling velocities and threshold shear stress values for the tracers as well as the maximum and minimum swash zone grain sizes during the experiments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling velocity (Ferguson and Church) (2004)(m s(^{-1}))</td>
</tr>
<tr>
<td>Magnetic tracer (178 µm)</td>
</tr>
<tr>
<td>Fine non-magnetic tracer (209 µm)</td>
</tr>
<tr>
<td>Coarse non-magnetic tracer (484 µm)</td>
</tr>
<tr>
<td>Non-magnetic (330 µm)</td>
</tr>
<tr>
<td>Non-magnetic (2870 µm)</td>
</tr>
<tr>
<td>Magnetic tracer (356 µm)</td>
</tr>
</tbody>
</table>

Decreasing total magnetic susceptibility and the disappearance of the visually distinctive magnetic tracers from the surface testified to the rapid burial of the magnetic tracers in the experiments. Burial of the non-magnetic tracers was more difficult to observe in the field, but the finer non-magnetic tracers were always located deeper in the sediment cores at the end of the experiments than the coarser non-magnetic tracers (Fig. 2.8). This suggests that despite the similar volume, mass, and projected area of the finer non-magnetic tracer grains, which were, respectively, 1.62, 0.82, and 1.38 times that of the magnetic tracers, lower shear stress thresholds and fall velocities allowed the finer non-magnetic grains to travel faster and further along the beach than the magnetic grains before they were buried. Because of higher threshold shear stresses and fall
velocities, the coarser non-magnetic tracers were probably unable to move as rapidly alongshore as the finer non-magnetic tracers, but because of their greater size, they were better able to stay on the surface and to continue moving alongshore, due to their exposure to wave action in the swash zone.

Their degree of shelter and exposure to the swash within the variable grain population may be another factor of the magnetic grains immobility. The generally much larger host grains would have sheltered all the tracer grains, but the effect of transport rates would have been greatest for the smaller magnetic and non-magnetic tracer grains while they were on the beach surface. The amount by which each tracer was able to protrude above the beach surface also affected its exposure to the driving forces, and this is much greater for the larger non-magnetic grains than for both the finer non-magnetic and magnetic grains (Fig 2.10). The higher protrusion of the coarser non-magnetic grains allows them to be exposed more to the drag parallel of the swash, thus entrained more readily than the finer grains. Consequently, in addition to differential sinking and burial of the tracers, sheltering and protrusion effects help to explain why the mobility of the coarser non-magnetic tracers was much greater than of the magnetic tracers, and why they were found at shallower depths and probably continued to move for a longer period, than the finer non-magnetic tracers.

Any remanent magnetization present in the magnetic grains may promote some grains to be attracted and attach to one another. If this were to occur during the experiments, the magnetic tracer would likely have higher settling velocity and threshold shear stress. For example in the simplest case, if two magnetic grains were
attracted, this would simulate the formation of a grain no smaller than 356 μm in diameter (double the magnetic tracers’ mean grain diameter). This increased size then results in the magnetic grains having a settling velocity of about 0.25 and 0.78 that of the fine and coarse non-magnetic tracers and 0.23 and 0.53 their threshold shear stresses. However, the corresponding values were still lower than for most of the sediment on the beach, and because of the observed decrease in magnetic susceptibility, shielding and especially burial are likely to be the major reason for magnetic mineral behavior in the swash zone (Table 2.3).

**Figure 2.10** – Degree of protrusion of the magnetic and non-magnetic tracers under variable sized host grains. The coarser non-magnetic grains protrude higher than both the finer non-magnetic and magnetic grains (in all host grain diameters). Despite having larger settling velocities and threshold shear stresses, this degree of protrusion allows the larger grains to stay on the surface of the beach and continue moving alongshore.

Although differences in transport rates (transport sorting) help to separate magnetic from non-magnetic minerals, the dominance of coarse non-magnetic host grains with higher threshold shear stresses and settling velocities than the magnetic
grains show that placer deposits cannot develop in this area through processes, including suspension, entrainment, and shear sorting, that preferentially remove lighter, non-magnetic minerals (Frihy et al., 1995; Frihy and Dewidar, 2003). Nevertheless, the exposure of beach placers after storms and their association with areas of erosion along the eastern coast of Point Pelee (Hatfield et al., 2010) suggest that during storms, strong swash removes consecutive layers of non-magnetic overburden. The finer magnetic grains resist removal not because they are more difficult to mobilize, however, but because of their tendency to sink between the larger, non-magnetic grains. This promotes progressive merging of the seams of magnetic grains and their exposure in the upper swash zone as the non-magnetic grains are removed. The lack of magnetic concentrations in the lower swash zone can be attributed to finer grains that inhibit magnetic grain burial, stronger swash that is able to remove both the magnetic and non-magnetic material, and the tendency, as demonstrated in this study, for magnetic grains to migrate to, and be buried in the upper swash zone.

The experiments indicate that the heavy magnetic minerals are unable to move along Point Pelee during the low to moderate wave conditions experienced in the experiments, but they also suggest, together with their distribution along the coast (Hatfield et al., 2010; Cioppa et al., 2010), that movement can occur during storms. During low to moderate wind and wave conditions, the magnetic minerals sink beneath the larger non-magnetic grains. Under higher energy conditions, removal of the non-magnetic grains and the continued sinking and concentration of the magnetic minerals exposes the placer deposits. The homogeneity of these deposits then prevents further
burial and facilitates movement in the cross-shore and longshore directions.

This study suggests that whereas magnetic susceptibility provides a useful tool to fingerprint sediment sources and transport paths in coastal environments, the distinctive hydrodynamic behaviour and episodic movement of magnetic minerals make it difficult to use them to determine longshore transport rates on dominantly non-magnetic beaches. Furthermore, magnetic and non-magnetic grains might even move in opposing directions if the stronger wave and swash conditions that concentrate and move magnetic minerals come from different directions than the weaker waves that transport lighter, non-magnetic minerals.

2.4.1 Conclusions

The main conclusions of this research are as follows:

a) Small, heavy magnetic minerals are rapidly buried beneath non-magnetic grains under low to moderate wave conditions and are unable to move in the longshore or cross-shore direction;

b) Magnetic susceptibility rapidly decreases with the rate and depth of burial of the magnetic minerals;

c) Laboratory experiments suggest that magnetic grain burial is most effective beneath coarser than finer non-magnetic sand and, for the latter sediments, under less rather than more energetic conditions;

d) The experiments imply that magnetic mineral concentrations develop through grain
burial under fairly mild conditions, followed by exposure and concentration of consecutive layers during more energetic periods when the non-magnetic grains are eroded from the upper swash zone. Longshore and cross-shore transport of the heavy minerals may then occur during these periods when the homogeneity of the deposits inhibits grain burial.

e) Changes in magnetic susceptibility can be useful in identifying sediment sources and tracing paths of movement, but the distinct hydrodynamic behaviour of magnetic grains makes it difficult to use them to determine rates of longshore transport in dominantly non-magnetic materials.
Bibliography


Chapter III

Summary and Future Work
3.1 Summary

This thesis has reported on the transport and sorting of magnetic minerals. A coastal sediment tracing technique has been used for the first time to measure the movement and burial of magnetic minerals in the field. The technique, as used on the narrow swash zones of Lake Erie, was non-invasive and allowed continuous measurement through the experiments; other tracing techniques only allow researchers to sample tracer distributions at the end the experiments. Preparation of the magnetic tracers was very easy and the sand grains did not have to be altered from their original form. The magnetic tracing technique allowed rapid tracking and data input and did not require the tedious counting of individual grains in order to determine their distribution.

The results demonstrate that magnetic minerals have slower rates of transport than more dominant non-magnetic minerals. The movement is sporadic and, under moderate to low energy wave conditions, short-lived, as the magnetic grains are quickly buried beneath the non-magnetic material. Hypothesis a), which stated that “The longshore and cross-shore transport of heavy magnetic minerals is significantly slower than of the more dominant non-magnetic minerals present on the beach. This is a result of the sinking of the heavy minerals due to their smaller grain size and greater weight”, can therefore be accepted. The second hypothesis stated that “Placer deposits or concentrations of heavy magnetic minerals are the result of erosion and removal of lighter non-magnetic minerals during storms, leaving behind the magnetic minerals.” This hypothesis cannot be accepted, as the magnetic minerals had lower threshold
shear stresses and settling velocities than all but the finest non-magnetic grains on the beach. Consequently, the magnetic minerals were more difficult to mobilize and more difficult to keep in suspension than the non-magnetic grains. Therefore concentration of magnetic minerals into placer deposits cannot be the result of the preferential removal of the lighter and consequently more mobile non-magnetic grains. An alternate explanation has been presented in this thesis which attributes the concentration of magnetic minerals to their burial beneath larger grains, and their movement during storms to the formation of homogeneous deposits of heavy minerals which inhibits further sinking.

3.2 Future Work

There are three main recommendations:

1. This thesis focused on the movement of magnetic minerals under a variety of wave conditions, generally over a period of up to 3.5 hours, with the distribution of some experiments being examined again after 24 hours. Future work should be conducted over longer periods, such as continuous monitoring for 12 hours, to confirm that magnetic minerals are permanently buried and immobile under low to moderate wave conditions.

2. The conclusions of this research pertain to heavy minerals that are also magnetic. Additional research should examine if these results also relate to non-magnetic heavy minerals that are commonly found in placer deposits.
3. In addition, future work should also focus, despite significant logistical challenges, on the movement of magnetic grains during high energy wave conditions, when the present work suggests that they form thick, mobile layers of black sand.
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