

Magnetic mineral enrichment and transport in coastal environments: Tauranga Harbour, Northeastern, New Zealand



Dissertation

Zur Erlangung des
Doktorgrades der Naturwissenschaften

Im Fachbereich der Geowissenschaften
der Universität Bremen

Vorgelegt von

Firoz Badesab

Bremen, October 2012-23-10

Gutachter

Prof. Dr. Tilo von Dobeneck, Universität Bremen, Germany

Dr. Karin Bryan, University of Waikato, New Zealand

Declaration

Name: Firoz Kadar Badesab

Address: In der Wisch 1, 28205, Bremen

Herewith i declare that

- I. This document and the accompanying data have been composed by myself, and describes my own work.
 - II. Material from the published or unpublished work of others, which is referred to in the dissertation, is credited to the author in the text.
 - III. This work has not been submitted for any other degree.
-

Firoz Kadar Badesab

23rd October, 2012

University of Bremen, Germany

Preface

The present PhD thesis was written at the Faculty of Geosciences, Universität Bremen, and Department of Earth and Ocean Sciences, University of Waikato, New Zealand. The study was funded by Deutsche Forschungsgemeinschaft DFG through the International Research Training Group INTERCOAST and supported by MARUM Center for Marine Environmental Sciences. The project has been supervised and reviewed by Prof. Dr. Tilo von Dobeneck (Universität Bremen) and Dr. Karin Bryan (University of Waikato). Co-supervisors were Dr. Hendrik Müller (Universität Bremen), Dr. Thomas Frederichs (Universität Bremen) and Prof. Dr. Roger Briggs (University of Waikato). The samples for the research were retrieved during three separate field surveys (February 2010, July 2011 and December 2011) in Tauranga Harbour onboard coastal research vessel *Tai Rangahau* of University of Waikato.

The dissertation aims at gaining fundamental understanding on the mechanisms and processes controlling the spatial distribution, enrichment and transport of heavy magnetic minerals in a range of coastal depositional environments. The first chapter of the cumulative thesis provides an introduction into the topic, motivation and scientific objectives of the study. The chapters two, three and four form the main part of the dissertation, comprising three research articles of which one is published and two await submission. The fifth chapter provides conclusions and potential perspectives for further research. The sixth chapter is an appendix and includes a manuscript published in collaboration with research partners at the National Institute of Oceanography, Goa, India.

Summary

Placers are locally enriched heavy minerals, which are commonly found in fluvial, coastal and shelf environments and can form economically important resources. Distribution, accumulation and preservation of heavy minerals in aquatic sediments are mainly dependent on the availability of minerals in respective source regions and the acting selective sediment sorting mechanisms under transport and deposition. The gravitational separation of heavy and light minerals according to their individual grain properties (densities, shapes and sizes) is mainly driven by currents and waves and results in the formation of heavy mineral enriched zones. Hence, understanding the concentration processes including mineral transport, settling, entrainment and burial in various sedimentary environments is necessary not only to detect the heavy mineral enriched zones, but also to delineate the underlying sediment dynamics and hydrodynamics.

The major aim of this thesis is to develop the potential of environmental magnetic methods, i.e. the application of rock magnetic measurements in a sedimentological context, for coastal zone research. We combined a range of laboratory based magnetic and non-magnetic methods with hydrodynamic modelling in the aim to identify and explain heavy mineral rich zones in and around a meso-tidal estuarine lagoon of Tauranga Harbour and in the nearshore Bay of Plenty located on the northeast coast of New Zealand. This thesis presents a comprehensive study on the distribution pattern and formation mechanisms of magnetite rich zones in estuary and near-shore environments and explores the responsible hydrodynamic conditions.

The magnetic measurements on surficial sediments collected offshore of Tauranga Harbour covering the inner shelf zone off Waihi Beach, Matakana Beach, Omanu Beach revealed the presence of two coast parallel magnetite-enriched belts. From trends in cross-shore and along-shore bulk and magnetic grain-size distributions in combination with hydrodynamic modelling the formative mechanism of these belts could be explained. The inner belt (< 10 m water depth) is formed as a result of active coast-parallel transport in combination with energetic surf zone processes while the outer belt (10-20m water depth) is mainly composed of relict sands, which were reworked during post-glacial sea level transgression (*Badesab et al.*, 2012, Chapter 2). Within the estuary, tidal channels such as Western and Cutter act as a high-energy depositional sites for magnetic minerals, which feed into coast-parallel magnetite enriched zones. A positive correlation between magnetite susceptibility and magnetic grain size indicates a strong linkage between these parameters. This relation could be utilized in future as a proxy for lag deposits if confirmed in other magnetically enriched coastal environments.

A grain size analysis following *Visher* (1969), combined with a high resolution 3D numerical flume tank experiment provided insights into the entrainment and transport dynamics of heavy mineral grains in a range of coastal depositional environments (*manuscript for submission*, Chapter 3). Results showed that the differences in shapes of distribution curves, percentage of each population, offset in grain sizes of bulk and magnetite fraction reflects the variability in grain transport, and enrichment processes in each environment. The lower flow velocities cause the differential settling of light and heavy mineral grains resulting in formation of heavy mineral lag enriched zones. Numerical model results showed that rate of erosion increases with increase in concentration of heavy minerals and enhances the heavy mineral enrichment, while in beach environment (e.g Matakana Beach) with sediment beds dominated by mineral grains (light & heavy) with equivalent grain sizes, the bed is more stable with negligible amount of erosion compared to any other bed composition.

Rock magnetic, petrological and sedimentological analyses of riverine and estuarine sediments of Tauranga Harbour elucidate that the variability in source characteristics, distinct local hydrodynamics and regional topography are the major factors controlling the sediment distribution and transport in the study area (*manuscript for submission*, Chapter 4). The results of this thesis add to the understanding on the factors controlling the enrichment of heavy (magnetic) mineral in various depositional environments and demonstrate the potential of environmental magnetism in coastal science.

Kurzfassung

Seifen sind Schwermineralanreicherungen, die lokal in Flüssen sowie Küsten- und Schelfgebieten vorkommen und als wirtschaftlich bedeutsame Rohstoffe dienen können. Verbreitung, Anreicherung und Erhaltung von Schwermineralen in fluviatilen und marinen Sedimenten sind hauptsächlich abhängig von den verfügbaren Mineralen in dem entsprechenden Ursprungsgebiet sowie von den selektiven Sortierungsmechanismen während Transport und Ablagerung. Strömung und Wellen bewirken eine Sortierung von Schwer- und Leichtmineralen entsprechend den individuellen Mineralkorneigenschaften (Dichte, Form und Größe) und erzeugen dadurch Formationen mit angereicherten Schwermineralen. Deshalb ist das Verständnis von Anreicherungsprozessen wie Mineraltransport, -ablagerung, -remobilisierung und -einlagerung nicht nur wichtig, um Schwermineralseifen zu lokalisieren, sondern auch, um die zugrundeliegenden sedimentdynamischen und hydrodynamischen Prozesse zu beschreiben. Das Hauptziel dieser Arbeit ist es, das Potential umweltmagnetischer Methoden für die Erforschung des Küstenbereichs weiterzuentwickeln.

Wir haben eine Reihe von magnetischen und nicht-magnetischen Labormessungen mit hydrodynamischen Modellberechnungen kombiniert, mit dem Ziel, Schwermineralseifen in und um ein mesotidales Ästuar am Tauranga Harbour und in der küstennahen Bay of Plenty an der Nordostküste Neuseelands zu identifizieren und zu erklären. In dieser Doktorarbeit wird eine umfassende Studie über Verbreitungsmuster und Formungsmechanismen magnetitreicher Gebiete präsentiert und die entsprechenden Bedingungen bezüglich Hydrodynamik und Ablagerung untersucht. Die magnetischen Messungen an Oberflächensedimenten des inneren Schelfs (Waihi Beach, Matakana Beach, Omanu Beach) zeigen zwei magnetitreiche Sedimentgürtel. Trends in der Korngrößenverteilung senkrecht und parallel zur Küste in Kombination mit hydrodynamischen Modellierungen erklären die Bildungsmechanismen dieser Gürtel. Die Entstehung des inneren Gürtels (< 10 m Wassertiefe) resultiert aus einem aktiven küstenparallelen Transport in Kombination mit dynamischen Prozessen in der Brandungszone. Dagegen ist der äußere Gürtel (10-20 m Wassertiefe) hauptsächlich aus Reliktsanden zusammengesetzt, die während des post-glazialen Meeresspiegelanstieges überarbeitet wurden. Innerhalb des Ästuars agieren Tidenkanäle wie der *Western* und *Cutter* als hochenergetische Ablagerungsräume. Eine positive Korrelation zwischen magnetischer Suszeptibilität und magnetischer Korngröße zeigt die starke Verbindung zwischen diesen Parametern. Bestätigt sich dies auch in anderen Küstengebieten mit Anreicherungen von magnetischen Mineralen, könnte diese Beziehung in der Zukunft als Proxy für residuale Ablagerungen dienen.

Eine Korngrößenanalyse nach *Visher (1969)* verbunden mit einer hochauflösenden numerischen dreidimensionalen Strömungskanalimulation bietet Erkenntnisse über die Mobilisierung und Transportdynamik von Schwerminerkörnern für eine Reihe von Ablagerungsgebieten verschiedener Küstenbereiche (siehe manuscript, Kapitel 3). Die Ergebnisse zeigen, dass die Form der Verteilungskurven, der prozentuale Anteil jeder Fraktion, der offset in den Korngrößen zwischen Gesamt- und magnetischer Fraktion die Variabilität von Transport- und Anreicherungsprozesse der einzelnen gebiete widerspiegeln. Geringere Fließgeschwindigkeiten verursachen ein unterschiedliches Absinken von leichten und schweren Mineralkörnern, dies führt zu der Bildung von residual schwermineral angereicherten zones. Die Ergebnisse numerischer Modelle zeigen, dass die Erosionsrate mit steigender Konzentration von Schwermineralen ansteigt und die Schwermineralanreicherung verstärkt. In Strandbereichen hingegen (z. B. Matakana Beach), wo Mineralkörner (leicht und schwer) mit ähnlichen Korngrößen dominieren, sind die Ablagerungen stabiler und weisen eine im Vergleich zu anderen Sedimentzusammensetzungen vernachlässigbare Erosion auf.

Magnetische, petrologische und sedimentologische Analysen von Fluss- und Flussmündungssedimenten vom Tauranga Harbour zeigen, dass die Variabilität der Herkunftsgebiete, die unterschiedlichen lokalen hydrodynamischen Verhältnisse sowie die regionale Topographie die Sedimentverteilung und den Transport im Arbeitsgebiet maßgeblich beeinflussen (siehe manuscript, Kapitel 4). Die Ergebnisse dieser Doktorarbeit tragen zum Verständnis der kontrollierenden Faktoren bezüglich der Anreicherung von (magnetischen) Schwermineralen in verschiedenen Ablagerungsgebieten bei und demonstrieren die Möglichkeiten, die die Umweltmagnetik bei der Erforschung der Küste bietet.

Acknowledgements

First of all, I am thankful to my family including the following Late Ameena Bi (mother), Kadar Badesab (father), Shahin Badesab, Parveen, Shamir Badesab and Ali Kallimani for your support and belief has meant everything to me. I would like to express my sincere appreciation to Prof. Dr. Tilo von Dobeneck for giving me the opportunity to pursue my PhD studies and his timely support, motivation and guidance provided throughout my dissertation writing. I am grateful to my co-supervisors Dr. Hendrik Müller, Dr. Thomas Frederichs, Dr. Karin Bryan and Assoc. Prof. Dr. Roger Briggs for all their efforts, support, guidance and patience at all times. I would like to thank Liane Brück, Dirk Immenga, Sebastian Boulay, Christopher Daly, Serena Fraccascia, Ruggero Capperucci, Max Kluger, and Gerhard Bartzke for their assistance during sediment sampling surveys in Tauranga Harbour. I also wish to thank my research students Florian Schmidt, Max Kluger and Steffen Wiers for helping me with laboratory measurements. Thanks to Inka Meyer and Jan-Berend Stuut W. for providing support with grain size measurements.

Many thanks to all the members of Marine Geophysics Group including Dr. Hendrik Müller, Dr. Thomas Frederichs, Christian Hilgenfeldt, Heike Piero, Liane Brück, Dr. Janna Just, Dr. Cletus Itambi, Benjamin Baasch, Lucy Korff, Sebastian Razik, Dr. Vera Bender and Martina Braun. I am grateful to all of you for making me feel so comfortable and homely during my three years of stay in Bremen. I would like to thank my friends Vigneshwaran Rajasekaran Abhinav Gogoi, Shungu Garaba, Jude Castelino, Jens Rose, Yuvaraj SN, Manjunatha Ramanagouda, Anil Kumbham, Govind Raju, Avinash Peter and all In der Wisch mates for all your help and support. Thanks to Bryna Flaim for providing comments and suggestions on scientific and grammatical writings.

Special thanks to all other supportive members of the Department of Earth & Ocean Science, University of Waikato including Prof. Dr. Chris Battershill, Sydney Wright, Chris McKinnon, Renat Radosinsky, Annette Rodgers, Jacinta Parenzee for providing all the help with laboratory analysis, personal official matters and making me feel homely during my nine months research stay in New Zealand. I am grateful to Max Oulton for providing me with the geological maps of Tauranga Harbour.

I am grateful to Prof. Dr. Terry Healy, Prof. Dr. Burghard Flemming, Dr. Christian Winter, Prof. Dr. Alexander Bartholomä, Dr. Willem de Lange and Prof. Dr. Katrin Huhn for providing timely scientific inputs during my doctoral work. I would also like to thank Dr. Hui Woon Tay for providing the

numerical hydrodynamic results. The Bay of Plenty Regional Council, Tauranga, New Zealand is thanked for providing the long term wave data for the study. I like to thank all the INTERCOAST mates for all their support and nice memories i had together during various times at my stay in Bremen and New Zealand. I would always remember and cherish them.

This thesis is an outcome of the research project within the framework of INTERCOAST-International Research Training Group funded by the Deutsch Forschungsgemeinschaft DFG via Bremen – Waikato Collaborative doctoral programme and MARUM Center for Marine Environmental Sciences.

Table of contents

1. Introduction	01
1.1. Heavy and magnetic minerals in coastal and shelf environment	
<i>1.1.1. Heavy minerals</i>	
<i>1.1.2. Magnetic minerals</i>	
1.2. Mechanisms of sediment sorting and placer formation	03
<i>1.2.1. Suspension sorting</i>	
<i>1.2.2. Entrainment sorting.</i>	
<i>1.2.3. Shear sorting</i>	
<i>1.2.4. Transport sorting</i>	
1.3. Motivation and main objectives	05
1.4. Thesis outline	06
1.5. References	07
2. Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand Firoz Badesab, Tilo von Dobeneck, Karin R. Bryan, Hendrik Müller, Roger M. Briggs, Thomas Frederichs and Eva Kwohl. <i>Geochemistry, Geophysics and Geosystems</i> , v13 (6), 2012	10
3. Selective transport and fractionation of magnetic particles in a transient coastal environment (Tauranga Harbour and Bay of Plenty, New Zealand). Firoz Badesab, Gerhard Bartzke, Tilo von Dobeneck , Katrin Huhn and Karin Bryan <i>Manuscript for submission to Sedimentology</i>	30
4. Controls on magnetic minerals and grain size distribution in a barrier enclosed estuarine lagoon (Tauranga Harbour, northeastern, New Zealand). Firoz Badesab, Tilo von Dobeneck, Roger M. Briggs, Karin Bryan and Janna Just, <i>Manuscript for submission to New Zealand Journal of Geology and Geophysics</i>	70

5. Conclusion and perspectives for future research

92

5.1.1. *Environmental magnetic parameters (magnetic mineral concentration and grain size)*

5.1.2 *Sediment grain size distribution patterns and local hydrodynamics*

5.1.3 *Magnetic and non-magnetic grain size distributions and their offsets*

5.1.4 *Flume tank numerical modelling & its implications for grain entrainment, transport and deposition*

5.1.5 *Future perspectives*

Appendix 1: Manuscript published in collaboration with National Institute of Oceanography, Goa, India

Sea bed morphology and gas venting features in the continental slope region of Krishna – Godavari basin, Bay of Bengal: Implications in gas – hydrate exploration, P. Dewangan, T. Ramprasad, M.V. Ramana, A. Mazumdar, M. Desa, F.K. Badesab (2010), *Marine and Petroleum Geology.*, v 27, 7, 1628–1641.

Appendix 2: Papers presented at national and international conferences during the PhD tenure (Oct 2009 – Oct 2012)

Paper 1 - Magnetic mineral enrichment and transport mechanisms in and off a mesotidal estuarine lagoon, northeastern, New Zealand, AGU Fall Meeting, Dec – 2012, San Francisco, USA

Paper 2 - Formation of magnetite-enriched zones in a mesotidal estuarine lagoon system: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand, Graduate Conference, 18 Oct 2011, University of Waikato, Hamilton, New Zealand.

Paper 3 - Sediment sorting and magnetic properties of barrier beach sediments, Northeastern New Zealand, vol 13, EGU General Assembly 4 – 8 April 2011, Vienna, Austria

1. Introduction

1.1. Heavy and magnetic minerals in coastal and shelf environments

1.1.1 Heavy minerals

Heavy mineral enriched lag deposits are common and manifold on the transport pathways of clastic sediments (Fig 1). They are found in rivers as alluvial placers, in estuaries and their ebb-tidal deltas, and on beaches as beach placers. In shelf environments, recent and past drift bodies as well as relict beach fronts and other high-energy environments show enhanced concentrations in trapped heavy minerals (Komar, 1989).

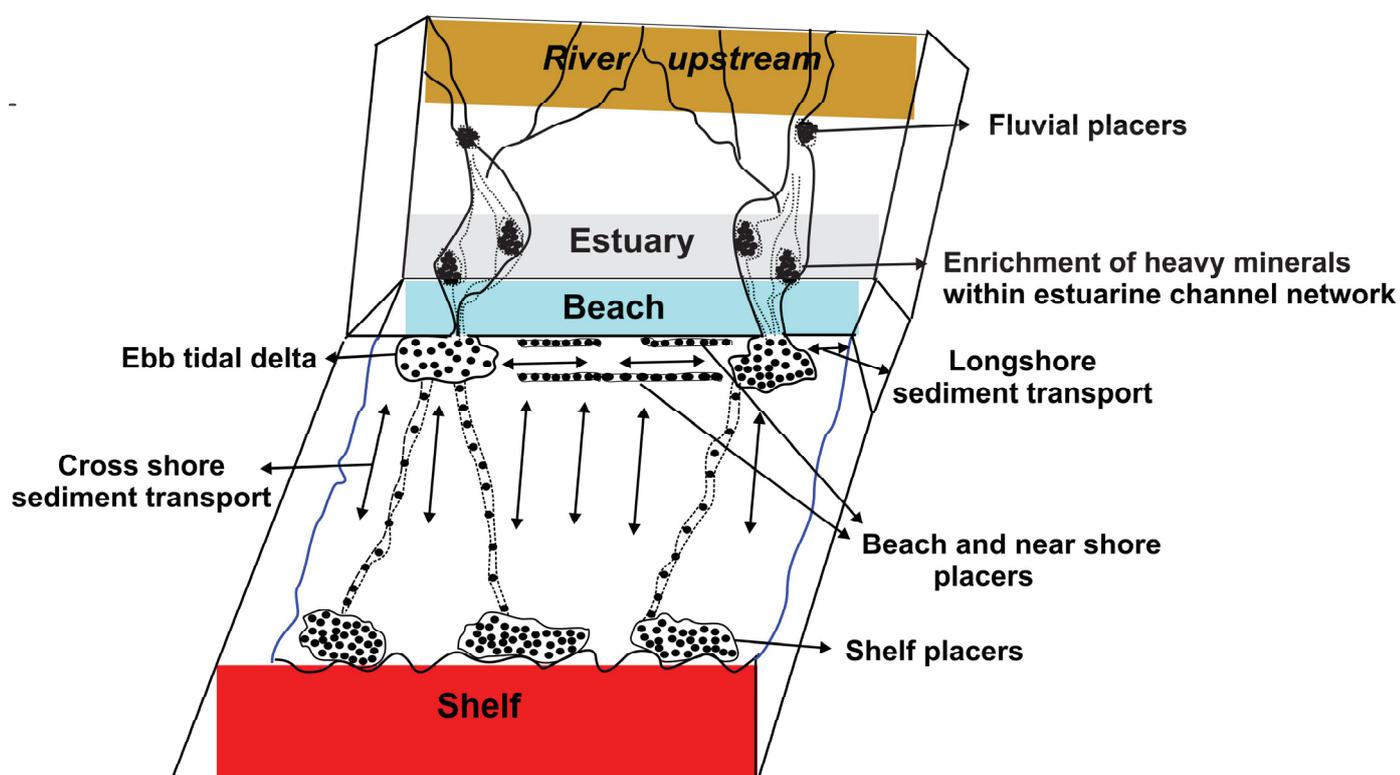


Fig 1: Schematic block diagram showing the occurrences of placer deposits in coastal and shelf environments.

Coastal placers can have considerable economic value if they contain noble metals and gemstones (gold, platinum, diamonds) or rare earth metal bearing minerals (monazite). Titanium rich minerals including ilmenite, rutile and magnetite are also found along many of the world's coasts and are increasingly gaining economic importance. They are also markers of present and past hydrodynamics and sediment dynamics in coastal regions. Once heavy minerals enter rivers, estuarine or marine

environments, they are transported as bedload, saltation and suspension population depending upon hydrodynamic conditions (*Visher, 1969*) (Fig 2). During their transport, they experience various mechanisms which can separate or concentrate these minerals to form deposits of higher concentration.

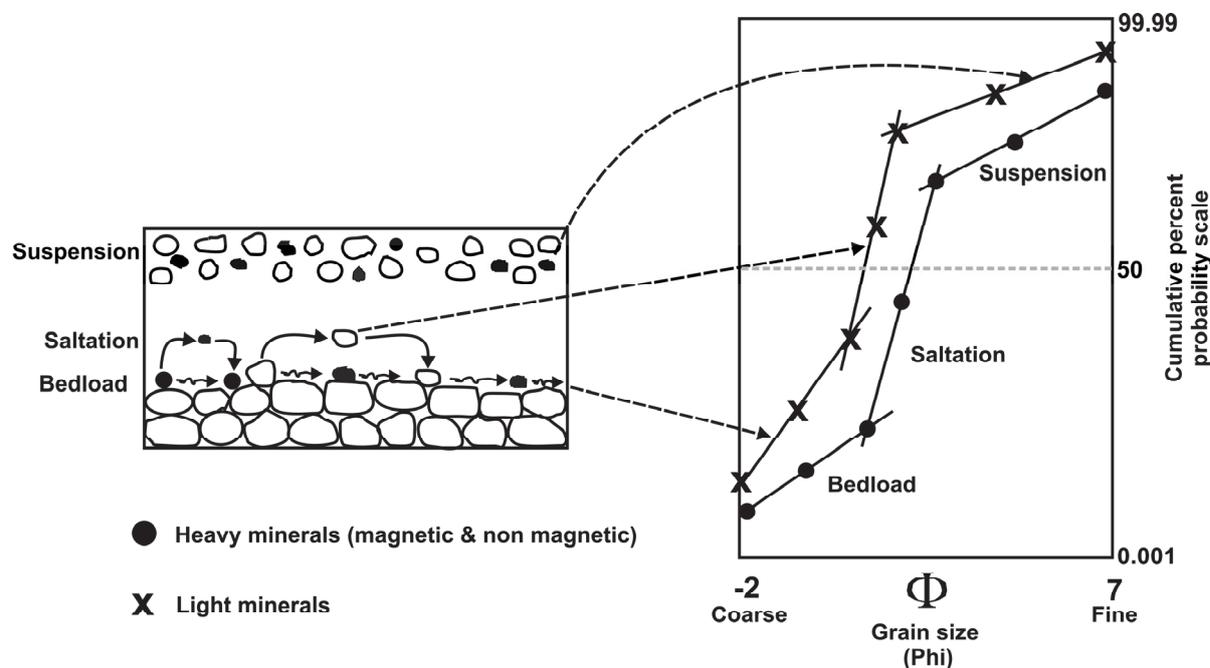


Fig 2: Conceptual diagram illustrating the transport modes of heavy and light mineral grains in relation to resulting grain-size distributions (modified from *Visher, 1969*).

The factors controlling the distribution, transport and deposition of detrital particles in aquatic systems are numerous and complex. Most important mechanism responsible for concentrating heavy minerals in coastal environments is sediment sorting, which depends on the individual grain physical, hydraulic and transport properties including density, grain size, differential rates of settling and transport, entrainment stresses and shear sorting (*Slingerland and Smith, 1986; Komar, 1989*). It is generally known that the heavy mineral population possesses finer mean grain sizes as compared to the total sediment population, in equivalence with their higher densities. Thus heavy minerals are more difficult to entrain or suspend and therefore remain concentrated or accumulated as lag deposits. Various concepts and theories were put forward to explain the formative mechanism of heavy mineral lag deposits including the law of settling equivalence (*Rubey, 1933*), selective entrainment (*Komar and Wang, 1984*) and differential transport (*Trask and Hand, 1985*). Burial of heavy minerals between interstices of the larger host grains (quartz) due to gravitational effects may also lead to enrichment (*Gallaway et al., 2012*). A fundamental understanding of all processes concentrating heavy minerals

from grain- to shelf-scale level is prerequisite to assess and predict placer deposit geometries in an increasingly quantitative approach. *Slingerland and Smith* (1986) and *Komar* (1989) provide detailed reviews on sorting mechanisms responsible for concentrating heavy minerals to form enrichment lags. Here we discuss these mechanisms in brief. Further details and illustrations on entrainment sorting, suspension sorting, transport sorting and shear sorting are presented in subchapter 1.2.

1.1.2 Magnetic minerals

(Titanio-)magnetite is the most common Fe-Ti oxide mineral in igneous and metamorphic rocks and by density ($5.1 - 5.18 \text{ g/cm}^3$) and an ubiquitous heavy mineral in aquatic sediments. Magnetic mineral concentration, mineralogy and grain sizes can be derived from the standard rock magnetic parameters using rapid bulk sediment measurements (*Thompson and Oldfield*, 1986). So far these methods have been successfully utilised for coastal investigations including sediment sources and transport pathways, and to determine the contamination of heavy metals in estuaries and tidal flats (*Oldfield*, 1985; *Lees and Pethick*, 1995; *Zhang et al.*, 2001). *Maher et al.* (2008, 2009, 2010, 2011) extensively used environmental magnetic methods (magnetic fingerprinting and magnetic inclusions) to resolve various coastal research problems including to investigate particulate pollution, to identify and characterize the sediment sources and to examine sediment dynamics in coastal environments.

Recently environmental magnetic methods have been used to map the distribution of heavy minerals, to assess their degree of sorting (*Cioppa et al.*, 2010). Studies by *Hatfield et al.*, 2010 used environmental magnetics to identify and monitor the areas of erosion and deposition on a coastal foreland. *Gallaway et al.*, 2012 investigated the mechanism of magnetic mineral transport and highlighted the role of burial mechanism in formation of magnetite enrichment in swash zones. However, the processes controlling magnetic mineral enrichment and transport in coastal depositional environments are not yet well enough understood to make detailed predictions about their distribution patterns and to draw deductions on the governing local hydrodynamic conditions.

1.2. Mechanisms of sediment sorting and placer formation

1.2.1 Suspension sorting

When particles are in suspension, their fractionation occurs due to their different settling velocity which in turn depends on the density, size and shape of the grain and fluid properties (*Slingerland and Smith*, 1986) (Fig. 3a). Given equal hydrodynamic properties, the lighter mineral grains tends to reside

in suspension for longer period, while the denser remain in suspension for a shorter period and settle down onto the bed, forming enrichments of heavy minerals.

1.2.2 Entrainment sorting

Preferential entrainment of less dense and accordingly larger particles is mainly dependent on grain entrainment threshold. Hence the mineral grains possessing the critical entrainment stress less the stress generated by flow undergo transport while the grains with higher critical entrainment stress than flow stress remains as a lag deposit. In entrainment sorting (Fig. 3b), it is the interaction of light and heavy mineral grains and their respective grain sizes, which determines the probability of the formation of concentrate zones of particular type of mineral. The lighter and coarser grains tend to protrude more into the boundary layer and experience higher flow velocities and drag forces. Such grains possess smaller pivoting angles and are more likely entrained (*Komar and Wang, 1984*) (Fig. 3c). In contrast, heavy mineral grains being denser and smaller have larger pivoting angle and are less exposed to the flow. Hence, their high density provides more resistance to their movement and transport leaving behind heavy mineral as lag deposits (*Komar and Wang, 1984*).

1.2.3 Shear sorting

During shear sorting (Fig. 3d), the separation of light and heavy takes minerals takes place due to differences in their dispersive pressure. Grains tend to accumulate in the vicinity of other grains possessing similar hydraulic properties (density and size) within a concentrated grain flow of a moving bed layer (*Bagnold, 1954*). This type of sorting produces thin layers of heavy minerals covered by larger and lighter mineral grains. In a mixed (light and heavy) mineral populations, it was found that lighter and coarser grains move upwards in the region of lower shear, whereas denser and finer grains move down into the sediment bed in the region of higher shear.

1.2.4 Transport sorting

A separation of heavy and light mineral grains caused by differences in their transport rates (velocities) is called transport sorting. The transport velocity of individual mineral grain depends on the density, size, and shape of the grains, the flow velocities and the composition / configuration of the bed. In this mechanism, grains which are entrained must undergo suspension before they are transported away depending on the intensity of the fluid flow. Thus transport sorting also takes into the account entrainment and suspension sorting (Fig 3e). Studies also showed that smaller grain sizes of heavy minerals allows them to hide within the interstices of the larger light and coarser grains so that these

grains remains in place for longer period without further entrainment or transport (*Gallaway et al., 2012*)

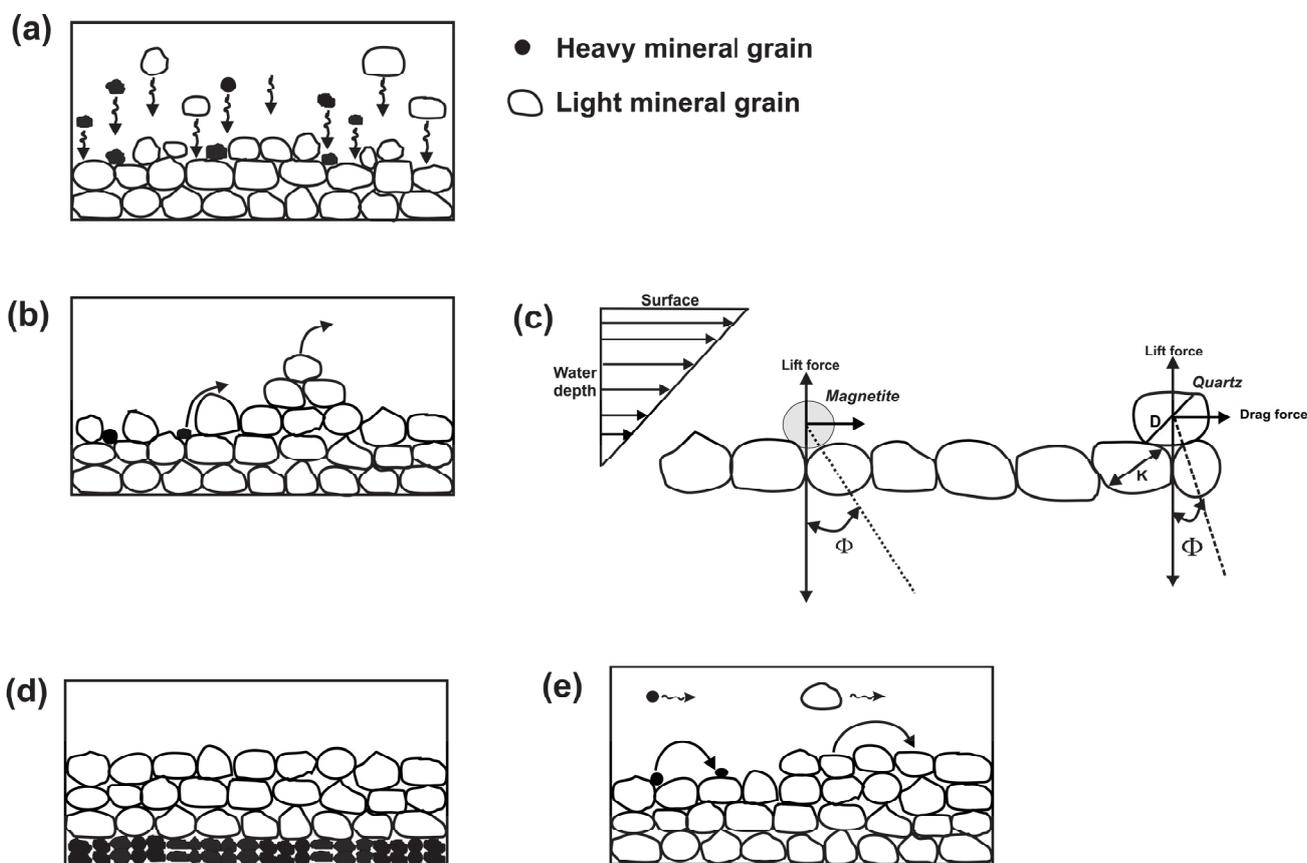


Figure 3: Schematic illustration of sorting mechanisms (a) suspension sorting, (b) & (c) entrainment sorting, (d) shear sorting (e) transport sorting (*see text for a detailed description*).

1.3. Motivation and main objectives

The various sediment sorting mechanisms discussed above tend to concentrate the heavy, both magnetic and non-magnetic minerals to form enriched zones in coastal and shelf environments. Their distribution is closely coupled with sediment sorting, transport and depositional processes. Within a suite of heavy and light mineral fractions, selective sorting of grains takes place due to the differences in their exposure, entrainment and transport rates. Many studies including laboratory and theoretical have focussed on understanding the physical processes responsible for mineral sorting with a major emphasis being given on selective entrainment. Here we attempt to integrate and test their ideas in a given complex coastal setting with well-known environmental conditions. The mesotidal estuarine lagoon of Tauranga Harbour sheltered within Bay of Plenty Coast, possessing a relatively low natural

concentration of magnetic minerals sourced from proximal Taupo Volcanic Zone (TVZ) and a modern shelf sediment was chosen as a promising study site with an aim to accomplish following thesis objectives:

1. To investigate the spatial and temporal variability in heavy (magnetic) mineral concentration and the mechanism responsible for their enrichment and transport in a coastal setting.
2. To explore the link between the magnetic mineral properties (concentration, grain size) and the underlying hydro- and sediment dynamics in the study area.
3. To combine environmental magnetics and sedimentological methods, hydrodynamic modelling and numerical flume tank modelling in the objective to gain further insight into the mechanisms of heavy (magnetic) mineral enrichment and transport at grain-scale level.

1.5. Thesis Outline

Three manuscripts present the major outcomes of these studies focussing (a) on the identified enrichments zones and their formative mechanisms, (b) on the granulometric signature of heavy mineral enrichment processes and (c) on heavy mineral sources and transport within Tauranga Harbour:

Chapter 2: Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand

In this manuscript, environmental magnetic measurements (concentration, grain size) and sedimentological analyses on surficial sediments were used to detect heavy (magnetite) mineral enriched zones and their distributional pattern in and around Tauranga Harbour. The hydrodynamic modelling in combination with sedimentology could explain the formation mechanisms of a modern magnetite enrichment belt off Tauranga Harbour. A positive correlation between magnetite susceptibility and magnetic grain size indicates strong linkage between these parameters and could be utilized as a proxy for lag deposits and needs to be explored in various placer dominated environments. We demonstrate the potential of environmental magnetics to identify and differentiate various individual magnetite enrichment bodies.

Chapter 3: Selective transport and fractionation of magnetic particles in a transient coastal environment (Tauranga Harbour and Bay of Plenty, New Zealand)

Cumulative grain-size distributions of bulk sediments and their magnetic mineral fractions plotted on a log-probability scale were analyzed for a range of near-coast depositional environments (river upstream, river mouth, estuary, beach, nearshore region and inner shelf). Their comparison provided insights into the modes (traction, saltation, suspension) of transport of light and heavy minerals and resulting enrichment mechanisms under exposure to varying local hydrodynamics. The grain-size offset (difference between the grain sizes of light and heavy minerals) calculated for range of grain sizes provides information on the settling behaviour of individual grain size fractions. The differences in the shapes of the grain-size distributions, percentages of each population and offsets reflect variability in entrainment, transport and depositional condition of the grains in each environment. A 3D high resolution numerical flume tank modelling results indicates that higher offsets between the heavy and light mineral grain sizes increase the settling rate of heavy mineral grains onto the bed, which in turn leads to enrichment. However in beach environments consisting of sediments beds with mineral grains of similar sizes, i.e no grain-size offset, it was shown that the stability of the bed increases and rate of erosion is almost negligible compared to any other depositional environment. This study helped to increase our understanding on the mechanism controlling the grain entrainment, transport and enrichment in range of depositional environments.

Chapter 4: Controls on magnetic minerals and grain size distribution in a barrier enclosed estuarine lagoon (Tauranga Harbour, northeastern, New Zealand)

In this study the riverine and estuarine sediments of Tauranga harbour are characterized using magnetic and sedimentological analyses to investigate the factors controlling the sediment distribution and transport with the lagoonal area. Results show that the variability in the terrigenous sediment inputs, distinct local hydrodynamics (both the basins) and regional topography are the major factors controlling the sediment distribution and transport in the study area.

References

- Bagnold, R. A., (1954), Experiments on gravity-free dispersion of large solid spheres in a Newtonian fluid under shear: Royal Society (London), *Proceedings, Series A*, 225, 49 – 63.
- Cioppa, M. T., N. J. Porter, A. S. Trenhaile, B. Igbokwe, and J. Vickers (2010), Beach sediment magnetism and sources: Lake Erie, Ontario, Canada, *J. Great. Lake. Res.*, 36(4), 674–685, doi:10.1016/j.jglr.2010.07.007.
- Foster, I. D. L., A. J. Albon, K. M. Bardell, J. L. Fletcher, T. C. Jardine, R. J. Mothers, M. A. Pritchard, and S. E. Turner (1991), High energy coastal sedimentary deposits: an evaluation of depositional processes in Southwest England, *Earth Surface Processes and Landforms.*, 16(4), 341–356, doi: 10.1002/esp.3290160407.
- Gallaway, E., A. S. Trenhaile, M. T. Cioppa, and R. G. Hatfield (2012), Magnetic mineral transport and sorting in swash-zone: Northern Lake Erie, Canada, *Sedimentology.*, doi: 10.1111/j.1365-3091.2012.01323.x.
- Hatfield, R. G., M. T. Cioppa, and A. S. Trenhaile (2010), Sediment sorting and beach erosion along a coastal foreland: Magnetic measurements in Point Pelee National park, Ontario, Canada, *Sed. Geol.*, 231(3-4),63–73. doi:10.1016/j.sedgeo.2010.09.007.
- Komar, P. D (1989), Physical processes of waves and currents and the formation of marine placers. *Reviews in Aquatic Sciences*, 1, 393-423.
- Komar, P. D., and C. Wang (1984), Processes of selective grain transport and the formation of placers on beaches, *The Journal of Geology*, 92(6), 637–655.
- Komar, P. D. (1998), *Beach Processes and Sedimentation*, Second edition, Prentice Hall, Inc, A Pearson Education Company, New Jersey, 07458.
- Lees, J. A., and J. S. Pethick (1995), Problems associated with quantitative magnetic sourcing of sediments of the Scarborough to Mablethorpe coast, Northeast England, U.K, *Earth Surface Processes and Landforms.*, 20 (9), 795–806, doi: 10.1002/esp.3290200905.
- Maher, B. A. and Kinnersley, R. (2011). Biomagnetic monitoring of industry-derived particulate pollution, *Environmental Pollution.*, 159, 1673-168.
- Maher, B.A. and Kinnersley, R. (2010). Rates of particulate pollution deposition onto leaf surfaces: temporal and inter-species analyses. *Environmental Pollution.*, 10pp.doi:10.1016/j.envpol.2009.12.029.
- Maher, B.A and Hatfield, R.G (2009) Fingerprinting upland sediment sources: particle size-specific magnetic linkages between soils, lake- and suspended sediments, *Earth Surface processes and Landforms.*, 34, 1359-1373.
- Maher, B.A., Watkins, S.J., Brunskill, G., Alexander, J. & Fielding, C. (2009), Sediment provenance in a tropical fluvial and marine context by magnetic fingerprinting, *Sedimentology.*, 56, 841-861.
- Maher, B.A., Pates, J.M and Barker, P.A (2008), Sediment dynamics in an upland temperate catchment: changing sediment sources, rates and deposition, *J. Paleolimnology.*, 40, 1143-1158.

Oldfield, F., and L. Yu (1994), The influence of particle size variations on the magnetic properties of sediments from the north-eastern Irish Sea, *Sedimentology*, 41(6), 1093–1108, doi:10.1111/j.1365-3091-1994.tb01443.x.

Oldfield, F., B. A. Maher, J. Donoghue, and J. Pierce (1985), Particle-size related, mineral magnetic source sediment linkages in the Rhode River catchment, Maryland, USA, *J. Geol. Soc.*, 142(6), 1035–1046, doi: 10.1144/gsjgs.142.6.1035.

Roy, P. S., (1999), Heavy mineral beach placers in south eastern Australia. Their nature and genesis, *Economic Geology*, 94, 567 – 588.

Rubey, W. W (1933), The size distribution of heavy minerals within a water laid sandstone, *J. Sed. Petrol.*, 3 (1), 3–29, doi: 10.1306/D4268E37-2B26-11D7-8648000102C1865D.

Slingerland, R. L. (1977), The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands, *J. Sed. Res.*, 47(2), 753–770, doi: 10.1306/212f7243-2b24-11d7-8648000102c1865d.

Slingerland, R.L and Smith, N. D (1986), Occurrence and formation of water-laid placers, *Annu. Rev. Earth Planet. Sci.*, 14, 113.

Thompson R., and F. Oldfield (1986), *Environmental Magnetism*, 227 pp, Allen and Unwin, London.

Trask, C. B and Hand, B. M (1985), Differential transport of fall-equivalent sand grains, Lake Ontario, New York, *J. Sediment. Petrol.*, 55, 226-233.

Visher, G. S., (1969), Grain size distribution and depositional processes, *Journal of Sedimentary Petrology*, 39(3), 1074 – 1106

Zhang, W., L. Yu, and S. M. Hutchinson (2001), Diagenesis of magnetic minerals in the intertidal sediments of the Yangtze Estuary, China, and its environmental significance, *The Sci of Total Environ.*, 266(1-3), 169–175, doi: 10.1016/S0048-9697(00)00735-X.

Zhang, S., M. T. Cioppa, and Z. Shihong (2010), Spatial variation in particle size and magnetite concentration on Cedar Beach: Implications for grain sorting processes, Western Lake Erie, Canada, *Acta Geologica Sinica.*, 84(6), 1520–1532, doi: 10.1111/j.1755-6724.2010.00345.x.



Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand

Firoz Badesab

MARUM-Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Klagenfurter Strasse, DE-28359 Bremen, Germany (firoz@uni-bremen.de)

Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand

Tilo von Dobeneck

MARUM-Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Klagenfurter Strasse, DE-28359 Bremen, Germany

Karin R. Bryan

Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand

Hendrik Müller

MARUM-Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Klagenfurter Strasse, DE-28359 Bremen, Germany

Roger M. Briggs

Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand

Thomas Frederichs and Eva Kwohl

MARUM-Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Klagenfurter Strasse, DE-28359 Bremen, Germany

[1] Magnetic iron minerals are widespread and indicative sediment constituents in estuarine, coastal and shelf systems. We combine environmental magnetic, sedimentological and numerical methods to identify magnetite-enriched placer-like zones in a complex coastal system and delineate their formation mechanisms. Magnetic susceptibility and remanence measurements on 245 surficial sediment samples collected in and around Tauranga Harbour, the largest barrier-enclosed tidal estuary of New Zealand, reveal several discrete enrichment zones controlled by local hydrodynamic conditions. Active magnetite enrichment takes place in tidal channels, which feed into two coast-parallel nearshore magnetite-enriched belts centered at water depths of 6–10 m and 10–20 m. A close correlation between magnetite content and magnetic grain size was found, where higher susceptibility values are associated within coarser magnetic crystal sizes. Two key mechanisms for magnetite enrichment are identified. First, tide-induced residual currents primarily enable magnetite enrichment within the estuarine channel network. A coast-parallel, fine sand magnetite enrichment belt in water depths of less than 10 m along the barrier island has a strong decrease in magnetite

content away from the southern tidal inlet and is apparently related to active coast-parallel transport combined with mobilizing surf zone processes. A second, less pronounced, but more uniform magnetite enrichment belt at 10–20 m water depth is composed of non-mobile, medium-coarse-grained relict sands, which have been reworked during post-glacial sea level transgression. We demonstrate the potential of magnetic methods to reveal and differentiate coastal magnetite enrichment patterns and investigate their formative mechanisms.

Components: 9800 words, 9 figures, 1 table.

Keywords: environmental magnetism; magnetite enrichment; placer deposit; residual currents.

Index Terms: 1512 Geomagnetism and Paleomagnetism: Environmental magnetism; 4217 Oceanography: General: Coastal processes; 4534 Oceanography: Physical: Hydrodynamic modeling.

Received 27 February 2012; **Revised** 7 May 2012; **Accepted** 14 May 2012; **Published** 16 June 2012.

Badesab, F., T. von Dobeneck, K. R. Bryan, H. Müller, R. M. Briggs, T. Frederichs, and E. Kwohl (2012), Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand, *Geochem. Geophys. Geosyst.*, 13, Q06012, doi:10.1029/2012GC004125.

1. Introduction

[2] Heavy mineral enrichments known as ‘placers’ are found along many of the world’s coasts, with the economically most significant deposits being in Alaska (gold), India (magnetite), New Zealand (titanomagnetite) and Australia (rutile, monazite and zircon) [Rao, 1957; Gow, 1967; Komar and Wang, 1984; Li and Komar, 1992]. These enrichments are formed by physical concentration of detrital heavy mineral particles by action of winds, waves and currents mainly owing to their much greater density, but occasionally also supported by greater wear and weathering resistance. The concentration of detrital heavy mineral grains in fluvial estuaries and beaches is mostly explained by selective entrainment and dispersal of hydraulically equivalent particles of lesser densities and therefore large sizes [Slingerland, 1977]. Rapid burial of denser mineral particles due to gravitational effects may be an essential further enhancement process, which has been accounted for swash zone magnetite enrichment [Galloway *et al.*, 2012]. Numerous investigations [Rao, 1957; Komar and Wang, 1984; Frihy and Dewidar, 2003] highlight the role of wave-induced currents, selective entrainment and gravitational sorting processes in concentrating heavy minerals especially on open coast beaches. Precise knowledge of the location, shape and composition of enrichment structures can also provide clues about past and present hydrodynamic conditions.

[3] Titanomagnetite is a common iron-titanium oxide mineral, which occurs as an accessory in both igneous and metamorphic rocks. Because of its widespread occurrence and high specific density, it is frequently concentrated in placer deposits and is often associated with other heavy minerals of higher economic value. Such ‘ironsand’ or ‘black sand’ placer deposits are particularly prevalent on the open west coast of the North Island of New Zealand [Carter, 1980; Bryan *et al.*, 2007], and form an economically important resource for New Zealand’s titanium and iron ore industry. Previous studies have shown that andesitic rocks from Mt Taranaki are the primary source of this black sand and that the northerly directed littoral drift system plays a key role in accumulation and distribution of these deposits along the west coast [Kear, 1979; Hamill and Ballance, 1985]. Bryan *et al.* [2007] investigated the spatial and temporal variability of titanomagnetite placers on west coast beaches using hydrodynamic modeling and mineralogical analyses. However, few attempts have been made to investigate New Zealand’s more sheltered, deeply embayed and partly lagoonal northeast coast for heavy mineral enrichments, largely because of the generally much lower and hence economically irrelevant titanomagnetite and ilmenite contents.

[4] Embayed, estuarine and lagoonal coastal environments are hydrodynamically more complex settings with wave and current intensities that vary widely over short distances due to changing fetch and morphological constrictions such as tidal channel networks. A better understanding of heavy

mineral concentration processes in such systems can help not only to detect localized enrichments but also to reveal unknown aspects and details of the underlying hydro- and sediment dynamics. Several factors can determine the morphology and evolution of barrier-enclosed estuaries, including sea level rise, sediment sources, river runoff, tidal exchange and hydrodynamics of the nearshore region [Komar, 1998]. Tide-induced residual currents contribute greatly to mass sediment transport. Such currents are generated by nonlinear interaction of tidal flow with variable bathymetry [Zimmerman, 1981], which produces changes in flood-ebb asymmetries and long-term transport of sediment. Conversely, on open coasts, wave-induced littoral drift systems play a dominant role in transportation and distribution of sediments. Rates of net littoral drift can vary progressively along the coast, which results in a non-uniform distribution of sediments.

[5] In this study, we set out to investigate how tidal exchange, nearshore hydrodynamics and sea level change determine the patterns of heavy mineral enrichment in the meso-tidal estuarine lagoon of Tauranga Harbour and in the nearshore Bay of Plenty on the northeast coast of New Zealand. This economically active and ecologically sensitive region has recently gained world-wide attention with the wreck and oil and debris spills of the container ship MV *RENA* on 5 October 2011. From the viewpoint of sediment petrology, fluvial influx of magnetite from the Taupo Volcanic Zone through the lagoon contrasts with a comparably low background magnetite concentration of modern shelf sediments, which makes this study area ideal to investigate formative mechanisms of heavy mineral enrichment in sheltered, mesotidal, transitional coastal environments. Here, we focus on the ferrimagnetic heavy mineral (titano-)magnetite, which can be easily quantified and characterized by rock magnetic (laboratory) and electromagnetic (in situ) methods.

[6] Magnetic mineral concentrations and grain sizes can be derived from standard rock magnetic parameters [Thompson and Oldfield, 1986; Maher *et al.*, 1999]. This so-called environmental magnetic approach has been used to investigate sediment sources and transport pathways, and to assess heavy metal pollution in coastal systems [Oldfield *et al.*, 1985; Foster *et al.*, 1991; Razjigaeva and Naumova, 1992; Oldfield and Yu, 1994; Lees and Pethick, 1995; Wheeler *et al.*, 1999; Zhang *et al.*, 2001; Hatfield and Maher, 2008, 2009]. The

method has also been used to map the spatial distribution and composition of magnetic minerals in the coastal zone, to assess their degree of sorting, and to identify areas of sediment accumulation and erosion [Cioppa *et al.*, 2010; Hatfield *et al.*, 2010; Zhang *et al.*, 2010]. The technical ability to resolve magnetite distribution patterns in detail has been improved by the development of benthic electro-magnetic profiling, which permits rapid mapping of magnetic susceptibility together with electrical conductivity [Müller *et al.*, 2011, 2012]. This sample-based study is aimed at deepening fundamental understanding of geological and hydrodynamic processes as a prerequisite for future high-resolution mapping and modeling.

2. Study Area

2.1. Geography and Geology

[7] The Bay of Plenty region extends across a tectonically and volcanically active region of the North Island of New Zealand. Erosion can be intense and severe rain storms can generate and transport sediments to the coast resulting in rapid changes in the coastal zone. Most of the sediments reaching the Bay of Plenty are derived from proximal source rocks from the Taupo and Coromandel volcanic zones (Figure 1b), and have been extensively reworked during Holocene post-glacial sea level transgression [Beanland and Berryman, 1992].

[8] Tauranga Harbour is a large mesotidal estuarine lagoon situated centrally within the Bay of Plenty covering an area of 851 km² [Krüger and Healy, 2006]. It is enclosed by two Holocene tombolos and a 24-km-long sand barrier island, Matakana Island. Two tidal inlets, the natural Katikati entrance at the northern and the artificially deepened Tauranga entrance at the southern end, connect the lagoon with the bay area (Figure 1a). The seaward side of Matakana Island consists of shore-parallel relict foredunes, transgressive dunes and extensive back barrier deposits. The landward side of the island is covered by a mantle of tephras and other volcanic deposits [Shepherd *et al.*, 2000]. Coastal sand barriers in New Zealand developed during the late Pleistocene and Holocene. Changes in sea level influenced the sediment flows and played a key role in barrier development [Shepherd and Hesp, 2003].

[9] The southern part of Tauranga Harbour is New Zealand's largest natural harbor and the country's biggest export port. The entrance has a mean tidal

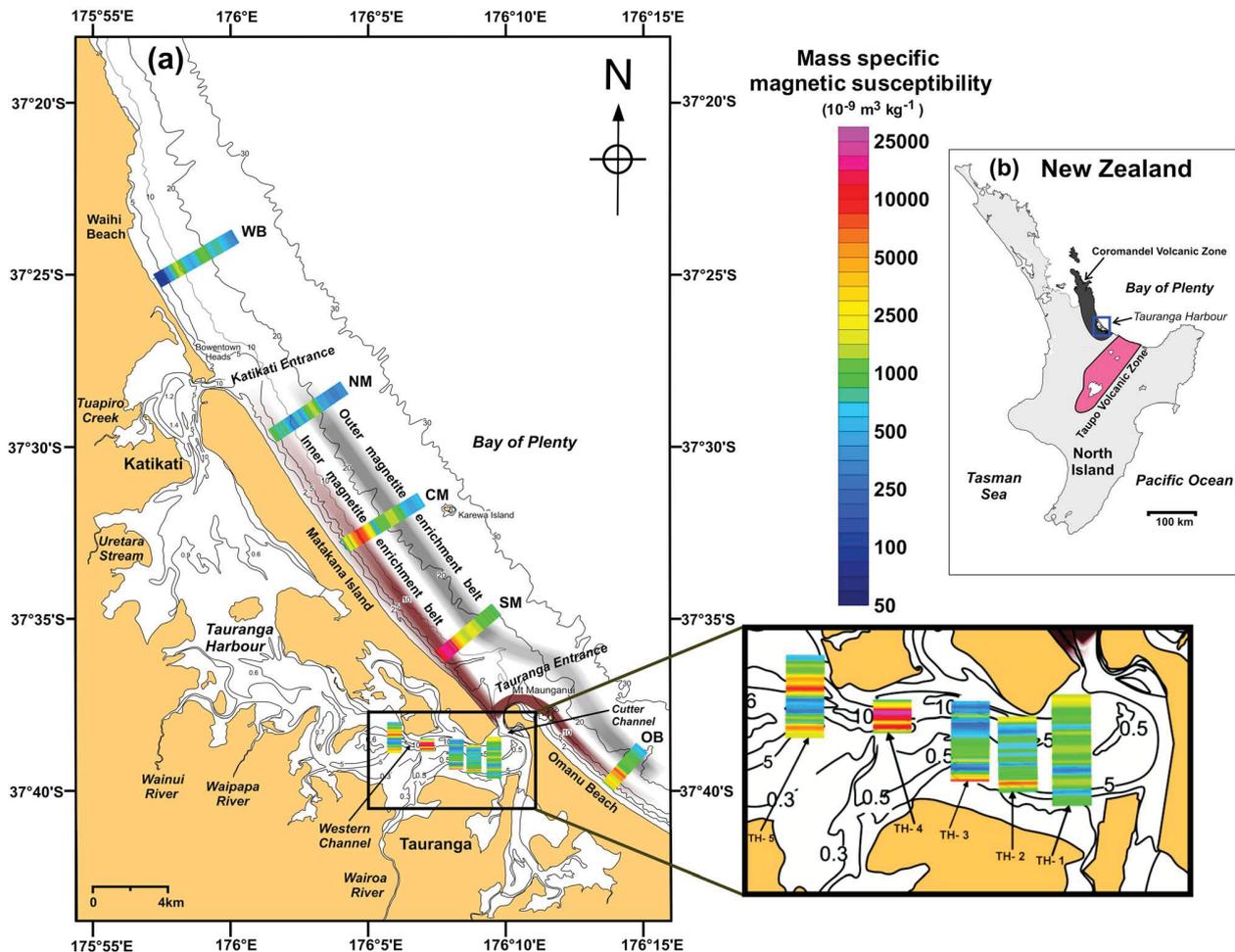


Figure 1. (a) Spatial distribution of magnetic minerals as indicated by concentration dependent magnetic susceptibility along the Bay of Plenty coast, New Zealand. TH-1, TH-2, TH-3, TH-4 represent the N–S oriented sediment sampling profiles within the southern basin of Tauranga Harbour. Five cross-shore profiles were named after Waihi Beach (WB), Northern Matakana (NM), Central Matakana (CM), Southern Matakana (SM) and Omanu Beach (OB). (b) Location map of the study area. This region is bounded by two major volcanic zones, the Coromandel Volcanic zone (CVZ) on the northwest and Taupo Volcanic zone (TVZ) on the southeast. Two hypothesized coast-parallel magnetite enrichment belts are highlighted using color gradients. The inner magnetite enrichment belt is indicated by dark brown and the outer belt is indicated with gray shading.

range of 1.4 m and a mean annual significant wave height of 0.5 m [De Lange, 1991]. The width of the entrance throat is 500 m with a maximum water depth of 34 m and a mean depth of 15 m [Krüger and Healy, 2006]. Wairoa River is the major fresh water source into Tauranga Harbour and has a large, mostly volcanic catchment area of about 465 km². It contributes a sediment load of about 28,000 tonnes per year to the southern part of Tauranga Harbour which is approximately 42% of the total received load. Present-day sedimentation within the southern Tauranga Harbour is generally low because the majority of riverine sediments are flushed out to sea.

2.2. Wave Climate and Sediment Dynamics

[10] The Bay of Plenty coast is sheltered from New Zealand's westerly and southwesterly winds and waves and has a much milder wave climate compared to the exposed west coast. The wave climate is mainly dominated by northeasterly waves produced by tropical cyclones and from barometric depressions that move down from the northwest and pass through north of New Zealand. Shallow water waves of 0.5–1.5 m wave height and 7–9 s periods dominate the region [Pickrill and Mitchell, 1979; Gorman *et al.*, 2003]. The Bay of Plenty coast is an open sand system exposed to wave

energy and contains the longest littoral drift system of the northeast region. The net littoral drift is around $70,000 \pm 20,000 \text{ m}^3$ per year and is generally southeasterly directed.

[11] The hydrodynamics at the southern Tauranga Harbour entrance are dominated by tidal currents and waves. Sediment transport is mainly controlled by tidal currents with wave action having a significant effect only in shallow areas. Within the southern port of Tauranga Harbour, the two main tidal channels, Western and Cutter channels (Figure 1a), merge at the southern entrance and are characterized by ebb-directed sediment transport [Kwoll and Winter, 2011]. A conceptual model of sediment dynamics explains that flood tidal currents transport sediment into the inlet, where a sediment circulation pattern develops. Sediment jetted out of the southern Tauranga entrance tends to move landward along the Matakana coast due to wave action.

3. Materials and Methods

[12] A sediment sampling survey with research vessel *Tai Rangahau* (University of Waikato, Hamilton, New Zealand) was undertaken during February – March 2010, in the framework of the International Research Training Group INTERCOAST- ‘Integrated Coastal Zone and Shelf Sea Research’ at the Universities of Bremen and Waikato. With an objective to develop the potential of magnetic minerals as markers of coastal zone evolution, a total of 245 surface sediment samples (uppermost 1–5 cm) were collected from the seafloor at water depths from 2.5 to 25 m using a Van Veen grab sampler. Five cross-shore profiles at Waihi Beach (WB), Northern (NM), Central (CM) and Southern (SM) Matakana Island, and Omanu Beach (OB) were sampled at intervals of 50 m in the nearshore region and stepwise increased intervals of 100, 200 and 400 m in the offshore region. Surface sediment samples were also collected along five north–south oriented transects (TH-1, TH-2, TH-3, TH-4 and TH-5) in the southern part of Tauranga Harbour (Figure 1a).

3.1. Environmental Magnetic Analyses

[13] Magnetic measurements were made on dried surface sediment bulk samples. Samples were weighed and densely packed into 6.2 cm^3 plastic cubes. Magnetic susceptibility was measured at low frequency (0.47 kHz) using a Bartington Instruments MS2B meter. An anhysteretic remanent magnetization (ARM) was imparted in a 100 mT alternating field (AF) and a $40 \mu\text{T}$ direct current

(DC) bias field using an automated 2G Enterprises 755R DC SQUID pass-through cryogenic magnetometer. An isothermal remanent magnetization (IRM) was imparted and measured at 22 incremental steps up to 700 mT. The IRM at this maximum field was considered as the saturation IRM (SIRM). All results are presented as dry mass specific susceptibilities and remanences.

[14] Raw volume specific magnetic susceptibility values κ were converted to respective mass specific susceptibility χ using the calculated density based on known sample mass and volume. Magnetic susceptibility is often used as an indicator for ferrimagnetic mineral concentration due to the particle size independence of this parameter [Heider et al., 1996] and because para- and antiferromagnetic minerals generally make a minor magnetic contribution to susceptibility [Thompson and Oldfield, 1986]. Magnetite percentage was calculated considering a value of $660 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$ for pure multidomain magnetite [Maher, 1988]. The ARM/IRM ratio is a common magnetic grain size proxy, which is proportional to the relative content of single domain (SD) particles e.g., for equidimensional magnetite, the (30–100 nm grain size range) and pseudo-single domain (PSD) magnetite (i.e., the 100 nm–1 μm size range) [Muxworthy and Williams, 2006].

3.2. Physical Grain Size and Hydraulic Behavior

[15] Grain size distributions within the 0.4–2000 μm range were measured using a Coulter LS 200 laser particle size analyzer to investigate the influence of particle size on hydraulic behavior and magnetic properties. Suspensions were prepared by placing about 4–5 g of moist sediment into 100 ml of distilled water with addition of 300 mg of a dispersing agent ($\text{Na}_4\text{P}_2\text{O}_7 \times 10 \text{ H}_2\text{O}$) and treated with ultrasonics before measurements were taken. For determination of settling velocities, bulk sediment samples were sieved to remove gravel and clay size particles and were chemically treated to remove organic- and carbonate-rich materials [Carver, 1971]. Measurements were performed in an automated settling tube at the Senckenberg Institute for Marine Geology, Wilhelmshaven, Germany.

3.3. Magnetic Grain Size Fractions

[16] Based on bulk magnetic measurements and grain size analyses, four representative samples from each identified unit (beach zone, inner and outer magnetite enrichment belts, offshore zone) were

sieved for 15 min in an automated sieve shaker and separated into the six particle size fractions $>500 \mu\text{m}$, $355\text{--}500 \mu\text{m}$, $250\text{--}355 \mu\text{m}$, $125\text{--}250 \mu\text{m}$, $63\text{--}125 \mu\text{m}$, and $40\text{--}63 \mu\text{m}$. The particle assemblages obtained in each size fraction were then subjected to the above mentioned magnetic measurements.

3.4. Wave Parameters

[17] The cross-shore distribution of physical wave parameters (wave energy, seabed orbital velocity, alongshore wave energy flux) for studying the influence of waves on the bottom sediments were calculated for the open coast sites following equations from Komar [1998] with the influence of breaking in the surf-zone modeled using the method presented by Thornton and Guza [1983]. The model was initialized using wave data over seven years (23 Sept. 2003–02 June 2010) from the Pukehina wave buoy located to the southeast of the study area (37.3812°S , 176.947°E) in 62 m water depth. This wave buoy was operated by the Bay of Plenty Regional Council and measured H (wave height), θ (wave direction relative to the orientation of the coast) and T (wave period).

[18] Based on the Pukehina wave buoy data, the wave energy E was calculated following Thornton and Guza [1983]:

$$E = \frac{1}{8} \rho g H_{rms}^2, \quad (1)$$

where ρ is the density of water, H_{rms} is the root mean square of wave height and g is the acceleration due to gravity. The alongshore wave energy flux S was calculated using the identity:

$$S = EC_g \sin(\theta). \quad (2)$$

The cross-shore distribution of wave energy was calculated numerically by solving:

$$\frac{\Delta(C_g E)}{\Delta x} = \langle \varepsilon_b \rangle, \quad (3)$$

where C_g is the wave group speed, and x is the cross-shore distance. The wave dissipation due to surfzone breaking $\langle \varepsilon_b \rangle$ is calculated following Thornton and Guza [1983]:

$$\langle \varepsilon_b \rangle = \frac{3\sqrt{\pi}}{16} g \rho B^3 f \frac{H_{rms}^7}{\gamma^4 h^5}, \quad (4)$$

where h is the water depth, f is the cyclic wave frequency, γ is a breaking constant set to 0.42 and B is a fitting constant set to 1.2 as recommended by

Thornton and Guza [1983]. The seabed orbital velocity u for intermediate water depth and pure wave motion was calculated using their equation:

$$u = \frac{\pi H}{T} \frac{\cosh(k(h+z))}{\sinh(kh)}, \quad (5)$$

where k is the radian wave number and z is the elevation below still water level. The critical velocities u_m under waves needed to entrain the sediments of fine and medium sands, representing the inner and outer enrichment belts, were calculated following Komar and Miller [1973]:

$$\frac{\rho u_m^2}{(\rho_s - \rho)gD} = a''(d_o/D)^{1/2}, \quad (6)$$

where $a'' = 0.21$ is the proportionality coefficient calculated based on the average of Bagnold [1946] and Manohar [1955], ρ_s is the sediment grain density, D is the sediment grain size and d_o is the seabed orbital diameter given by:

$$d_o = \frac{H_{rms}}{\sinh(kh)}. \quad (7)$$

The 1D wave transformation model was applied along an average transect for each wave record in the 7-year time series and provided the across-shore distribution of wave characteristics, including the effects of shoaling and wave breaking. The 10%, 50% and 90% probability of occurrence of wave conditions were then calculated from this data set.

3.5. Numerical Modeling of Tidal Currents

[19] The estuarine tidal currents were calculated using the 3D hydrodynamic model software “Estuary, Lake and Coastal Ocean Model” (ELCOM), which was earlier set up and calibrated to determine the velocities and direction of tide-induced residual currents within Tauranga Harbour. This model has been previously used to predict velocity, temperature and salinity distribution in natural water bodies [Hodges et al., 2000]. The hydrodynamics simulation method solves the unsteady Reynolds-averaged, hydrostatic Boussinesq, Navier–Stokes and scalar transport equations. Water level conditions along the open ocean boundary of the model domain were derived from the National Institute of Water and Atmospheric Research (NIWA) tidal model (<http://www.niwa.co.nz/our-services/online-services/tides>). The freshwater inflow boundaries into the southern basin of Tauranga Harbour were sourced from Bay of Plenty Regional Council’s monitoring data archives. The bathymetry grid was obtained from hydrographic surveying undertaken by the NZ Navy and

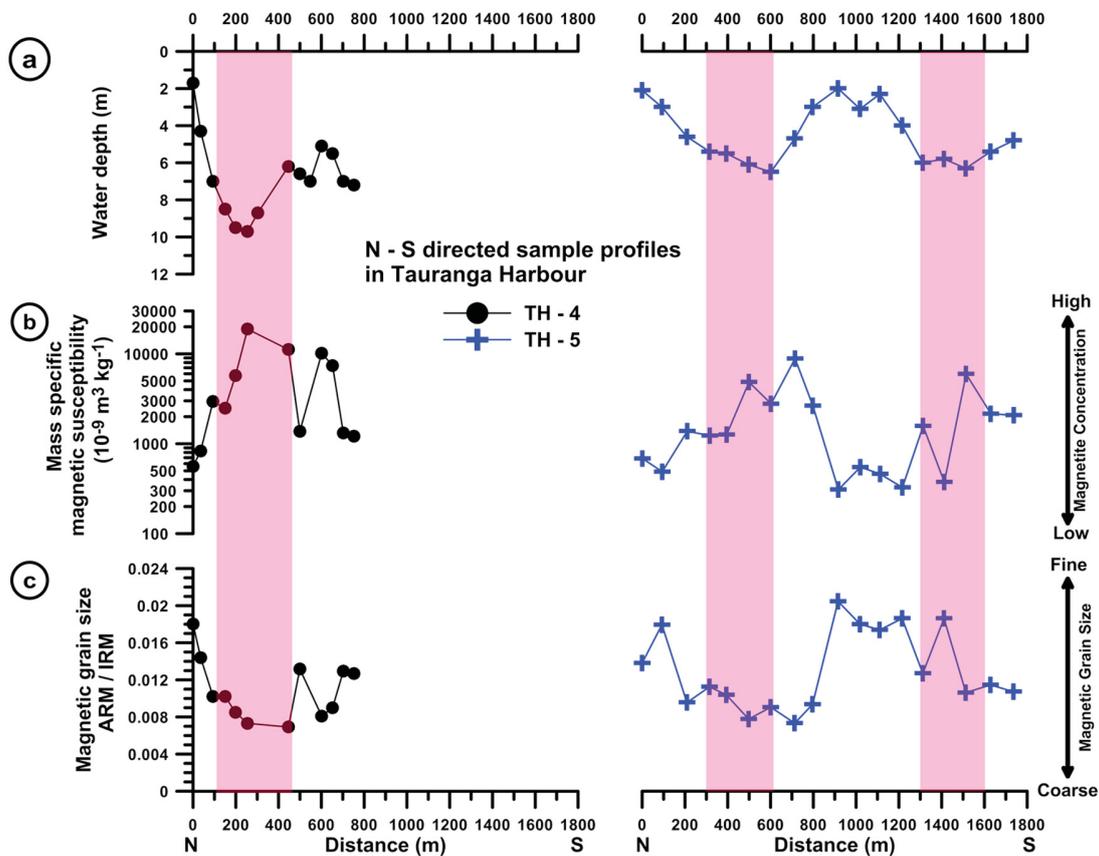


Figure 2. Variation of magnetic properties along N–S directed profiles within the southern basin of Tauranga Harbour. The zero on the x axis marks the north of the sample profiles. (a) Variation in water depth. (b) Mass specific magnetic susceptibility represents the abundance of ferrimagnetic minerals (magnetite), and (c) the ratio of ARM/IRM is used as an indicator of magnetic grain size. Data from profiles TH-4 and TH-5 are shown to illustrate clear trends in magnetic properties compared to all other profiles. Samples from the tidal channel (Western Channel) are highlighted by a pink background. Lower ratios indicate the dominance of coarser magnetic grains, while higher ratios indicate the dominance of finer grains.

the Port of Tauranga. The model was run for a 14-day spring-neap cycle and the output averaged to provide net residual currents.

4. Results

4.1. Surficial Variation of Magnetite Concentration

[20] Magnetic susceptibility and ARM/IRM data for surficial sediments in and offshore Tauranga Harbour indicate highly variable magnetite concentration and grain size (Figures 1–3). Within the southern basin of Tauranga Harbour, susceptibility varies over two orders of magnitude from 309 to $18,823 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$ (~ 0.05 to 3 mass % magnetite), with highest values found within tidal channels (Figure 2b). The ARM/IRM ratio for profiles TH-4 and TH-5 varies from 0.006 to 0.020. Higher magnetic susceptibility

values are dominated by coarser magnetic grain sizes and are concentrated in the tidal channels of the southern basin of Tauranga Harbour (Figures 1, 2b, and 2c).

[21] Off Matakana Beach, two coast-parallel belts of magnetite enrichment were identified based on the magnetic susceptibility of five cross-shore profiles (Figure 1). The inner magnetite enrichment belt, which extends from about 800 to 1800 m offshore, appears to connect to the southern entrance (profile SM) and vanishes toward the northern entrance of Tauranga Harbour (profile NM). The outer belt extends from about 2000 to 3500 m from the shoreline and appears to be a larger feature extending toward the north (Figure 1a). The two magnetite enrichments belts are centered in water depths of 6–10 and 10–20 m, respectively (Figure 3b).

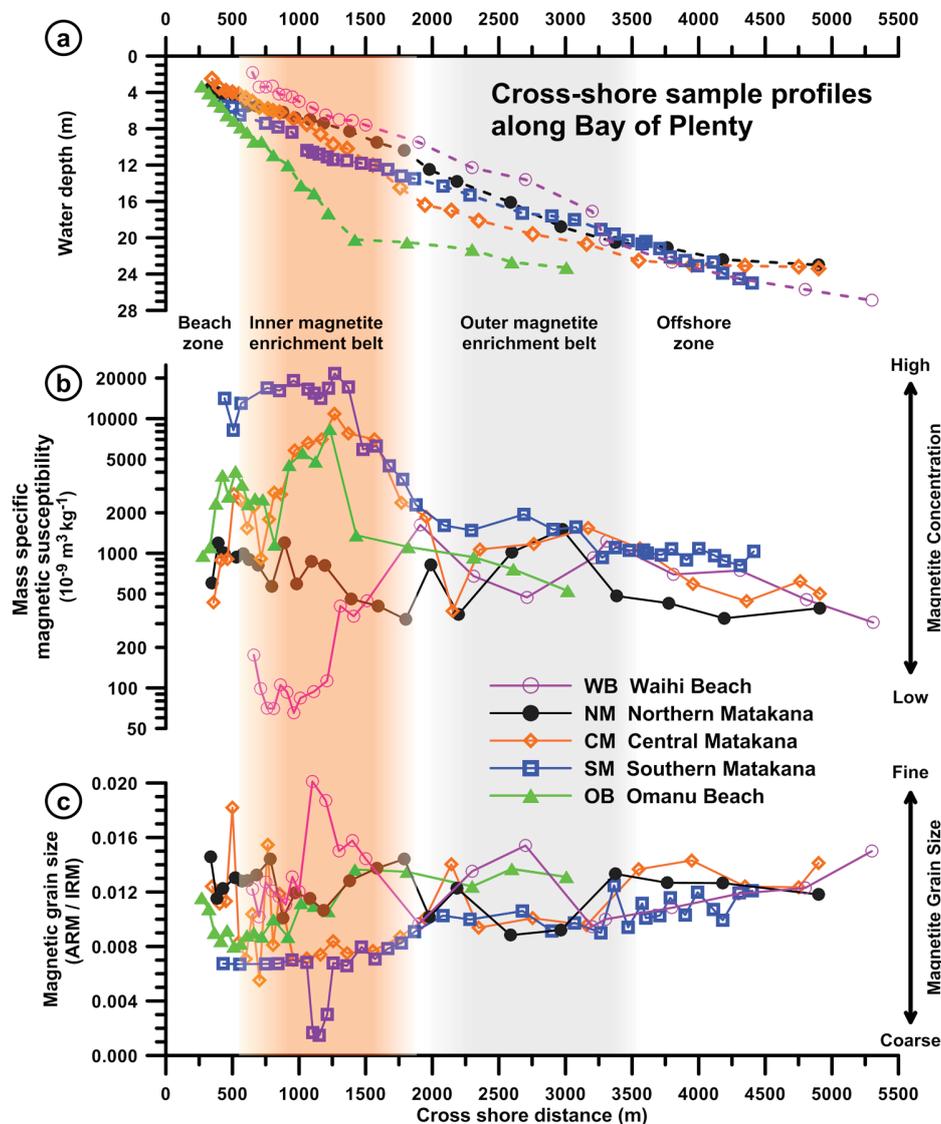


Figure 3. Cross-shore variation in (a) water depth, (b) magnetic susceptibility, and (c) magnetic grain size measured on sediment samples from the five offshore profiles shown in Figure 1. Two coast-parallel magnetite enrichment belts are highlighted using color gradients. The inner magnetite enrichment belt is indicated by light brown and the outer belt by gray shading. Lower ARM/IRM ratios indicate the dominance of coarser magnetic grain sizes.

[22] Four different zones were defined by changes in the surficial magnetic susceptibility: the beach zone (water depth 0–6 m), the inner magnetite enrichment belt (6–10 m), the outer magnetite enrichment belt (10–20 m) and an offshore zone (20–25 m) (Figure 3). Overall, the magnetic susceptibility of offshore samples varies over three orders of magnitude from 65 to $21,606 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$ (~ 0.01 to 3.3 mass% magnetite) with the highest values within the inner magnetite enrichment belt of profile SM (Figure 3b). The magnetic susceptibility increases from the beach zone to the inner magnetite enrichment belt and then generally decreases with

increasing cross-shore distance. A small susceptibility peak at 2000 to 3500 m offshore marks the outer magnetite enrichment belt (Figure 3b). However, separation between the inner and outer belt is less distinct in profile SM. A general fining trend in magnetite grain size with cross-shore distance is observed in three profiles (CM, SM, OB) as indicated by the increasing ARM/IRM ratio (Figure 3c). In profiles NM and WB, in the beach zone and the inner magnetite enrichment belt the ARM/IRM ratio is relatively high, but it still mirrors the magnetic susceptibility trend.

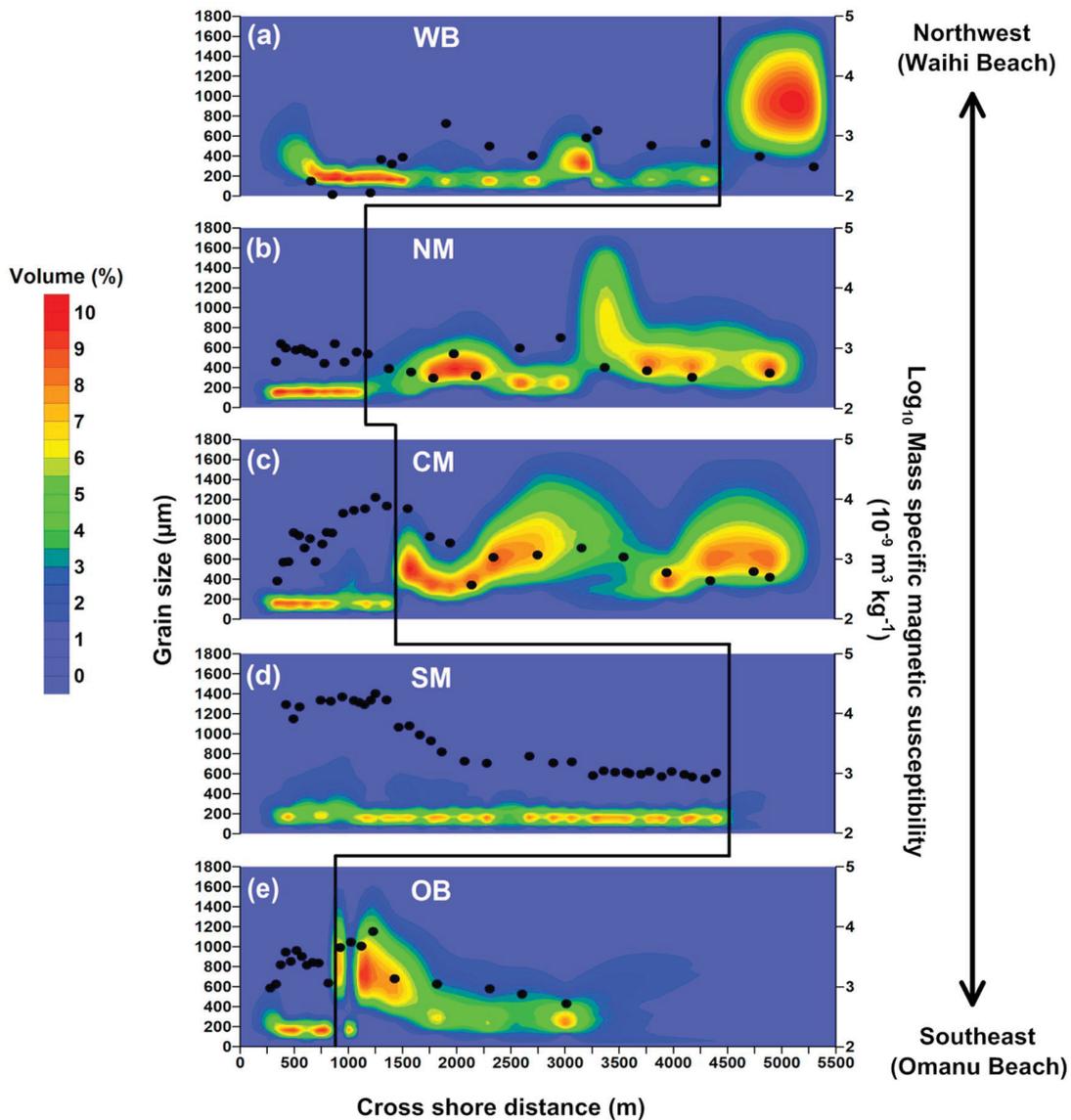


Figure 4. Grain size distributions along the five cross-shore profiles. (a) Waihi Beach (WB), (b) Northern Matakana (NM), (c) Central Matakana (CM), (d) Southern Matakana (SM), and (e) Omanu Beach (OB). The vertical scales indicate grain sizes, while those on the right-hand side represent \log_{10} mass specific magnetic susceptibilities. Solid black circles mark variations in magnetite concentration along the profile as indicated by mass specific magnetic susceptibility values. A solid black line indicates the seaward limit of fine sand along cross-shore profiles.

4.2. Grain Size Distribution Patterns

[23] Grain sizes in and offshore of Tauranga Harbour vary from fine to coarse sand. Well sorted, fine to medium sand dominates the southern basin (data not shown). Offshore of Tauranga Harbour, we observed two different patterns in the cross-shore and along-shore distribution of sediment grain sizes (Figure 4). The nearshore region, including the beach zone and inner magnetite enrichment belt (<10 m water depth), is dominated by fine sand (~ 150 μm) and further

coarsens toward the outer belt and offshore zone (>10 m water depth) as observed in profiles NM, CM, and OB (Figures 4b, 4c, and 4e).

4.3. Particle Size Dependent Magnetic Measurements

[24] In highly energetic coastal environments, magnetic properties have a strong dependence on particle size [Oldfield *et al.*, 1985; Yu and Oldfield, 1993;

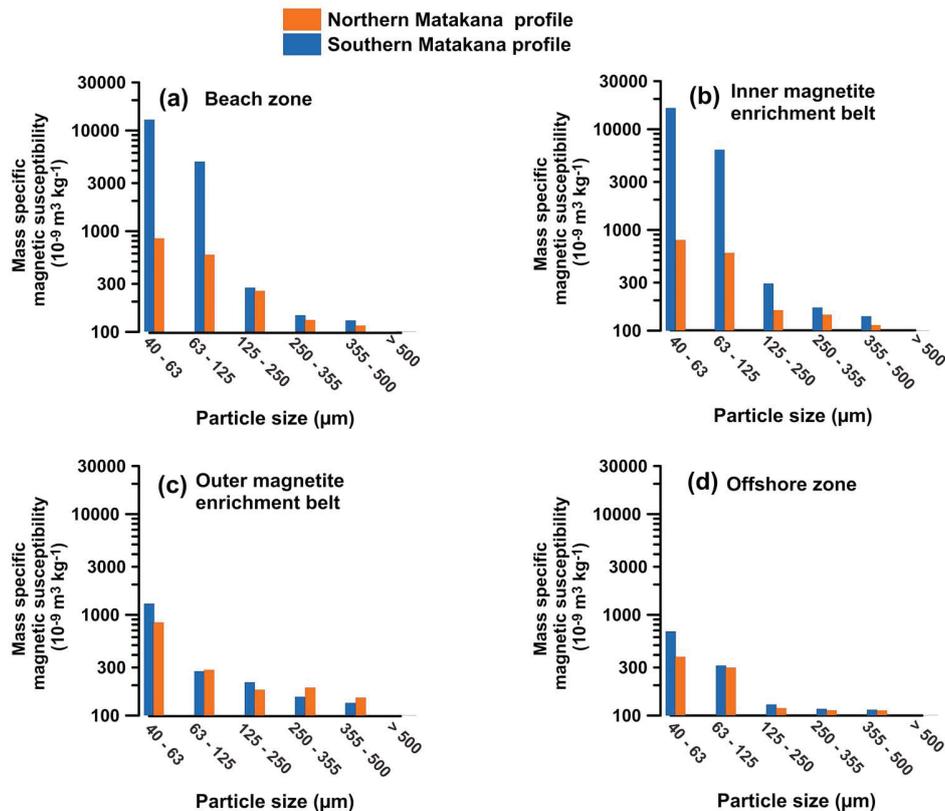


Figure 5. Bar plot of cross-shore variations in magnetic mineral concentration for six particle size fractions extracted from bulk sediment samples. The northern and southern Matakana profiles are divided into four different regions: (a) beach zone, (b) inner magnetite enrichment belt, (c) outer magnetite enrichment belt, and (d) offshore zone. Higher susceptibility values correspond to higher magnetite concentrations in each of the sieved fractions.

Hatfield and Maher, 2008]. Measurements of magnetic susceptibility of sieved fractions provide a more detailed understanding of prevailing depositional processes compared to bulk sample measurements. The results of magnetic measurements on different particle size fractions from cross-shore profiles NM and SM are shown in Figure 5. These profiles were chosen because they have the most contrasting differences in magnetic susceptibility and magnetic grain size. Magnetic susceptibility decreases with increasing particle size, with the highest values in the inner magnetite enrichment belt (Figures 5a–5d). For example, in profiles NM and SM, the finer fractions (40–63 μm and 63–125 μm) generally have a higher magnetic susceptibility than the coarser fractions (>125 μm) although magnetic susceptibility is variable in the outer belt with much higher values in coarser particle size fractions (125–250 μm , 250–355 μm ; Figure 5c). Overall, the magnetic susceptibility for the SM profile samples is higher and varies over one order of magnitude compared to samples collected from profile NM,

especially in the beach zone and the inner magnetite enrichment belt (Figures 5a and 5b).

4.4. Wave Induced Initiation of Sediment Grain Motion

[25] A mean significant wave height of 0.6 m was calculated in the shallow waters off Tauranga at water depths up to 26 m. Seabed orbital velocities for fair (10%), average (50%), and storm (90%) weather conditions have been calculated based on equation (5) and the wave parameters are given in Table 1. Seabed orbital velocities are high in the beach zone and decrease away from shore (Figure 6a). Critical velocities for the two dominant grain sizes (150 and 400 μm) that represent the inner and outer magnetite enrichment belt were calculated using equation (6) and are shown as horizontal lines in Figure 6a. The median wave conditions are most likely to suspend the 150 μm grain size fraction in water depths shallower than 10 m. In storm conditions, particles with this grain

Table 1. Wave Parameters and Critical Velocities for Two Dominant Grain Sizes

Cross-Shore Distance (m)	Water Depth (m)	Wave Height (m)			Seabed Orbital Velocity (m/s)			Critical Velocity (m/s)	
		10%	50%	90%	10%	50%	90%	150 μm	400 μm
120	0.5	0.127	0.145	0.152	0.268	0.315	0.331	0.198	0.253
540	5.02	0.281	0.542	1.058	0.140	0.315	0.659	0.202	0.258
1400	10.19	0.277	0.518	1.113	0.053	0.168	0.418	0.178	0.227
2300	15.89	0.280	0.521	1.107	0.015	0.105	0.285	0.163	0.209
3300	20.27	0.285	0.528	1.114	0.005	0.074	0.218	0.155	0.198
4300	23.43	0.289	0.531	1.122	0.002	0.057	0.182	0.148	0.190

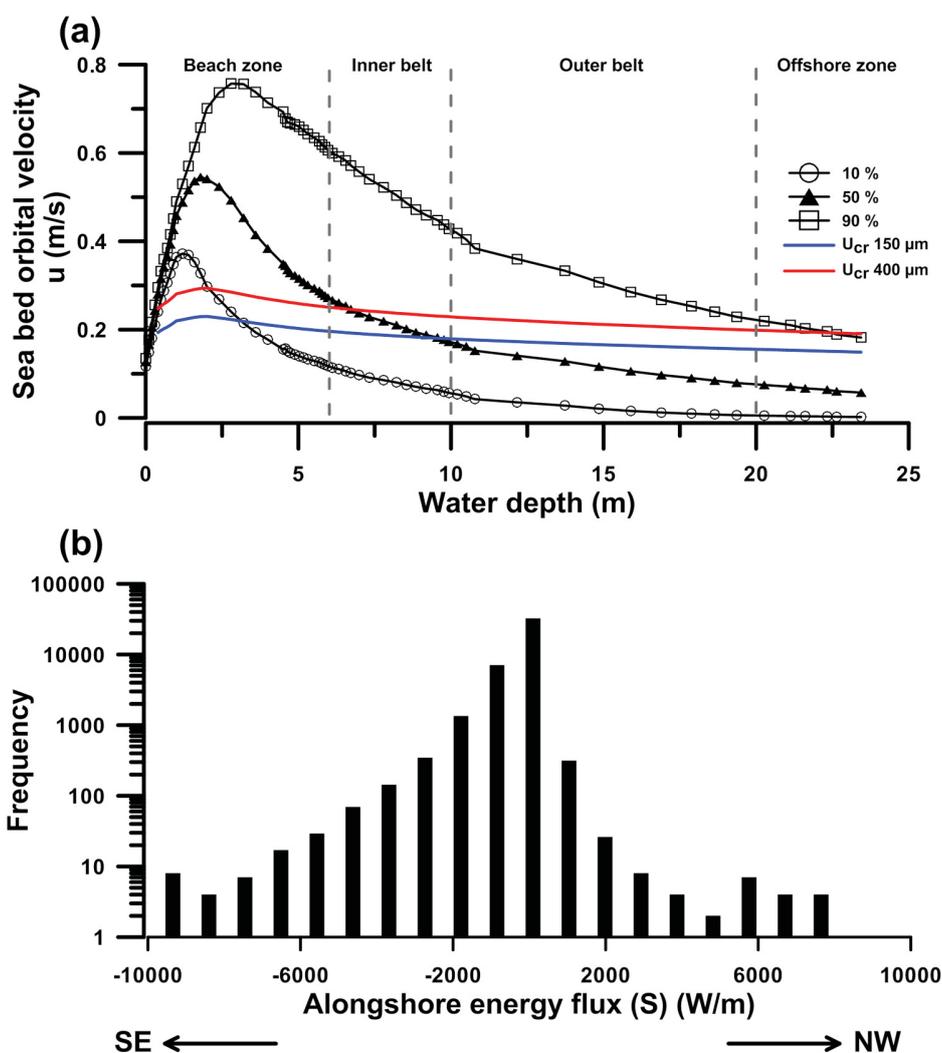


Figure 6. Computed wave parameters. (a) Seabed-orbital velocity (calculated using model runs on wave data and equation (5), from which the 10% (fair), 50% (median) and 90% (storm) probabilities were calculated). The horizontal lines marked in blue and red are the critical velocities for the two dominant grain sizes (150 μm and 400 μm) that were calculated using equations (6) and (7). (b) The probability distribution of alongshore energy flux at the buoy location, calculated using 41655 measurements of wave height and direction data and equations (1) and (2).

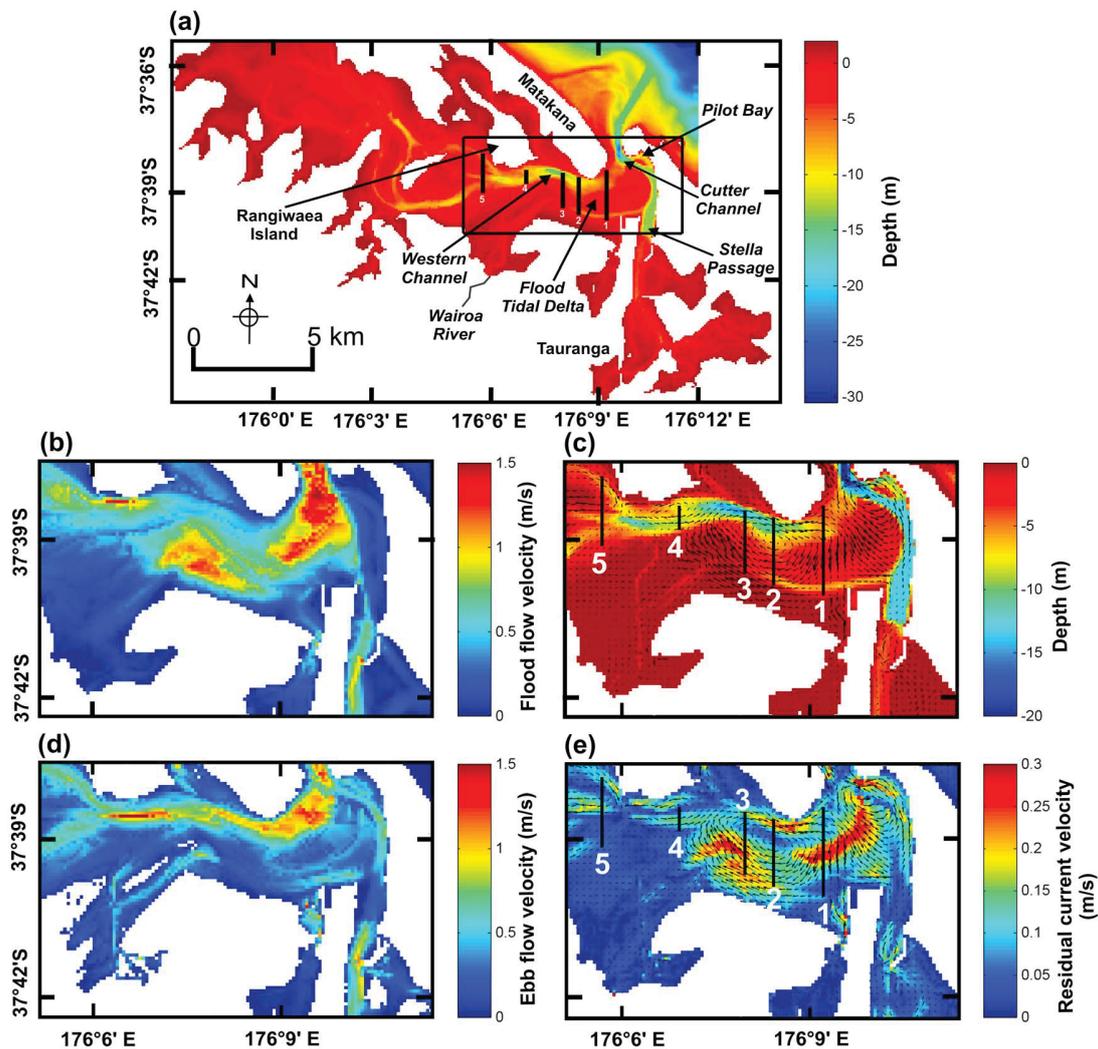


Figure 7. (a) Overall bathymetric map of Tauranga Harbour with positions of sediment sampling profiles, (b) modeled peak flood flow velocities (ms^{-1}), (c) time-averaged residual current vectors, (d) peak ebb flow velocities (ms^{-1}), and (e) time-averaged residual current velocities (ms^{-1}). Sediment sampling profiles within Tauranga Harbour are labeled as 1–5. The flood, ebb and residual current velocities are averaged over the entire water column.

size are in continuous motion along the whole profile. Conversely, the coarser grain size fraction ($400 \mu\text{m}$) is suspended only in storm conditions. There are no normal conditions where waves will suspend this size fraction in the offshore zone where it dominates the seabed, which implies that current hydrodynamic conditions are not responsible for deposition of these sediments. The alongshore wave energy flux calculated for the seven years of available wave data indicates that the alongshore transport is bidirectional, but predominantly southeasterly directed (Figure 6b). This indicates that in the region where the grains are suspended by wave processes (shallow region), they will be moved both up and

down the coast, but with a marginal probability that the SE direction will dominate.

4.5. Residual Tidal Currents

[26] Residual vector plots in which the tidal current vector is summed over a spring-neap cycle (14 days) are used to indicate potentially net-driven sediment transport. Peak flood tidal velocities are dominant along the western side of the lagoon entrance and progressively diverge over the shallower central intertidal areas of the flood tidal delta (Figure 7b). Conversely, the peak ebb flow pattern indicates strong currents at the eastern side of the lagoon

entrance and at the Western Channel, while currents are weak over the flood tidal delta (Figure 7d). Time-averaged residual current vectors and velocities within the southern basin of Tauranga Harbour are shown in Figures 7c and 7e. The eastern side of the entrance channel at Pilot Bay, Stella Passage and Western Channel are ebb dominated (Figure 7e), while flood tidal delta and shallower intertidal regions of the upper reaches of Tauranga Harbour are dominated by flood tides. The strength of residual current intensity at Western Channel and the flood tidal delta indicates the importance of tidal asymmetries, ebb and flow dominance, bathymetry and tidal current intensity in driving overall sediment movement within Tauranga Harbour.

4.6. Relationship Between Magnetic Properties and Physical Grain Size

[27] In order to evaluate the relationship between magnetic mineral concentration and physical grain size, bivariate plots are used to indicate magnetic mineral concentration, magnetite grain size and physical grain size (Figure 8). A clear relationship exists between magnetic susceptibility and magnetic grain size in all samples in and offshore of Tauranga Harbour, with highest values dominated by coarser magnetic grain sizes (Figures 8b and 8e). Within the lagoon tidal channel, samples from profiles TH-4 and TH-5 have higher magnetic susceptibilities and coarser physical grain sizes ($\sim 300\text{--}500\ \mu\text{m}$) compared to non-tidal channel samples which have mainly lower magnetic susceptibilities and finer physical grain sizes (Figures 8a and 8c).

[28] Offshore Tauranga Harbour, magnetic susceptibilities are much higher for the inner belt than for the outer belt samples. Inner belt samples from profiles CM, SM and OB have higher susceptibility, coarser magnetic and finer physical grain size compared to outer belt samples; however, this trend is not observed in profile NM and is reversed in profile WB (Figures 8e and 8f). Relevant magnetite enrichments in the Bay of Plenty study area are only observed for fine, mobile ($\leq 150\ \mu\text{m}$) and coarse, non-mobile ($\geq 600\ \mu\text{m}$) sands. Compared to these shelf sediments, samples taken from Tauranga Harbour are generally coarser and lack a fine fraction ($< 200\ \mu\text{m}$; Figures 8a and 8c).

[29] Coupling between magnetic grain size and physical grain size is generally weak for both sample sets (Figures 8a and 8d). Within Tauranga Harbour (Figure 8a), our observations indicate that physical and magnetic grain sizes follow equivalent trends in

response to bottom current conditions. Offshore of Tauranga Harbour (Figure 8d), we observe two populations, where mobile median grain sizes $< 200\ \mu\text{m}$ have a wide range of magnetite grain sizes that fine with distance from the southern inlet. Immobile sand samples with median grain sizes $> 200\ \mu\text{m}$ have relatively uniform magnetic grain sizes.

5. Discussion

[30] Our results demonstrate the presence, spatial distribution and hydrodynamic drivers of magnetically enriched zones in and around Tauranga Harbour. As verified by electron microscopy (data not shown) and standard mineral magnetic techniques, the magnetic properties are controlled by sedimentary (titano-) magnetite with variable concentration and grain size. We now discuss some of the environmental factors that influence heavy mineral (magnetic and non-magnetic) enrichment processes in estuarine and nearshore regions.

5.1. Influence of Sediment Particle Size on Magnetic Properties

[31] Particle size has a decisive influence on certain magnetic properties of sediments [Oldfield and Yu, 1994; Clifton et al., 1999; Zhang et al., 2001]. Magnetic measurements on sieved fractions are often preferred over bulk measurements to discard the generally nonlinear grain size effects. As highlighted by Hounslow and Maher [1996], magnetic minerals, in particular magnetite, often occur as inclusions within silicate minerals such as quartz or feldspar. It is therefore likely that magnetic properties of coarser particle size fractions are partially due to magnetite inclusions in silicate or polycrystalline particles, which decouples magnetic crystal and physical grain size.

[32] In the beach zone and inner magnetite enrichment belt, the fine grain size fractions ($40\text{--}63\ \mu\text{m}$ and $63\text{--}125\ \mu\text{m}$) have the highest magnetite enhancement, the most prominent alongshore decrease and the largest relative contribution to total magnetic susceptibility (Figures 5a, 5b, and 5d). In the outer magnetite enrichment belt, the magnetite enrichment in the fine fractions is far less prominent and more magnetite occurs in coarser grain size fractions (Figure 5c). In the offshore zone, magnetite contents are generally lower and mainly concentrated in the $< 125\ \mu\text{m}$ fractions. Grain size distributions offshore of Tauranga Harbour indicate that sediments of the outer belt, i.e., the inner shelf, are dominated

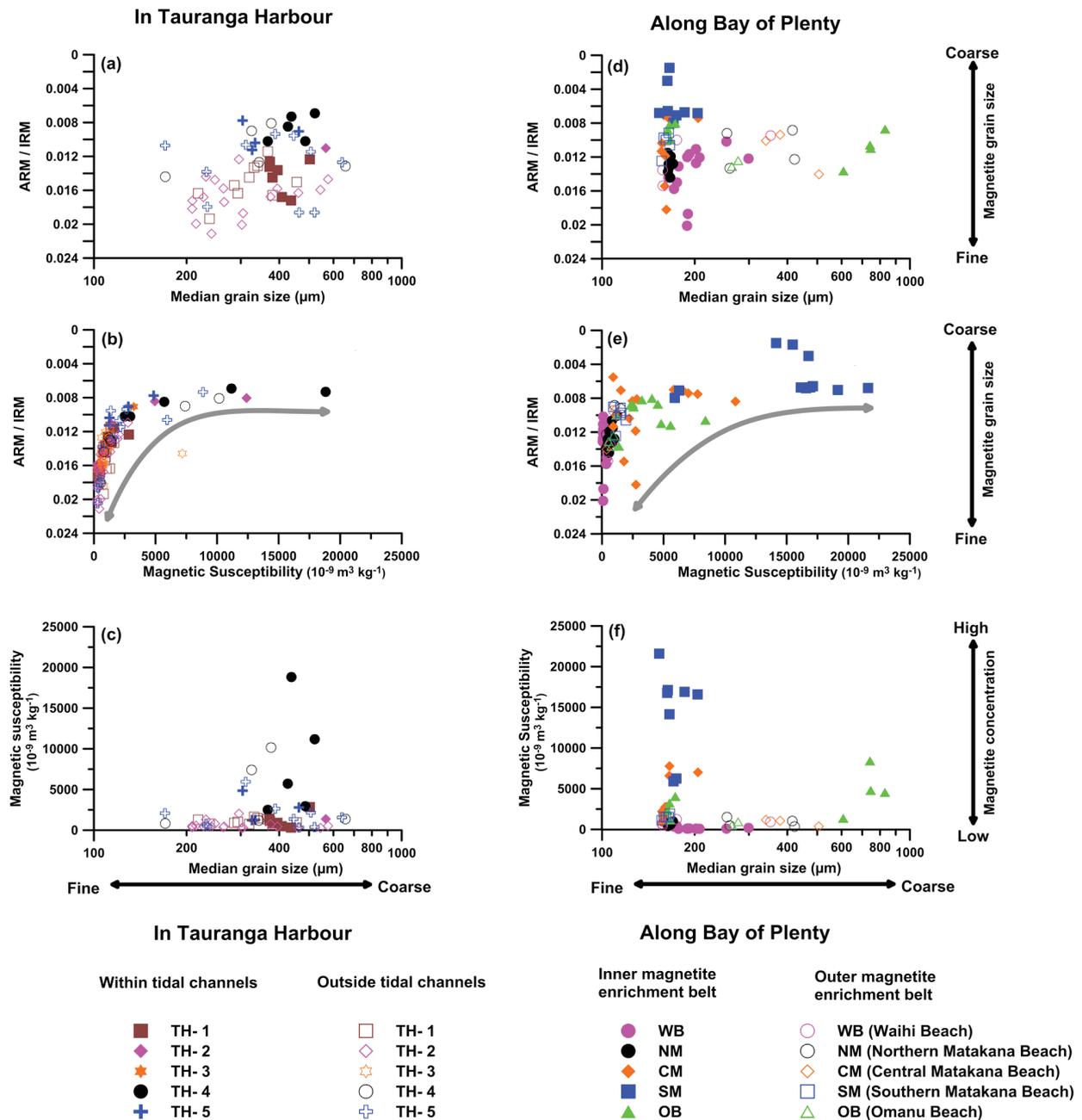


Figure 8. Bivariate scatterplots of magnetic grain size (ARM/IRM) versus physical (median) grain size and magnetic susceptibility of surface sediment samples. (a–c) Samples collected within the southern part of Tauranga Harbour. Closed symbols indicate samples from the western tidal channel, and open symbols indicate samples from the non-tidal channel region. (d–f) Samples collected along cross-shore beach profiles along the Bay of Plenty coast covering Waihi, Matakana and Omanu Beach. Closed symbols indicate samples within the inner magnetite enrichment belt, while outer belt samples are marked with open symbols. Note that ordinate scales of Figures 8b and 8e are reversed.

by medium–coarse-grained sand. Previous studies indicate that these sands are relict Pleistocene deposits that were reworked during the last glacial [Harms, 1989; Bradshaw et al., 1994; Michels and Healy, 1999; Krüger and Healy, 2006]. A clear

positive correlation is evident between magnetic susceptibility and magnetic grain size in offshore samples in bivariate plots (Figure 8). This could be a fingerprint for lag deposits and should be further exploited in placer forming environments.

5.2. Tide-Induced Residual Currents and Magnetite Enrichment Within Tauranga Harbour

[33] Sediment transport and water circulation in coastal estuaries and lagoons are largely controlled by tides under competing influences of wind stress and river inflow. During flooding, the water depth inside the tidal channels increases and tidal flats are inundated at the peak high tide. These areas are subsequently drained and remain exposed during low tide. These flooding-drying cycles of shallow intertidal flats create or enhance the asymmetry between flood and ebb regimes over a tidal cycle and result in equally asymmetric tidal currents and large-scale residual flows within the lagoon.

[34] Previous studies indicate that sediment dynamics within the southern basin of Tauranga Harbour are mainly dependent on tidal currents. Ebb and flood dominant flows control overall sediment movement within the basin. A residual circulation pattern is developed within the harbor which originates from the lagoon entrance and then moves in a clockwise loop over the flood tidal delta and through the Western Channel before finally returning toward the entrance (Figures 7c and 7e). Sediments from Wairoa River entering the southern basin of Tauranga Harbour are circulated or transported through this residual circulation loop within the harbor.

[35] Residual currents and sediment transport are stronger in Western Channel, Cutter Channel and the flood tidal delta as well as at the lagoon entrance, and are directed toward the inner part of the harbor and contribute to net sediment and water transport within the harbor (Figure 7e). In the upper reaches of Western Channel (Rangiwaea Island), residual currents are smaller, ebb currents are dominant and hence favor sediment deposition by increasing the residence time of mineral grains. As defined by *Dronkers and Zimmerman* [1982], residence time is the period that a water parcel starting from a particular location within a water body remains in the system before exiting. At the lower end of Western Channel and Tauranga Harbour entrance, sediments are flushed more frequently due to stronger tidal action. Profiles TH-4 and TH-5 are located within the upper reaches of the Western Channel and have higher magnetite enrichments in the vicinity of Rangiwaea Island (Figure 7a). This suggests that the smaller ebb-directed residual currents favor higher sediment deposition, and by increasing the residence time of grains, enhance magnetite enrichment within Tauranga Harbour.

[36] There are two related principles for heavy mineral enrichment under strong tidal bottom currents: heavy minerals such as magnetite suspended in hydraulic settling equivalence with larger silicate grains can be less easily entrained from a rough bed after temporary deposition because of their smaller grain size and hence smaller exposure to shear stress compared to lighter minerals. Possibly more importantly, denser minerals at the practically viscous sediment/water interface have negative buoyancy relative to lighter minerals and therefore quickly sink into the deeper, and more protected part of the viscous interface [*Galloway et al.*, 2012]. They are consequently less often remobilized, which over longer terms, results in burial of heavy mineral enriched lag zones. While lighter and smaller particles are continuously lost to the open shelf, heavy mineral enrichments accumulate until they are eventually displaced onto the sublittoral shelf by extreme bottom current velocities such as those associated with spring tides, storm floods or seasonal runoff peaks.

5.3. Surf-Zone Processes and Magnetite Enrichment Offshore Tauranga Harbour

[37] Heavy minerals are found enriched on modern beaches, Pleistocene marine terraces, and on the continental shelf. In highly dynamic swash- and surf-zone environments, especially in barrier beaches, placer minerals have been largely concentrated due to reworking of modern and Pleistocene sands. Large amounts of sand in the nearshore region are sorted into heavy mineral enriched lag deposits, while lighter minerals are transported further offshore because of their more frequent remobilization and therefore shorter residence time [*Roy*, 1999].

[38] Our magnetic profile data offshore of Tauranga Harbour reveals the existence of two coast-parallel magnetite enrichment belts in water depths of 6–10 m and 10–20 m. The highest magnetite enrichments were not found in the high-energy beach and breaker zones, but in the calmer nearshore sublittoral zone where sediments consist of well-sorted, fine-grained, mobile Holocene sands. The offshore extension and magnetic enhancement of this facies decreases drastically from E to W. This suggests that this sediment body is not fed by wave action but by coast-parallel transport from Tauranga Harbour's southern entrance. Consequently, the inner magnetite enrichment belt must represent a steady state equilibrium structure, which is progressively dissipated by orbital wave action away from the source. The less prominent, but regionally more uniform,

outer magnetite belt has much lower heavy mineral enrichment, which is comparable to the modern beach facies of the more distal Matakana and Omanu Beach profiles. Owing to immobility of its medium- to coarse-grained sands and its greater lateral continuity, the outer magnetite enrichment belt could therefore represent a late glacial transgression beach front.

[39] Our findings agree with observations from previous investigations that described two dominant sediment lithofacies (fine and coarse sand) offshore of Tauranga Harbour. These investigations were based on side scan survey and surface sediment sampling campaigns within nearshore and inner shelf areas offshore of Tauranga Harbour [Harms, 1989; Bradshaw *et al.*, 1994; Michels and Healy, 1999; Krüger and Healy, 2006]. These authors showed that coarse-grained sands were partially covered by thin patches and sheets of transgressive fine sands that are transported under low energy conditions, while coarser-grained sands remain in place on the inner shelf as erosional lag or relict deposits.

5.4. Influence of Coastal Hydrodynamics and Morphology on Magnetite Enrichment

5.4.1. Littoral Drift System and Magnetite Enrichment

[40] The sandy littoral system of Bay of Plenty extends for about 170 km from Waihi Beach in the northwest to Opape in the southeast [Healy, 1980; Hume and Herdendorf, 1990, 1992]. The net littoral drift along Bay of Plenty is generally SE-directed and Waihi Beach is the northernmost end of the littoral drift system [Harray and Healy, 1978; Healy, 1980].

[41] Littoral drift plays a dominant role in along-shore movement of sediments in the nearshore region. Several types of barriers such as headlands, tidal inlets and jetties tend to interrupt the normal littoral drift and cause accumulation of sediments instead of further transport, e.g., near Oregon coast headlands [Peterson *et al.*, 1986]. In our study, this situation corresponds to that of profile SM, which is close to the southern inlet and has the highest concentrations of magnetic minerals. It is possible that the headland at the southern inlet of Tauranga Harbour (Mt. Maunganui) is a potential barrier to the southeasterly directed littoral drift. It disrupts normal delivery of coast parallel sediment flux to the southeast, and causes higher accumulation of finer sediments on the updrift side of the inlet and its ebb-

tidal delta, i.e., along Eastern Matakana Beach. The dredged navigation channel at the southern inlet of Tauranga Harbour also acts as a potential sediment trap for the interrupted littoral drift. Transported offshore by tidal currents, sediments over-spilling from the channel could add to the accumulation of sediment near the southern inlet [Spiers *et al.*, 2009]. However, it is highly unlikely that this alternative W-E offshore enrichment mechanism would gradually lead to a nearly 300-fold increase in magnetite content along the Matakana shore, with nearly the same magnetite enhancement level as an independently acting 60-fold tidal enrichment process of magnetite within the channel network of Tauranga Harbour. We therefore dismiss this explanation for heavy mineral enrichment.

5.4.2. Sediment Sorting, Selective Entrainment and Alongshore Sediment Transport

[42] Heavy mineral enrichment in the nearshore region has been well documented in numerous examples around the world [e.g., Komar and Wang, 1984; Bryan *et al.*, 2007]. Accumulation of heavy minerals on the beach and nearshore region produces placer deposits mostly due to gravity separation under the action of waves and currents. For example, in the surf zone, wave breaking results in intense suspension of sediment grains, with fine and heavy grains tending to settle quickly onto the bed whereas lighter and coarser grains are easily entrained and carried away by large waves. Such processes tend to concentrate fine and heavy mineral grains leading to accumulations of fine and dense mineral grains as lag deposits.

[43] Observed resemblances in settling velocities of magnetic and non-magnetic particles within our investigated offshore sediment samples are consistent with the concept of hydraulic equivalence developed by Rubey [1933]. Such similarity in settling velocities is caused by the equivalent and hence reciprocal effect of greater particle density and size, which is commonly observed in placer deposits [Peterson *et al.*, 1986]. This suggests that settling behavior does not play a significant role for heavy mineral enrichment and supports the importance of selective entrainment and burial mechanisms.

[44] Critical velocities calculated for the two dominant grain sizes of the inner and outer magnetite enrichment belts indicate that the finer fraction ($<150 \mu\text{m}$) is regularly suspended in water depths less than 10 m which suggests that these sediments are actively involved in beach zone processes (Figure 6a) while the coarser fraction ($400 \mu\text{m}$) at

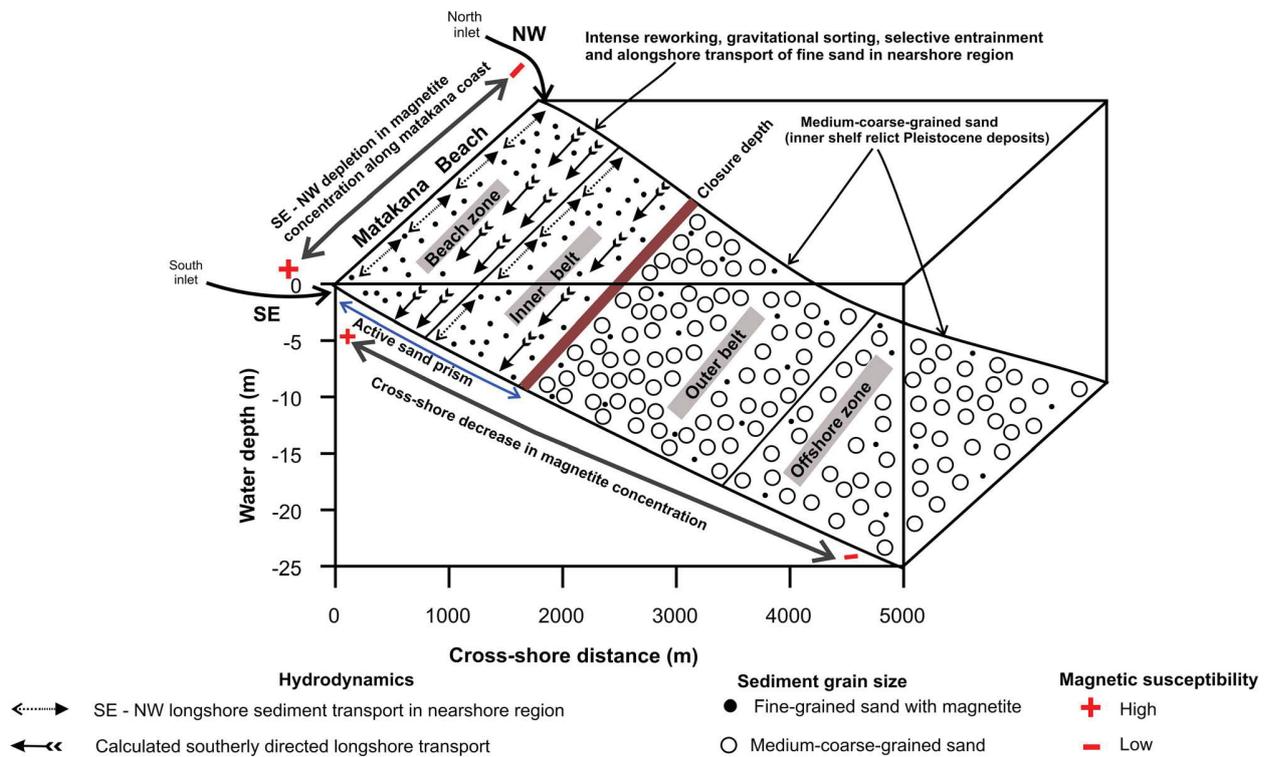


Figure 9. Conceptual model for nearshore and inner shelf sediment dynamics off Tauranga Harbour (modified from Bradshaw *et al.* [1994], copyright 1994, with permission from Elsevier).

greater depths of the outer belt and offshore zone remains unsuspected under available energy conditions and form a coarse-grained lag deposit. We therefore hypothesize that the lower boundary of the inner belt (i.e., 10 m water depth) forms the seaward end of the active sand prism or closure depth offshore of Tauranga Harbour, beyond which there is no significant cross-shore or longshore sediment transport. The sharp shift in grain size from fine (150 μm) to medium (400 μm) sand is observed in all cross-shore profiles except WB and SM, where sediments are entirely dominated by fine sand (Figures 4a and 4d). An alongshore trend of declining fine sand content is visible in a northwesterly direction between profile SM and NM (Figures 4b–4d). This trend is in accordance with the previously observed decrease in magnetic susceptibility along this profile and indicates a NW-directed alongshore transport of fine sediments in shallow waters.

[45] The alongshore wave energy flux calculation indicates that sediments along Matakana coast generally move southeastward (Figure 6b), but the probability of northwestward movement of sediment

is nearly equivalent. Periodic changes in wave direction and wind pattern provide continuous mixing generated by waves, while more fine-grained sediment is released and suspended at the lagoon entrance forming coast-parallel concentration gradients. Therefore, there will be net drift away from the source (southern inlet) into the northwestern direction, but also into the southeastern direction if the embayments west and east of Mt. Maunganui were interconnected by littoral drift as suggested by consistencies of the Omanu Beach profile. The longshore change in magnetite content and fine sand volume along the Bay of Plenty coast provides evidence for these hypotheses.

6. Conclusions

[46] We demonstrate that the combined approach of environmental magnetic, sedimentological and numerical modeling methods is useful to demarcate heavy mineral enriched zones and to delineate their formative processes. Our findings are summarized in a conceptual model (Figure 9), which can probably be generalized to the other offshore

regions. An inner fine-grained heavy mineral belt forms where sediments are diffused away from the lagoonal entrance in the sufficiently energetic nearshore region, while outer enrichment zones are more likely remnants of Pleistocene inner shelf lag deposits. Two key mechanisms that control magnetite enrichment within and offshore of Tauranga Harbour are revealed: tide-induced residual currents control sediment transport within the lagoon and play a key role in forming magnetite-enriched sediment facies. The alongshore distribution of exported and magnetically enriched fine sand is enabled by nearshore wave dynamics and fluctuations in littoral drift, while modern (highstand) surf and swash zone processes yield lower heavy mineral enrichment factors and do not seem to contribute much to the material budget of the inner magnetite enrichment belt. This situation has been different in the past when coastal sands were intensely reworked by rising beachfronts.

[47] Magnetic susceptibility is a useful and easily determined parameter, which efficiently identifies heavy-mineral-rich areas in coastal settings. Heavy minerals represent key indicators of the sedimentary regimes and energy conditions of coastal environments. Determination of magnetic susceptibility of the seafloor by sediment sampling or future electromagnetic profiling has considerable potential to be used as routine tool for coastal and shelf placer mineral exploration.

Acknowledgments

[48] We acknowledge funding by the Deutsche Forschungsgemeinschaft DFG via the Bremen-Waikato International Research Training Group INTERCOAST and the MARUM Center for Marine Environmental Sciences at the University of Bremen. Liane Brück, Dirk Immenga, Christopher Daly, Serena Fraccascia, Ruggero Capperucci, Max Kluger, Gerhard Bartzke and Sebastien Boulay provided assistance during sampling and Hui Woon Tay provided valuable numerical hydrodynamic modeling results. We are grateful to Terry Healy, Burghard Flemming, Christian Winter and Willem de Lange for their support and helpful inputs. The Bay of Plenty Regional Council, Tauranga, New Zealand is thanked for contributing long-term wave data. Alexander Bartholomä gave access to the automated settling tube facility at the Senckenberg Institute for Marine Geology, Wilhelmshaven, Germany. The Hanse Wissenschaftskolleg, Germany, supported KRB during her study leave at the University of Bremen. The authors thank Stefanie Brachfeld and an anonymous reviewer for detailed and helpful reviews of the manuscript.

References

- Bagnold, R. A. (1946), Motion of waves in shallow water. Interaction between waves and sand bottoms, *Proc. R. Soc. London, Ser. A*, *187*, 1–18, doi:10.1098/rspa.1946.0062.
- Beanland, S., and K. R. Berryman (1992), Holocene coastal evolution in a continental rift setting; Bay of Plenty, New Zealand, *Quat. Int.*, *15–16*, 151–158, doi:10.1016/1040-6182(92)90043-2.
- Bradshaw, B. E., T. R. Healy, C. S. Nelson, P. M. Dell, and W. P. De Lange (1994), Holocene sediment lithofacies and dispersal systems on a storm-dominated, back-arc shelf margin: The east Coromandel coast, New Zealand, *Mar. Geol.*, *119*, 75–98, doi:10.1016/0025-3227(94)90142-2.
- Bryan, K. R., A. Robinson, and R. M. Briggs (2007), Spatial and temporal variability of titanomagnetite placer deposits on predominantly black sand beach, *Mar. Geol.*, *236*, 45–59, doi:10.1016/j.margeo.2006.09.023.
- Carter, L. (1980), Iron sand in continental shelf sediments of western New Zealand—A synopsis, *N. Z. J. Geol. Geophys.*, *23*, 455–468, doi:10.1080/00288306.1980.10424116.
- Carver, R. E. (1971), *Procedures in Sedimentary Petrology*, John Wiley, New York.
- Cioppa, M. T., N. J. Porter, A. S. Trenhaile, B. Igbokwe, and J. Vickers (2010), Beach sediment magnetism and sources: Lake Erie, Ontario, Canada, *J. Great Lakes Res.*, *36*, 674–685, doi:10.1016/j.jglr.2010.07.007.
- Clifton, J., P. McDonald, A. Plater, and F. Oldfield (1999), Derivation of a grain-size proxy to aid the modelling and prediction of radionuclide activity in salt marshes and mud flats of the eastern Irish Sea, *Estuarine Coastal Shelf Sci.*, *48*, 511–518, doi:10.1006/ecss.1998.0461.
- De Lange, W. P. (1991), Wave climate for No 1 Reach, Port of Tauranga, Tauranga Harbour, report, Port of Tauranga Ltd., Hamilton, New Zealand.
- Dronkers, J., and J. T. F. Zimmerman (1982), Some principles of mixing in tidal lagoons, *Oceanol. Acta*, *4*, 8–14.
- Foster, I. D. L., A. J. Albon, K. M. Bardell, J. L. Fletcher, T. C. Jardine, R. J. Mothers, M. A. Pritchard, and S. E. Turner (1991), High energy coastal sedimentary deposits: An evaluation of depositional processes in southwest England, *Earth Surf. Processes Landforms*, *16*, 341–356, doi:10.1002/esp.3290160407.
- Frihy, O. E., and K. M. Dewidar (2003), Patterns of erosion/sedimentation, heavy mineral concentration and grain size to interpret boundaries of littoral sub cells of the Nile delta, Egypt, *Mar. Geol.*, *199*, 27–43, doi:10.1016/S0025-3227(03)00145-2.
- Galloway, E., A. S. Trenhaile, M. T. Cioppa, and R. G. Hatfield (2012), Magnetic mineral transport and sorting in the swash-zone: Northern Lake Erie, Canada, *Sedimentology*, doi:10.1111/j.1365-3091.2012.01323.x, in press.
- Gorman, R. M., K. R. Bryan, and A. K. Laing (2003), Wave hindcast for the New Zealand region: Nearshore validation and coastal wave climate, *N. Z. J. Mar. Freshwater Res.*, *37*(3), 567–588, doi:10.1080/00288330.2003.9517190.
- Gow, A. G. (1967), Petrographic studies of iron sands and associated sediment near Hawera, South Taranaki, *N. Z. J. Geol. Geophys.*, *10*, 675–696, doi:10.1080/00288306.1967.10431086.
- Hamill, P. F., and P. F. Ballance (1985), Heavy mineral rich beach sands of the Waitakere coast, Auckland, *N. Z. J.*

- Geol. Geophys.*, 28, 503–511, doi:10.1080/00288306.1985.10421203.
- Harms, C. (1989), Dredge spoil dispersion from an inner shelf dump mound, M.Phil. thesis, Dep. of Earth and Ocean Sci., Univ. of Waikato, Hamilton, New Zealand.
- Harray, K. G., and T. R. Healy (1978), Beach erosion at Waihi Beach Bay of Plenty, New Zealand, *N. Z. J. Mar. Freshwater Res.*, 12, 99–107, doi:10.1080/00288330.1978.9515731.
- Hatfield, R. G., and B. A. Maher (2008), Suspended sediment characterization and tracing using a magnetic fingerprinting technique: Bassenthwaite Lake, Cumbria, UK, *Holocene*, 18, 105–115, doi:10.1177/0959683607085600.
- Hatfield, R. G., and B. A. Maher (2009), Holocene sediment dynamics in an upland temperate lake catchment: Climatic and land-use impacts in the English Lake District, *Holocene*, 19, 427–438, doi:10.1177/0959683608101392.
- Hatfield, R. G., M. T. Cioppa, and A. S. Trenhaile (2010), Sediment sorting and beach erosion along a coastal foreland: Magnetic measurements in Point Pelee National Park, Ontario, Canada, *Sediment. Geol.*, 231, 63–73, doi:10.1016/j.sedgeo.2010.09.007.
- Healy, T. R. (1980), Erosion and sediment drift on the Bay of Plenty coast, *Soil Water*, 16, 12–14.
- Heider, F., A. Zitzelsberger, and K. Fabian (1996), Magnetic susceptibility and remanent coercive force in grown magnetite crystals from 0.1 μm to 6 mm, *Phys. Earth Planet. Inter.*, 93, 239–256, doi:10.1016/0031-9201(95)03071-9.
- Hodges, B. R., J. Imberger, A. Saggio, and K. B. Winters (2000), Modelling basin scale waves in a stratified lake, *Limnol. Oceanogr.*, 45, 1603–1620, doi:10.4319/lo.2000.45.7.1603.
- Hounslow, M. W., and B. A. Maher (1996), Quantitative extraction and analysis of carriers of magnetization in sediments, *Geophys. J. Int.*, 124, 57–74, doi:10.1111/j.1365-246X.1996.tb06352.x.
- Hume, T. M., and C. E. Herdendorf (1990), Morphological and hydrological characteristics of tidal inlets on a headland dominated, low littoral drift coast, northeastern New Zealand, *J. Coastal Res.*, 9, 527–563.
- Hume, T. M., and C. E. Herdendorf (1992), Factors controlling tidal inlet characteristics on low drift coasts, *J. Coastal Res.*, 8, 355–375.
- Kear, D. (1979), Geology of iron resources of New Zealand, 164 pp., N. Z. Dep. of Sci. and Ind. Res., Wellington.
- Komar, P. D. (1998), *Beach Processes and Sedimentation*, 2nd ed., Prentice Hall, Upper Saddle River, N. J.
- Komar, P. D., and M. C. Miller (1973), The threshold of sediment movement under oscillatory water waves, *J. Sediment. Petrol.*, 43, 1101–1110, doi:10.1306/74D7290A-2B21-11D7-8648000102C1865D.
- Komar, P. D., and C. Wang (1984), Processes of selective grain transport and the formation of placers on beaches, *J. Geol.*, 92, 637–655, doi:10.1086/628903.
- Krüger, J., and T. R. Healy (2006), Mapping the morphology of dredged ebb tidal delta, Tauranga Harbour, New Zealand, *J. Coastal Res.*, 22, 720–727, doi:10.2112/03-0117.1.
- Kwoll, E., and C. Winter (2011), Determination of initial grain size distribution in a tidal inlet by means of numerical modelling, *J. Coastal Res.*, 64, 1081–1085.
- Lees, J. A., and J. S. Pethick (1995), Problems associated with quantitative magnetic sourcing of sediments of the Scarborough to Mablethorpe coast, northeast England, U.K., *Earth Surf. Processes Landforms*, 20, 795–806, doi:10.1002/esp.3290200905.
- Li, M. Z., and P. D. Komar (1992), Longshore grain sorting and beach placer formation adjacent to the Columbia River, *J. Sediment. Petrol.*, 62, 429–441, doi:10.1306/D426791A-2B26-11D7-8648000102C1865D.
- Maher, B. A. (1988), Magnetic properties of some synthetic sub-micron magnetites, *Geophys. J.*, 94, 83–96, doi:10.1111/j.1365-246X.1988.tb03429.x.
- Maher, B. A., R. Thompson, and M. W. Hounslow (1999), *Introduction to Quaternary Climates, Environments and Magnetism*, Cambridge Univ. Press, Cambridge, U. K., doi:10.1017/CBO9780511535635.
- Manohar, M. (1955), Mechanics of bottom sediment movement due to wave action, *Tech. Memo.*, 75, Beach Erosion Board, U.S. Army Corps of Eng., Washington, D. C.
- Michels, K. H., and T. R. Healy (1999), Evaluation of an inner shelf site off Tauranga Harbour, New Zealand, for disposal of muddy-sandy dredged sediments, *J. Coastal Res.*, 15, 830–838.
- Müller, H., T. von Dobeneck, W. Nehmiz, and K. Hamer (2011), Near-surface electromagnetic, rock magnetic, and geochemical fingerprinting of submarine freshwater seepage at Eckernförde Bay (SW Baltic Sea), *Geo Mar. Lett.*, 31, 123–140, doi:10.1007/s00367-010-0220-0.
- Müller, H., T. von Dobeneck, C. Hilgenfeldt, B. SanFillipo, D. Rey, and B. Rubio (2012), Mapping the magnetic susceptibility and electric conductivity of marine surficial sediments by benthic EM profiling, *Geophysics*, 77, E43–E56, doi:10.1190/geo2010-0129.1.
- Muxworthy, A. R., and W. Williams (2006), Low-temperature viscous magnetization of multidomain magnetite: Evidence for disaccommodation contribution, *J. Magn. Magn. Mater.*, 307, 113–119, doi:10.1016/j.jmmm.2006.03.052.
- Oldfield, F., and L. Yu (1994), The influence of particle size variations on the magnetic properties of sediments from the north-eastern Irish Sea, *Sedimentology*, 41, 1093–1108, doi:10.1111/j.1365-3091.1994.tb01443.x.
- Oldfield, F., B. A. Maher, J. Donoghue, and J. Pierce (1985), Particle-size related, mineral magnetic source sediment linkages in the Rhode River catchment, Maryland, USA, *J. Geol. Soc.*, 142, 1035–1046, doi:10.1144/gsjgs.142.6.1035.
- Peterson, C. D., P. D. Komar, and K. F. Scheidegger (1986), Distribution, geometry, and origin of heavy mineral placer deposits on Oregon beaches, *J. Sediment. Res.*, 56, 67–77, doi:10.1306/212f8887-2b24-11d7-8648000102c1865d.
- Pickrill, R. A., and J. S. Mitchell (1979), Ocean wave characteristics around New Zealand, *N. Z. J. Geol. Geophys.*, 13, 501–520, doi:10.1080/00288330.1979.9515827.
- Rao, C. B. (1957), Beach erosion and concentration of heavy mineral sands, *J. Sediment. Res.*, 27, 143–147, doi:10.1306/74D70682-2B21-11D7-8648000102C1865D.
- Razjigaeva, N. G., and V. V. Naumova (1992), Trace element composition of detrital magnetite from coastal sediments of northwestern Japan Sea for provenance study, *J. Sediment. Res.*, 62, 802–809, doi:10.1306/d42679e2-2b26-11d7-8648000102c1865d.
- Roy, P. S. (1999), Heavy mineral beach placers in southeastern Australia: Their nature and genesis, *Econ. Geol.*, 94, 567–588, doi:10.2113/gsecongeo.94.4.567.
- Rubey, W. W. (1933), The size distribution of heavy minerals within a water laid sandstone, *J. Sediment. Petrol.*, 3, 3–29, doi:10.1306/D4268E37-2B26-11D7-8648000102C1865D.
- Shepherd, M. J., and P. A. Hesp (2003), Sandy barriers and coastal dunes, in *The New Zealand Coast: Te Tai Aotearoa*,

- edited by J. R. Goff, S. L. Nichol, and H. L. Rouse, pp. 163–189, Dunmore, Palmerston North, New Zealand.
- Shepherd, M. J., B. G. McFadgen, and D. G. Sutton (2000), Geomorphological evidence for a Pleistocene barrier at Matakana Island, Bay of Plenty, New Zealand, *N. Z. J. Geol. Geophys.*, *43*, 579–586, doi:10.1080/00288306.2000.9514910.
- Slingerland, R. L. (1977), The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands, *J. Sediment. Res.*, *47*, 753–770, doi:10.1306/212f7243-2b24-11d7-8648000102c1865d.
- Spiers, K., T. R. Healy, and C. Winter (2009), Ebb-jet dynamics and transient eddy formation at Tauranga Harbour: Implications for entrance channel shoaling, *J. Coastal Res.*, *25*, 234–247, doi:10.2112/07-0947.1.
- Thompson, R., and F. Oldfield (1986), *Environmental Magnetism*, 227 pp., Allen and Unwin, London, doi:10.1007/978-94-011-8036-8.
- Thornton, E. B., and R. T. Guza (1983), Transformation of wave height distribution, *J. Geophys. Res.*, *88*, 5925–5938, doi:10.1029/JC088iC10p05925.
- Wheeler, A. J., F. Oldfield, and J. D. Orford (1999), Depositional and post-depositional controls on magnetic signals from salt marshes on the north-west coast of Ireland, *Sedimentology*, *46*, 545–558, doi:10.1046/j.1365-3091.1999.00236.x.
- Yu, L., and F. Oldfield (1993), Quantitative sediment source ascription using magnetic measurements in a reservoir-catchment system near Nijar, S.E. Spain, *Earth Surf. Processes Landforms*, *18*, 441–454, doi:10.1002/esp.3290180506.
- Zhang, S., M. T. Cioppa, and S. Zhang (2010), Spatial variation in particle size and magnetite concentration on Cedar Beach: Implications for grain sorting processes, western Lake Erie, Canada, *Dizhi Xuebao*, *84*, 1520–1532, doi:10.1111/j.1755-6724.2010.00345.x.
- Zhang, W., L. Yu, and S. M. Hutchinson (2001), Diagenesis of magnetic minerals in the intertidal sediments of the Yangtze Estuary, China, and its environmental significance, *Sci. Total Environ.*, *266*, 169–175, doi:10.1016/S0048-9697(00)00735-X.
- Zimmerman, J. T. F. (1981), Dynamics, diffusion and geomorphological significance of tidal residual eddies, *Nature*, *290*, 549–555, doi:10.1038/290549a0.

Selective transport and fractionation of magnetic particles in a transient coastal environment (Tauranga Harbour and Bay of Plenty, New Zealand)

Firoz Badesab^{1,2}, Gerhard Bartzke^{1,2}, Tilo von Dobeneck¹ and Katrin Huhn¹

¹MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Germany

²Department of Earth and Ocean Sciences, University of Waikato, Hamilton, New Zealand.

Manuscript for Sedimentology

Abstract

Heavy (magnetic & non-magnetic) minerals are found concentrated by natural processes in many fluvial, estuarine, coastal and shelf environments with a potential to form economic placer deposits. Understanding the processes of heavy mineral transport and enrichment is prerequisite to interpret sediment magnetic properties in terms of hydro- and sediment dynamics. In this study, we combine rock magnetic and sedimentological laboratory measurements with numerical 3D discrete element models to investigate differential grain entrainment and transport rates of magnetic minerals in a range of coastal environments (riverbed, mouth, estuary, beach and near-shore). We analyzed grain-size distributions of representative bulk samples and their magnetic mineral fractions to relate grain-size modes to respective transport modes (traction, saltation, suspension). Rock magnetic measurements showed that distribution shapes, population sizes and grain-size offsets of bulk and magnetic mineral fractions hold information on the transport conditions and enrichment process in each depositional environment. A downstream decrease in magnetite grain size and an increase in magnetite concentration was observed from riverine source to marine sink environments. Lower flow velocities permit differential settling of light and heavy mineral grains creating heavy mineral enriched zones in estuary settings, while lighter minerals are washed out further into the sea. Numerical model results showed that higher heavy mineral concentrations in the bed increased the erosion rate and enhancing heavy mineral enrichment. In beach environments where sediments contained light and heavy mineral grains of equivalent grain sizes, the bed was found to be more stable with negligible amount of erosion compared to other bed compositions. Heavy mineral transport rates calculated for four different bed compositions showed that increasing heavy mineral content in the bed decreased the transport rate. There is always a lag in transport between light and heavy minerals which increases with higher heavy mineral concentration in all tested bed compositions. The results of laboratory experiments were validated by numerical models and showed good agreement. We demonstrate that the presented

approach bears the potential to investigate heavy mineral enrichment processes in a wide range of sedimentary settings.

Key words: environmental magnetism, magnetic minerals, grain size distributions, numerical modelling (DEM, FDM) enrichment, transport.

1. Introduction

Enrichment of heavy minerals in coastal environment has been well studied by numerous workers (Komar & Wang, 1984; Frihy and Komar, 1991; Li & Komar, 1992; Hughes *et al.*, 2000; Bryan *et al.*, 2007; Badesab *et al.*, 2012). Magnetic and non magnetic heavy mineral grains in sands mainly fall within the finer fraction of the total sediment population. Compared to lighter minerals such as quartz and feldspar, they possess different hydrodynamic properties due to their contrasting densities, sizes and shapes. It is well known that heavy minerals are more difficult to transport or entrain by currents in the flowing water than lighter minerals (Slingerland, 1977; Komar & Wang, 1984; Li & Komar, 1992). Due to their higher settling velocity and smaller grain sizes they tend to settle quickly and accumulate in the sediment bed forming a lag deposits enriched in heavy minerals. Lighter minerals are selectively removed from the bed and transported further downstream depending on flow regime. The transport of heavy mineral grains in the sediment bed occurs mostly as bedload (movement on the bed) or by saltation (sliding and bouncing) rather than in suspension. Selective transport, settling, entrainment and burial play an important role in concentrating heavy minerals in coastal environments (Slingerland, 1977; Komar & Wang, 1984; Frihy & Dewidar, 2003). These processes are schematically illustrated in Figure 1. During entrainment, the sediment grains moving out of the bed and entering the flow are carried along and deposited where the flow energy decreases.

A recent study by Gallaway *et al.*, 2012 highlighted the importance of burial mechanisms in the formation of heavy mineral enrichments in the swash zone. They found that magnetic minerals get rapidly buried and sheltered within the interstices of larger and lighter mineral grains under the influence of gravitation and therefore require much higher energies for their entrainment. Differential entrainment and transport also produces variability in the enrichment patterns and grain-size distributions of heavy minerals. Studies by Badesab *et al.*, 2012 showed that differential rates in entrainment and transport of heavy and lighter mineral grains in combination with localized surf zone processes and littoral drift lead to the formation of coast parallel magnetite enrichment belts off a mesotidal estuarine lagoon. The grain size distribution characteristics of these coastal sediment bodies reflect their small scale transport processes. As we will see, more complex coastal morphologies,

varying rates of sediment input and localized hydrodynamics also produce more complex grain size distribution patterns.

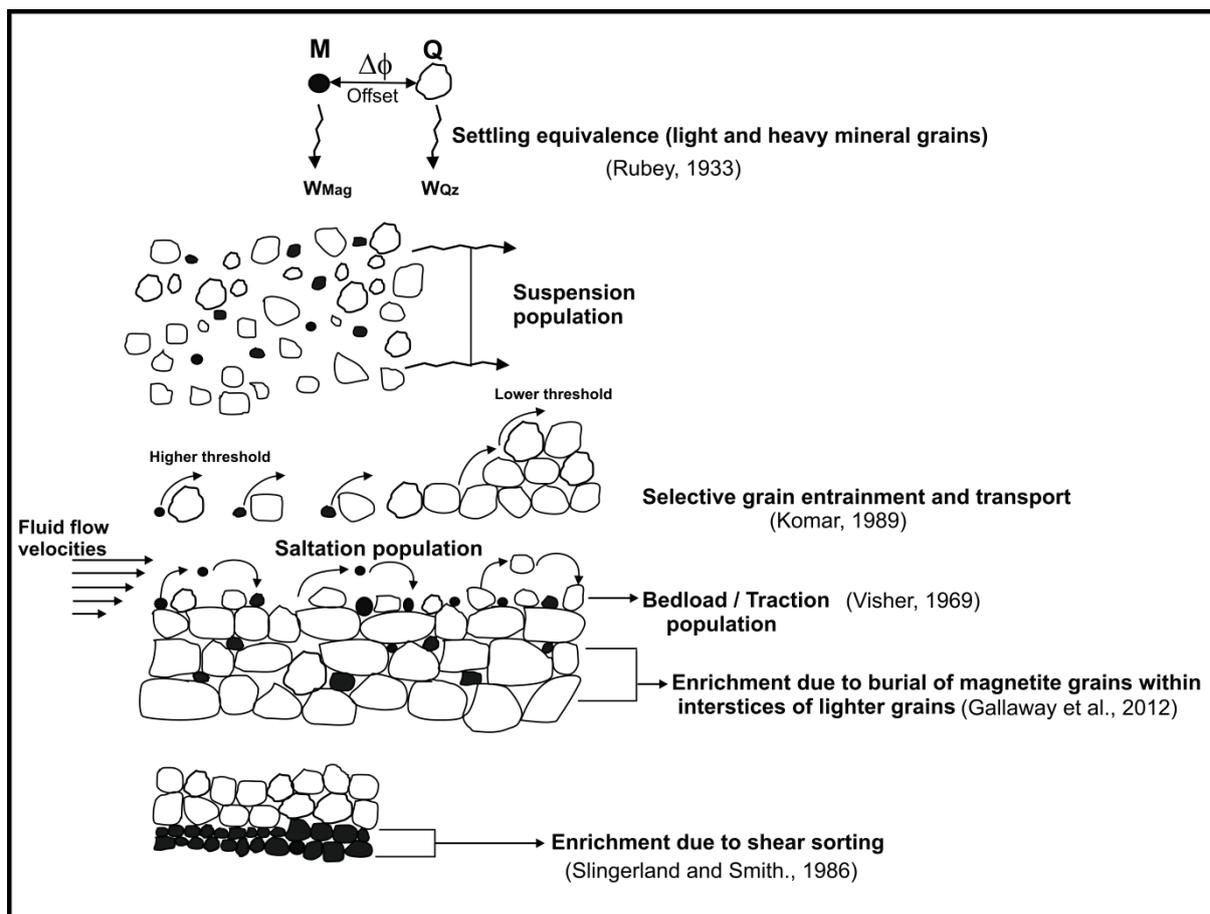


Figure 1: Conceptual model illustrating the entrainment, enrichment and transport processes of light and heavy minerals grains.

Many researchers made an attempt to characterize depositional processes and environments based on grain-size distribution of sediments (*Inman, 1949; Sindowski, 1958; Moss, 1962; Pettijohn et al., 1972; McLaren, 1981; Bowles, 1985; Gao & Collins, 1992*). The statistical parameters mean, dispersion, skewness and kurtosis were mostly used to investigate the effects of sediment transport on grain size distributions, but also to characterize the depositional environments (*Mason and Folk, 1958; McLaren, 1981*). *Visher (1969)* described a method to determine the modes of sediment transport by analyzing the log-normal probability curves of cumulative grain size distributions. The sieved grain size distribution data was plotted against normal probability percentage scale. His method was based on the hypothesis that each grain-size mode could be linked to particular type of sediment transport. Straight lines connecting several points of a given grain size distribution were used to subdivide the grain-size

spectrum according to the various transport modes traction (bedload), saltation (mix load) and suspension (washload) (*McQuivey & Keefer, 1969*).

Settling velocities of different mineral grains play a key role in enrichment processes. The differences in the densities and the turbulence of the flow determines the settling behaviour of mineral grains. Grains with lower settling velocities experience more time in the flow and are carried further by turbulent eddies compared to grain with higher settling velocities. Many researchers investigated the sorting of heavy and light mineral grains during transport and deposition in function of their different settling velocities. According to concept of hydraulic equivalence developed by Rubey (1933), smaller and denser grains such as magnetite will have the same settling velocity compared to larger and light quartz grains in any given conditions. *Baba & Komar (1981)* determined the settling velocities of heavy minerals and quartz sand grains with spherical shapes. They showed that differences in the settling rates of heavy minerals mostly occur due to the grain sphericity and asymmetries. The application of this concept in our present study has been described in detail in the methods chapter.

Magnetic minerals are abundant in coastal environments and are found concentrated in association with other heavy minerals as lag deposits in fluvial, estuarine, beach and nearshore regions. They have been widely used as a markers to provide information on sediment source, transport, deposition, identifying the areas of erosion and accretion, to assess heavy metal pollution and to examine hydrodynamic conditions in coastal regions (*Razjigaeva and Naumova, 1992; Bloemendal et al., 1992; Oldfield and Yu, 1994; Robinson et al., 1995; Wheeler et al., 1999; Jenkins et al., 2002; Liu et al., 2003; Booth et al., 2005; Zhang 2007; Maher et al., 2008; Cioppa et al., 2010*). Magnetic measurements are fast, cost-effective and help to characterize the sediment in terms of their concentration, mineralogy and grain size (*Oldfield, 1994; Oldfield and Yu, 1994; Walden et al., 1997; Lees, 1999; Booth et al., 2005*). Magnetic mineral grain-size distributions can be easily quantified by sieving the total sediment and measuring the magnetic susceptibility of each sieve fraction, which is not much influenced by particle size. Thus it is possible to compare bulk sediment grain-size distribution against grain-size magnetite distribution - a strategy, which has promise to demonstrate differences in the transport modes of light and heavy mineral grains.

So far environmental magnetic studies on coastal sediments were mainly focussed on mapping the spatial distribution of magnetic minerals, examining the sediment sorting mechanism, estimating the cross-shore and longshore transport and detecting burial mechanism of magnetic minerals in coastal sediments (*Cioppa et al., 2010; Hatfield et al., 2010; Zhang et al., 2010; Gallaway et al., 2012*). The

role of density and grain size on the transport dynamics and fractionation of magnetic minerals in coastal environments has not yet received enough attention. The motivation for the present study was based on the findings of *Badesab et al. (2012)* who utilised the environmental magnetic approach to investigate the mechanism of magnetite enrichment in estuarine, nearshore and inner shelf region of Tauranga Harbour.

Prior studies traditionally used analogue, laboratory based techniques (i.e. flume tanks) as well as field investigations, to determine the physical processes causing selective grain entrainment and, hence, placer enrichment (*Komar et al., 2007*). Therefore, researchers focused on the relation of fluid forces causing particle motion by testing a variety of sediment samples differing in sediment composition, grain size, and density. Their findings were presented as conceptual models based on experimental results and theoretical assumptions. A recent overview of these experiments can be found in *Komar et al., (2007)*. However, these analogue techniques are limited in their ability, e.g., due to low resolution within the sensor range, the measurement of sediment erosion directly on a grain scaled level. Consequently it is extremely difficult to identify and quantify the physical processes causing selective grain entrainment from flume experiments. In particular the quantification of the processes occurring at the sediment water interface (*Komar et al., 2007*), and in the deeper parts of the bed (*Bartzke et al., in rev 2012*) is limited.

Numerical simulations are therefore required to clarify, and in particular, to quantify heavy mineral entrainment and enrichment processes. A high resolution 3D numerical modelling approach was used by coupling two simulation techniques – the Finite Difference Method (FDM) with the Discrete Element Method (DEM). This 3D model parameterizes general settings of analogue laboratory flume tanks to investigate the physical properties controlling heavy mineral accumulation (*Bartzke et al., in rev. 2012*). This technique allows the detection of heavy mineral accumulations and can concurrently reduce expensive and time consuming exploration activities for mining heavy mineral placers in the marine environment.

The aims of the present study are to

1. analyze and compare the grain size and magnetite distribution curves of sediments to investigate the transport modes, entrainment and deposition of lighter and heavier (magnetic) mineral grains in fluvial, riverine, estuarine, beach and nearshore sands within a single field setting of Tauranga Harbour, and

2. utilize a 3D high resolution numerical flume tank model in order to quantify the influence of flow velocities on numerical “sediment” bed in terms of density, grain sizes (offset), and light and magnetic mineral concentration on selective entrainment.

2. Study area

The study area chosen is a mesotidal estuarine lagoon located on the Bay of Plenty coast on the North Island of New Zealand (Fig 2).

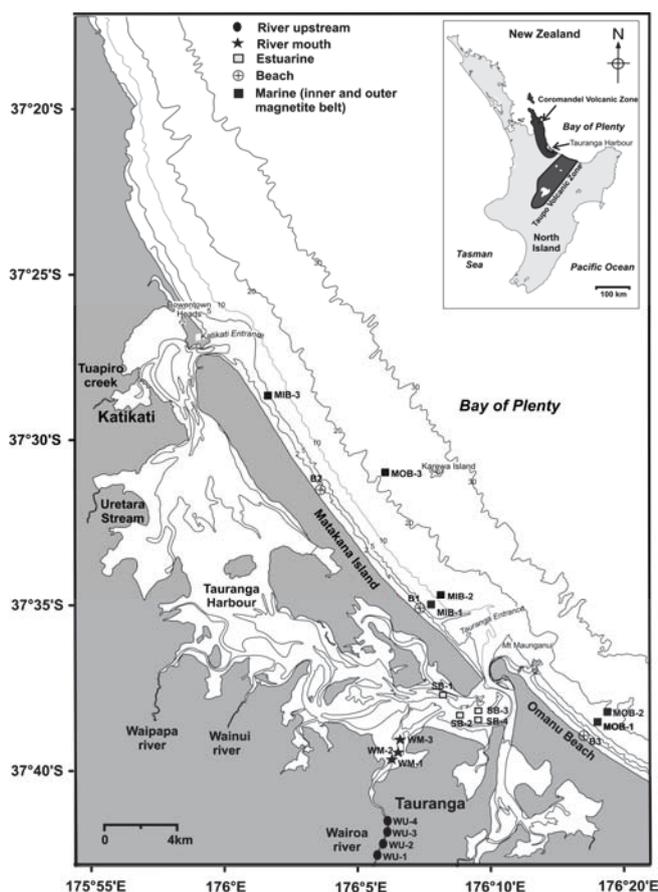


Figure 2: Location of study area and sediment sampling sites covering Wairoa river upstream, mouth, estuarine (southern basin of Tauranga Harbour), Beach (Matakana) and marine (off Tauranga Harbour) region in Bay of Plenty, New Zealand.

Tauranga Harbour has an area of 851 km² and is bounded by two Holocene barrier tombolos (Bowentown at the northwestern and Mt Maunganui at the southeastern end) and a 24 km long barrier island (Matakana Island). Tidal currents dominate both the northern and southern inlet of Tauranga Harbour. At the southern inlet there is a mean tidal range of 1.4 m and mean annual significant wave height of 0.5 m (*De Lange, 1991, Kruger & Healy, 2006*). The Taupo Volcanic zone (TVZ) and Coromandel Volcanic zone (CVZ) provide the main sediment supply to the Bay of Plenty coast. The majority of sediments reaching the southern basin of Tauranga Harbour are delivered by the Wairoa River, which is the main source of freshwater to the basin with a mean flow of 17.6 m³ s⁻¹. Its sedimentation load is around 28,000 tonnes annually which constitutes around 42 % of the total

riverine load entering the lagoon (Park, 2004). Most of the sediments within the harbour are transported through two tidal channels (Western and Cutter) before they move out of the lagoon and are deposited along Matakana Beach. The regional geology and wave climate has been described in detail by Badesab *et al.* (2012).

3. Materials and methods

3.1 Sample collection and laboratory measurements

About 25 sediment samples representing fluvial (Wairoa River), estuarine (Tauranga Harbour), beach (Matakana Island) and nearshore environments (inner and outer magnetite enrichment belts) were sieved into 17 fractions including <10, 10, 20, 32, 40, 63, 90, 125, 180, 250, 355, 500, 710, 1000, 1400, 2000 and 2800 μm . The fluvial, riverine and beach samples were collected using a clean plastic shovel to retrieve the top few centimetres of sediment by hand while the estuarine and nearshore samples were retrieved with a Van Veen grab sampler during sediment sampling surveys in February 2010 onboard coastal research vessel *Tai Rangahau*, University of Waikato, Hamilton, New Zealand (Fig 1). Each of these fractions were weighed to determine the total grain size distribution. Magnetic susceptibility measurements were carried on these sieve fractions using a KLY-2 Kappabridge to estimate their ferrimagnetic mineral concentration. The magnetite-equivalent distribution curve was generated by multiplying the bulk weight percentages with these magnetic susceptibility data. The grain size statistical parameters (mean, dispersion and skewness) were calculated using the moments method of *Krumbein and Pettijohn* (1938).

3.2 Background

Calculation of offset in mean grain sizes of light (quartz) and heavy (magnetite) minerals

The transport and deposition of individual mineral grains depends on their respective settling velocities and the intensity of the fluid flow. The differences in densities and grain sizes of mineral grains creates differential rates of movement and settling of sediments. According to the settling equivalence concept of Rubey (1933), the mean grain size of the magnetite is smaller compared to mean grain size of quartz grains and both grains have similar settling velocities in any given hydraulic condition. Baba & Komar. (1981) measured the settling velocities a suite of quartz and heavy mineral grains. From these curves, it is possible to determine the settling equivalences of lighter (quartz) and heavier (magnetite) minerals by drawing a horizontal line of constant velocity passing through their respective curves. The

points of intersection on each curve on phi scale would represent their individual mean grain sizes. Our work is based on the hypothesis that the difference in their mean grain sizes (offset) reflects the individual grain settling behaviour, hydrodynamic and depositional environment.

According to Stokes law, the settling velocity (W_s) of a grain is given by:

$$W_s = \frac{2(\rho_g - \rho_f)g}{9\mu} r^2, \quad (1)$$

Where ρ_g and ρ_f are grain and fluid densities, g is the acceleration due to gravity, r is the radius of the grains and μ is the dynamic viscosity. We now assume a magnetite and a quartz grain

$$W_{mag} = \frac{2(\rho_{mag} - \rho_{H_2O})g}{9\mu} r_{mag}^2 \quad (2)$$

$$W_{Qz} = \frac{2(\rho_{Qz} - \rho_{H_2O})g}{9\mu} r_{Qz}^2 \quad (3)$$

where $\rho_{mag} = 5.2 \text{ g/cm}^3$, $\rho_{Qz} = 2.65 \text{ g/cm}^3$ and $\rho_{H_2O} = 1 \text{ g/cm}^3$

If the grains are in settling equivalence (*Rubey, 1933*), i.e. $W_{mag} = W_{Qz}$, then equation is solved as follows:

$$\frac{2(\rho_{Mag} - \rho_{H_2O})g}{9\mu} r_{Mag}^2 = \frac{2(\rho_{Qz} - \rho_{H_2O})g}{9\mu} r_{Qz}^2 \quad (4)$$

$$\frac{r_{Mag}^2}{r_{Qz}^2} = \frac{(\rho_{Qz} - \rho_{H_2O})}{(\rho_{Mag} - \rho_{H_2O})} \quad (5)$$

$$\log_2 \frac{r_{Mag}}{r_{Qz}} = \log_2 \left[\frac{(\rho_{Mag} - \rho_{H_2O})}{(\rho_{Qz} - \rho_{H_2O})} \right]^{1/2} \quad (6)$$

In the logarithmic scale Φ corresponds to a constant size offset of magnetite and quartz grains given as

$$\Delta\Phi = -\log_2 d_{Mag} + \log_2 d_{Qz} = -\log_2 \frac{d_{Mag}}{d_{Qz}} = \log_2 \sqrt{\frac{(\rho_{Mag} - \rho_{H_2O})}{(\rho_{Qz} - \rho_{H_2O})}} = 1.432 \quad (7)$$

3.3 Numerical methods

For the quantification of the influence of increasing amounts of heavy minerals in sediment beds on sediment erosion behavior and placer enrichment at the sediment water – interface and in the interior of the sediment bed a high resolution 3D numerical ‘flume tank’ was used (Figure 3). In order to simulate sediment transport by a moving fluid, we combined two independent numerical simulation techniques, the Finite Difference Method (FDM) and the Distinct Element Method (DEM). Therein, the FDM model calculates the flow conditions (Fluid model, Figure 3) and the DEM model simulates the ‘sediment’ matrix (Sediment matrix model, Figure 3). Both were coupled via an Input Output routine which will be described in section 3.4.

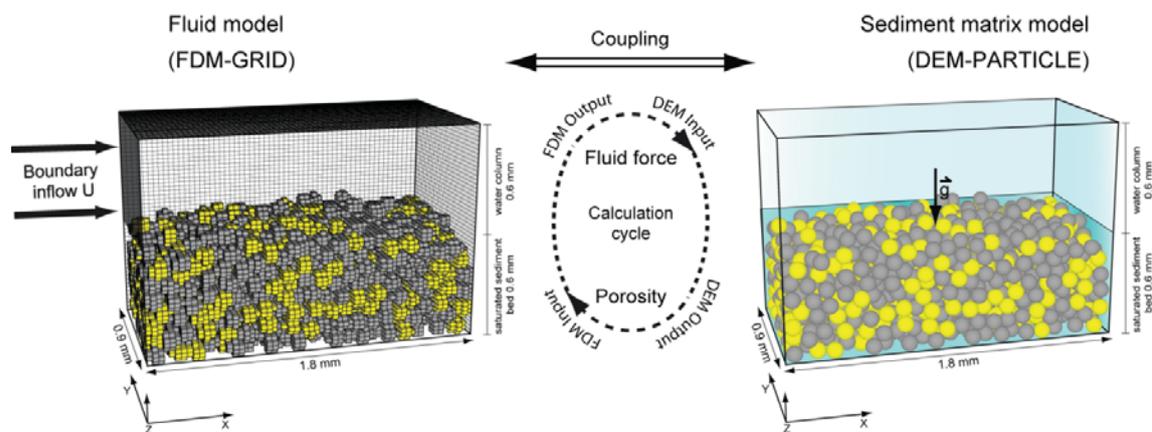


Figure 3: Sketch of the coupled Sediment matrix model (DEM - discrete elements method) and the Fluid model (FDM - finite difference method).

The 3D FDM Fluid model was generated using the commercial software FLAC 3D (Fast Ligurian Analysis of Continua; Itasca, 2004b). This technique is based on the spatial discretization of the study domain into a grid of a finite number of three dimensional rectangular polyhedral elements (Figure 6 (Itasca, 2004b)). The software allows the assignment of physical material properties, i.e. fluid parameters, to each cell in the grid, e.g., fluid density, viscosity etc. in order to mimic natural conditions. In addition, boundary conditions, e.g., inflow velocities and fluid sources, have to be applied to the model. Consequently, this FDM model calculates flow velocities in each grid cell driven by applied boundary conditions. Therefore the differential flow equations are approximated by numerical differentiation in defined time steps (Itasca, 2004b).

At the same time, a DEM model was used to mimic ‘sediment beds’ numerically. These were simulated as a particle assembly consisting of multiple, ideal and spherical particles, i.e., numerical ‘quartz’ and ‘magnetite’ grains (Figure 6). The software, i.e., PFC 3D, (Particle Flow Code; Itasca, 2004a), is based on the DEM theory by Cundall and Strack (1979) which describes the mechanical behavior of particle assemblages based on physical contact laws. In order to mimic natural conditions,

physical properties such as density, friction or hardness were assigned to each particle (Table 3). Similar to FDM, boundary conditions have to be given e.g., gravity, ball acceleration etc. The resultant particle assemblages or the ‘sediment body’, respectively, are deformable by these applied forces. Consequently, DEM allows the simulation of sediment particles, sediment particle interactions, internal structures, and also porosities. Thus, the method simulates the physical behavior of the particle assemblages during deformation processes, e.g., the initiation of motion of single spherical grains driven by defined boundary conditions, e.g. fluid forcing (Figure 3). A more detailed review of the involved algorithms of the FDM and DEM exceeds the scope of this paper. A complete description of the numerical procedure of the FDM code can be found e.g., in Itasca (2004a). Further descriptions of the numerical DEM code can be found in e.g., Cundall and Hart (1989), Cundall and Strack (1979; 1983), Itasca (Itasca, 2004a), and Kock and Huhn (2007). Please note that in the following the term grains as well as sediment will be used, interchangeably whether the context is related to numerical or real grains at the same time. The same applies to quartz and magnetite respectively.

3.4 Model configuration

Numeric sediment beds (Figure 4) consisting of various amounts of heavy and light particles were generated in order to quantify of the physical processes controlling selective grain entrainment with respect to erosion behavior. In the following all sediment beds were exposed to a range of flow velocities. For simulation of fluid motion and particle transport with the 3D numerical flume tank, both the DEM and the FDM models had identical dimensions (1.8 x 0.9 x 1.2 mm), geometries, material properties as well as boundary conditions (Figure 3). At the beginning of the simulation, the grain or sediment model was generated, isolating a micro-scale section of the sediment surface, from a sediment bed. In order to mimic a sediment bed numerically, a sample box was generated with the dimensions of 1.8 mm x 0.9 mm, and 1.2 mm in height, to be filled with the numerical sediment. Therein, 5 stiff un-deformable box walls were created (Table 3). For the generation of the sediment beds (Figure 4), two end members were used as a simplified treatment of, heavier, numerical magnetite grains ($\rho_m = 5.1 \text{ g/cm}^3$) and lighter i.e., numerical quartz grains ($\rho_q = 2.6 \text{ g/cm}^3$). In order to quantify the influence of increasing heavy mineral contents of heavy minerals on sediment erosion, three numeric sediment beds were generated. These were composed of randomly distributed heavy magnetite and light quartz particles in the same grain size ($D_{50} = 0.09 \text{ mm}$) and filled always half of the box (Figure 4). Within each experiment, the amount of quartz with respect to magnetite particles in the bed was changed: Experiment 1) 70 % magnetite and 30 % quartz (i.e., 889 magnetite and 381 quartz particles), Experiment 2) 30 % magnetite and 70 % quartz (i.e. 381 magnetite and 885 quartz

particles), and in Experiment 3) 50 % magnetite and 50 % quartz (i.e. 635 magnetite and 635 quartz particles).

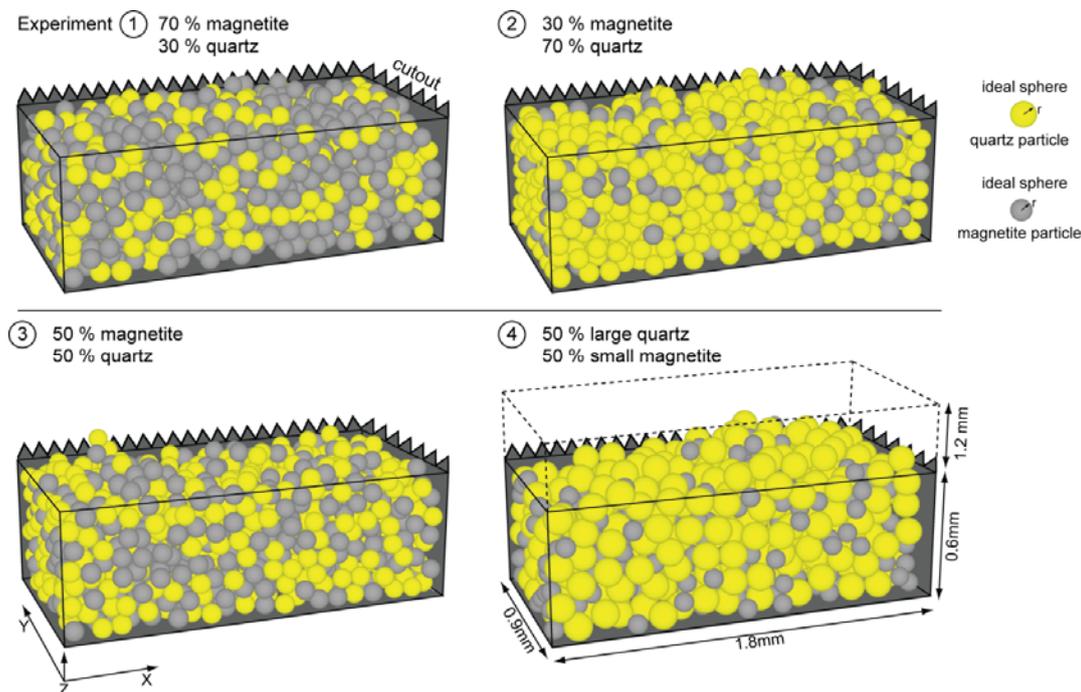


Figure 4: Four types of numerical sediment beds: Magnetite (gray particles) and quartz (yellow particles) were deposited under applied gravity into a sample box. The number of magnetite and quartz particles was changed ranging from: Experiment 1) 889 magnetite and 381 quartz particles, Experiment 2) 381 magnetite and 885 quartz particles, and in Experiment 3) 635 magnetite and 635 quartz particles. In Experiment 4) the grain size of the quartz particles was increased therefore 350 magnetite and 350 quartz particles were deposited.

For the quantification of grain size related effects in heavy and light mineral sediment beds one sediment bed (Experiment 4) was created by using magnetite ($D_{50} = 0.09$ mm) and larger numerical quartz grains ($D_{50} = 0.128$ mm). In this case 50 % magnetite and 50 % quartz (i.e. 350 magnetite and 350 quartz particles) were deposited into the box. Please note that all grains in the experiments were deposited under gravity and randomly distributed in the entire box. This ensures natural depositional conditions and packing. Physical properties, i.e. density, friction, normal stiffness, and shear stiffness were assigned to each particle with respect to natural conditions (Table 3).

For the simulation of a flow field the Fluid model was generated by using the FDM model (Figure 3). The spatial extensions of this Fluid model were chosen with identical dimensions as the Sediment matrix model. In order to simulate flow fields in highest resolution, the FDM grid was discretized into 288.000 elements (60x60x80 in X, Y and Z directions) with a uniform axes length of 0.025 mm

(Figure 6). Hence, smallest DEM grains are represented by at least 8 elements to ensure stable coupling between FDM – DEM model. The corresponding fluid properties were applied to the Fluid model (Table 3) to simulate natural coastal conditions based on the literature (Allen, 1970; Eisbacher, 1996) and to exclude any scalar discrepancies. The entire box model is flooded generating a fully saturated sediment bed.

Coupling of both models was undertaken after generation of these initial model configurations. In the first step, all information about from the sediment matrix, e.g. the spatial parameters x , y , and z coordinates and the radii of all particles, were sent from the DEM to the FDM model. Based on these data representing the grain distribution within the DEM model, the FDM grid elements are defined as either fluid cells or sediment cells. The resulting FDM model grid consists of elements where fluid streaming was allowed (fluid zones) or not allowed (solid matrix zones). After the grid was classified, a constant inflow above the fully saturated bed field was applied in X-direction at left box wall and outflow boundary condition at the right box wall (Figure 3). Starting with these initial stable conditions, a constant stream in positive x -direction above the sediment bed evolved. All flow velocities were calculated from cell to cell throughout the whole model (in the water column and the saturated matrix area) based on the initial porosity distribution. After the flow field reached stable conditions, all flow velocities were extracted. These flow velocities were transformed into forces according to the Stokes velocity law. These fluid forces were sent to the sediment matrix model at their corresponding X-Y and Z coordinates and applied to their corresponding particles. These velocity parameters serve now as boundary conditions for the Sediment matrix model. Based on this forcing, new particle contact forces and resulting particle displacements are calculated in the DEM model. If the added fluid forces are larger than the resisting force of the particles, the particle contacts break up and the grains are transported (Cundall and Strack, 1979). This caused new porosities within the DEM model and new particle configurations respectively. Hence, sediment transport and / or grain re-assembling is initiated. In cases grains are eroded from the matrix they are transported by the stream. The resultant new porosities (Sediment matrix model) were sent back to the Fluid model, and subsequently a re-meshing of the FDM model grid was initiated and a new calculation cycle starts.

This calculation cycle between both models was repeated until constant flow and transport conditions were reached. Whereby each model was coupled 140 times to ensure that the results were statistically stable and analyzable. Hence, high resolution information about, e.g., particle distribution, porosity, texture, and fluid velocities at the sediment surface as well as in the interior of the sediment matrix is

available in space and time. The applied boundary flow velocities were stepwise increased from $U = 10$ cm/s, 20 cm/s, 30 cm/s, and 40 cm/s.

3.5 Measurements and data statistics

To quantify the influence of increasing amounts of heavy minerals in sediment beds on sediment erosion behavior and hence placer enrichment we analyzed variations of particle positions and particle displacements at each time step in horizontal and vertical directions. All data has been processed using programmed routines in FLAC 3D, PFC 3D, and Matlab 2011 environments. These analyses revealed high resolution data of the particle transport distances in the sediment bed.

Transport distances

The total transport distance of singles grains was calculated within each Sediment matrix model as the difference between the initial and the final position after reaching steady state flow conditions. For further analyses only particles were considered which exceeded their own radius, which is considered as threshold for transport. Particle transport changes were extracted from a horizontal volume at the interface between sand and silt ($0 \text{ mm} \leq z \leq 0.3 \text{ mm}$; Base Slice in Figure 8). A similar procedure was processed for the uppermost sediment portion ($0.4 \text{ mm} \leq z \leq \text{top of sediment bed}$; Top Slice in Figure 5). In addition particle transport changes were extracted from a vertical volume ($0 \text{ mm} \leq x \leq 0.4 \text{ mm}$; vertical box in Figure 9). For comparison, the individual transport distances of magnetite and quartz particles were calculated the separately. Hence, the amount of transported quartz and magnetite particles was plotted as a percent in a horizontal bar plot.

4. Results

4.1 Analysis and comparison of bulk sediment grain size and magnetite distribution curves (log probability & cumulative) of representative samples from various depositional environments

The samples collected from various depositional environments including river upstream and mouth (Wairoa River), estuarine (Tauranga Harbour), Beach (Matakana Beach) and Marine inner and outer magnetite enrichment belt (off Tauranga harbour, Bay of Plenty) sediments were analyzed to gain information on the grain settling, transport and enrichment mechanism. Here we describe distribution curves of each sedimentary environment separately. Fig. 5 shows the comparison of log probability curves of bulk sediment and magnetite distributions of representative samples.

Wairoa River upstream

Examples of distribution curves for bulk sediment and magnetite grain size of samples from river upstream are shown in Figure 5 (a-c). The log probability curves for the representative samples indicate that sediments were mainly transported as two major population a) saltation and b) suspension as indicated in Figure 5a-c. The distribution shows well sorted saltation and suspension population developed within narrow range of total distribution.

The traction population has a size range from -2.0 to 0.5 phi with a truncation point at 0.5 phi. The break between traction (bedload) and saltation is mostly found at 0.5 phi, which is mainly in coarse sand. The percentage of saltation and suspension population of magnetite grains are in the range from (59.0 - 62.5 %) and (0.85 – 39 %) respectively (Table. 1). The break between saltation and suspension population is between 2 – 3 phi fine sand range, except sample WA-6 which doesn't possess traction population. The distribution of magnetite in river upstream and mouth samples are similar. The cumulative distribution curves shows that the magnetite is mostly concentrated with the range of very fine - fine – medium sand size with highest values in fine sand size grains Fig 6 (a-c). The offset between the bulk sediment and magnetite distribution ranges between 0.1 – 0.6 phi (Table 2).

Wairoa River mouth

Three distribution curves for bulk sediment and magnetite grain size of river mouth samples are shown in Fig. 5 (d-f). The log probability curves shows that mode of transport was similar to that of upstream samples i.e. two major population saltation and suspension, with saltation population being dominant. The distribution shows moderately sorted saltation and suspension population developed within narrow range of total distribution. The traction population has a grain size ranges from -2.0 to 1.5 phi with a truncation point at 1.5 phi. The break between traction (bedload) and saltation population varies in the range between 0.5 – 1.5 phi, which represents mainly medium - coarse sand. The percentage of saltation and suspension population of magnetite grains are in the range from (68.2 – 99.65 %) and (0.2 – 5.3 %) respectively (Table. 1). The break between saltation and suspension population is between 0.5 – 5.5 phi, i.e coarse silt – coarse sand range.

The cumulative distribution curves shows that the magnetite is mostly concentrated with the range of very fine sand size Fig. 6 (d-f). The offset between the bulk sediment and magnetite distribution is highest compared to rest of the environments and ranges between 1.3 –1.9 phi (Table. 2).

Estuarine (tidal & non tidal channel)

Examples of distribution curves for bulk sediment and magnetite grain size of samples from estuary are shown in Fig. 5 (g-i). The log probability curves for the representative samples indicate that sediments were as transported as all three populations (traction, saltation and suspension). The distribution shows well sorted saltation and suspension population developed within broad range of total distribution, compared to traction population.

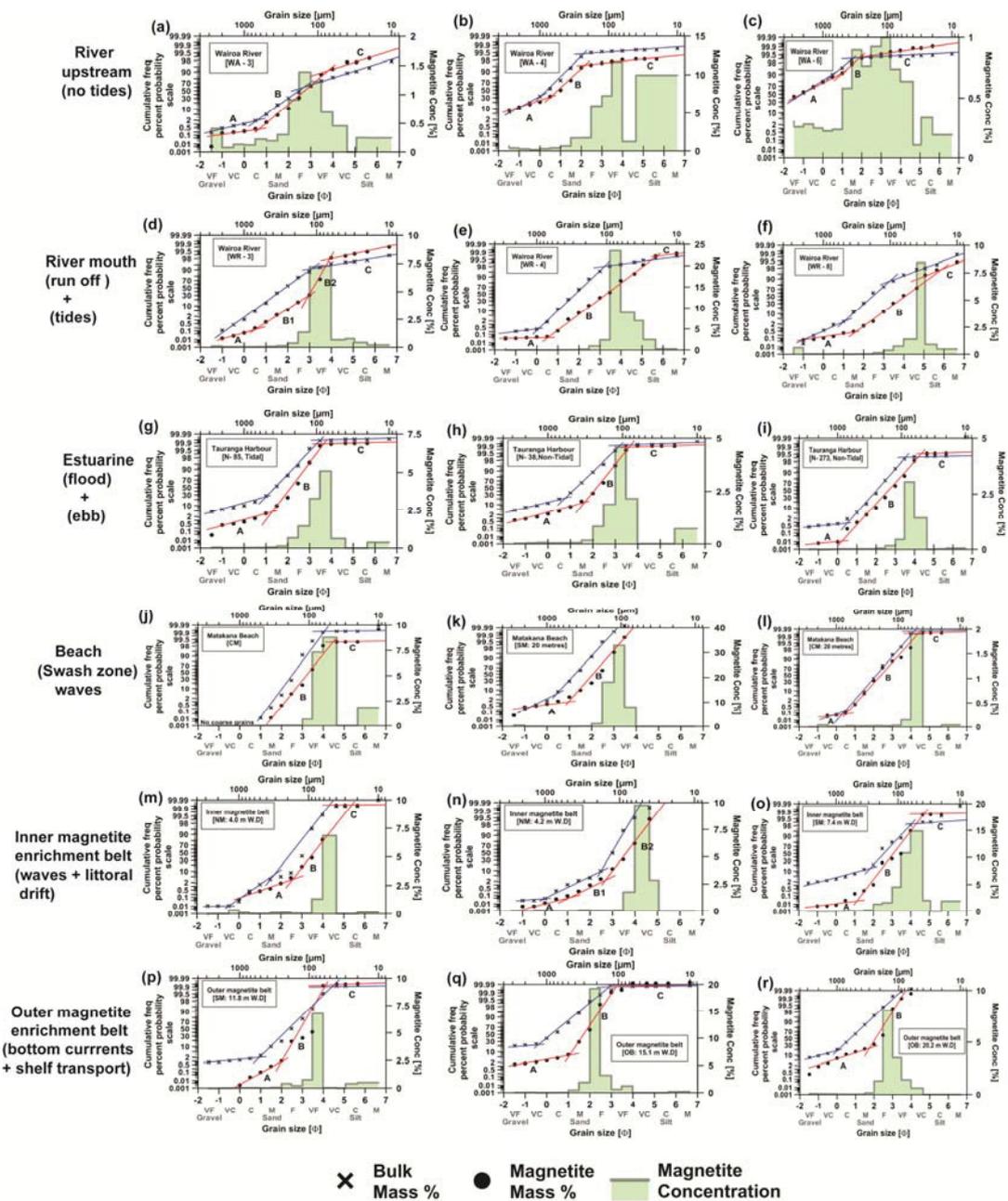


Figure 5: Examples of log probability curves for bulk sediment and magnetite fraction of representative samples from various depositional environments. I) Wairoa River upstream, II) Wairoa

River mouth, III) Estuarine (Tauranga Harbour), IV) Beach (Matakana Beach), V) Marine: Inner magnetite enrichment belt and VI) Outer magnetite enrichment belt off Tauranga Harbour.

The traction population has a size ranges from -1.5 to 1.5 phi with a truncation point at 1.5 phi, except one sample which has much smaller truncation (0.0 phi) compared to other samples. The break between traction (bedload) and saltation population are in the range of 0.5 – 4 phi.

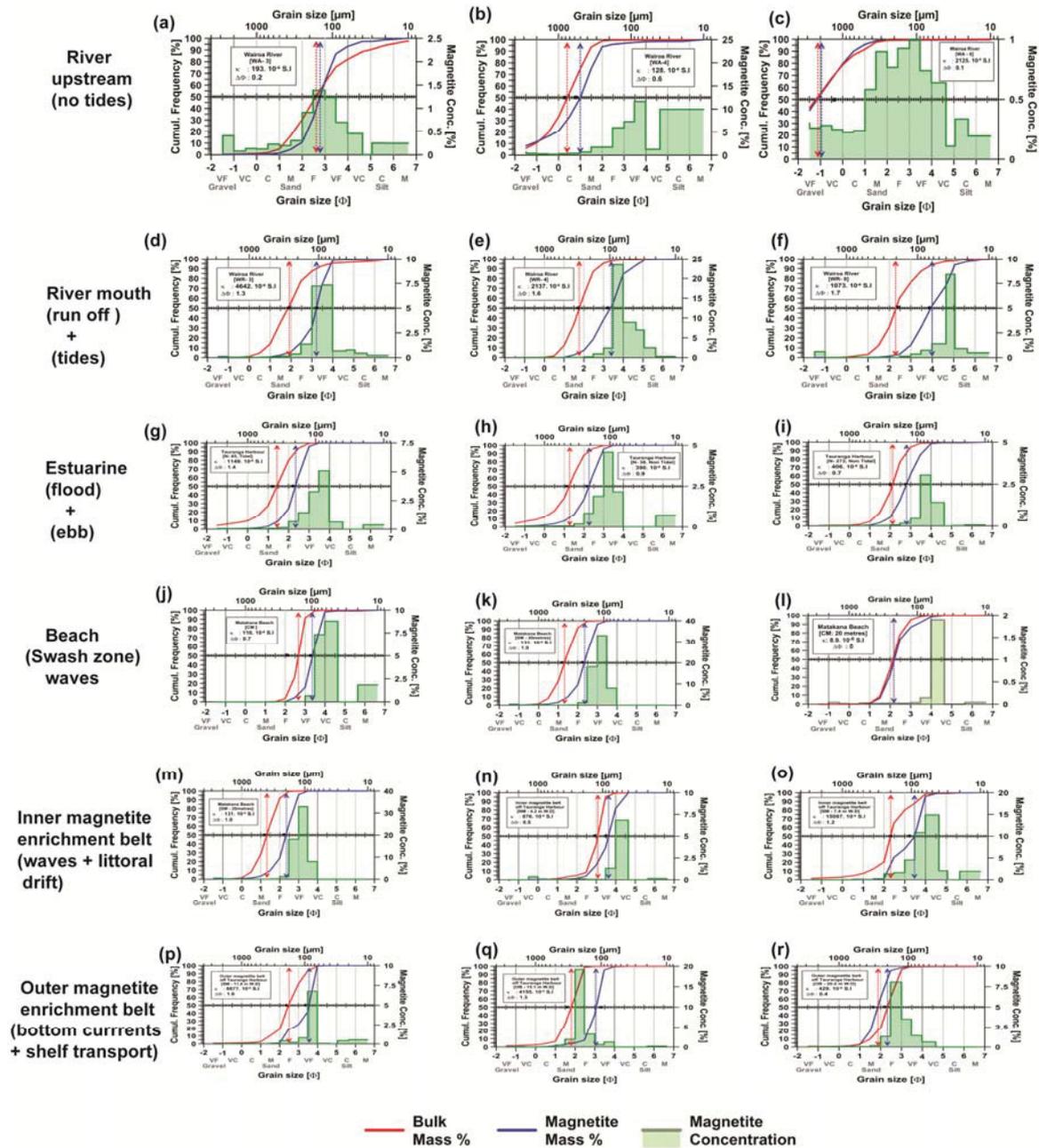


Figure 6: Cumulative curves for bulk and magnetite distribution of samples from range of depositional environment. The black dots in the plot represent the mean grain size of bulk & magnetite fraction calculated using mathematical method proposed by *Krumbein and Pettijohn, 1938*.

The percentage of traction, saltation and suspension population of magnetite grains are in the range from (0.005 – 11.4 %), (87.7 – 98.1%) and (0.25 – 1.6%), respectively (Table. 1). The break between saltation and suspension population is between 1.5 – 4 phi. The cumulative distribution curves shows that the magnetite is equally distributed within the range of very coarse silt – very fine sand. Fig. 6 (g-i). The offset between the bulk sediment and magnetite distribution ranges between 0.4 – 1.4 phi (Table. 2).

Matakana Beach

Fig. 5 (j-l) illustrates the distribution curves for the bulk sediment samples from Matakana Beach. The log probability curves indicate that sediments were mainly transported as two major population saltation and suspension with hardly any traction population. The distribution shows well sorted saltation and suspension population. The traction population was lacking from the total distribution. The percentage of saltation and suspension population of magnetite grains are in the range from (98.2 – 99.86 %) and (0.01 – 0.9 %) respectively, with suspension population being dominant (Table. 1). The break between saltation and suspension population is between 1.5 – 4.5 phi i.e very coarse silt – medium sand range. The cumulative distribution curves shows that the magnetite is mostly concentrated within the range of very coarse silt fraction Fig. 4 (j-l). The offset between the bulk sediment and magnetite distribution ranges between 0.7 – 1.0 phi (Table. 2). Interestingly we observed a zero offset in one of the beach sample (Fig. 6i).

Marine (Inner and outer magnetite enrichment belt)

Examples of distribution curves for bulk sediment and magnetite grain size of samples from inner and outer magnetite enrichment belts are shown in Figure 5 (m-r). The log probability curves for the inner belt samples indicate that sediments were transported mainly as saltation population with minor load transported as traction and suspension population. The saltation population has a size ranges from 0 to 3.5 phi with a truncation point at 1.5 phi. The break between traction and saltation population are in the range of 1 to 4 phi. The percentage of traction, saltation and suspension population of magnetite grains are in the range of (0.025 – 1.95 %), (2.9 – 97.9%) and (0.01 – 4.7%), respectively (Table. 1). The cumulative distribution curves shows that the magnetite is distributed with the range of very coarse silt – very fine sand Figure 6 (m-o). The offset between the bulk sediment and magnetite distribution ranges between 0.5 – 1.2 phi (Table. 2).

The curves for the outer belt samples showed that sediments are mostly transported as traction and saltation population with very minor amount of load as suspension population (Fig. 3 p-r). The

percentage of traction, saltation and suspension population are in the range of (0.99 – 19.8 %), (79.9 – 98.9%) and (0.05 – 0.09 %) respectively (Table. 1). The cumulative distribution curves shows that the magnetite is contained in the range of very fine to fine sand. There appears to be a shift in the magnetite distribution in all three samples varying between very fine – fine sand Figure 6. (m-o). The offset varies between 0.4 – 1.3 phi.

Distribution of statistical parameters

Statistical parameters calculated from grain size distribution provides information on the energies of the depositional environments. The statistical parameters (mean, dispersion, skewness) of river upstream, mouth, estuary, beach and marine samples have been analyzed scatter plot (Fig. 7).

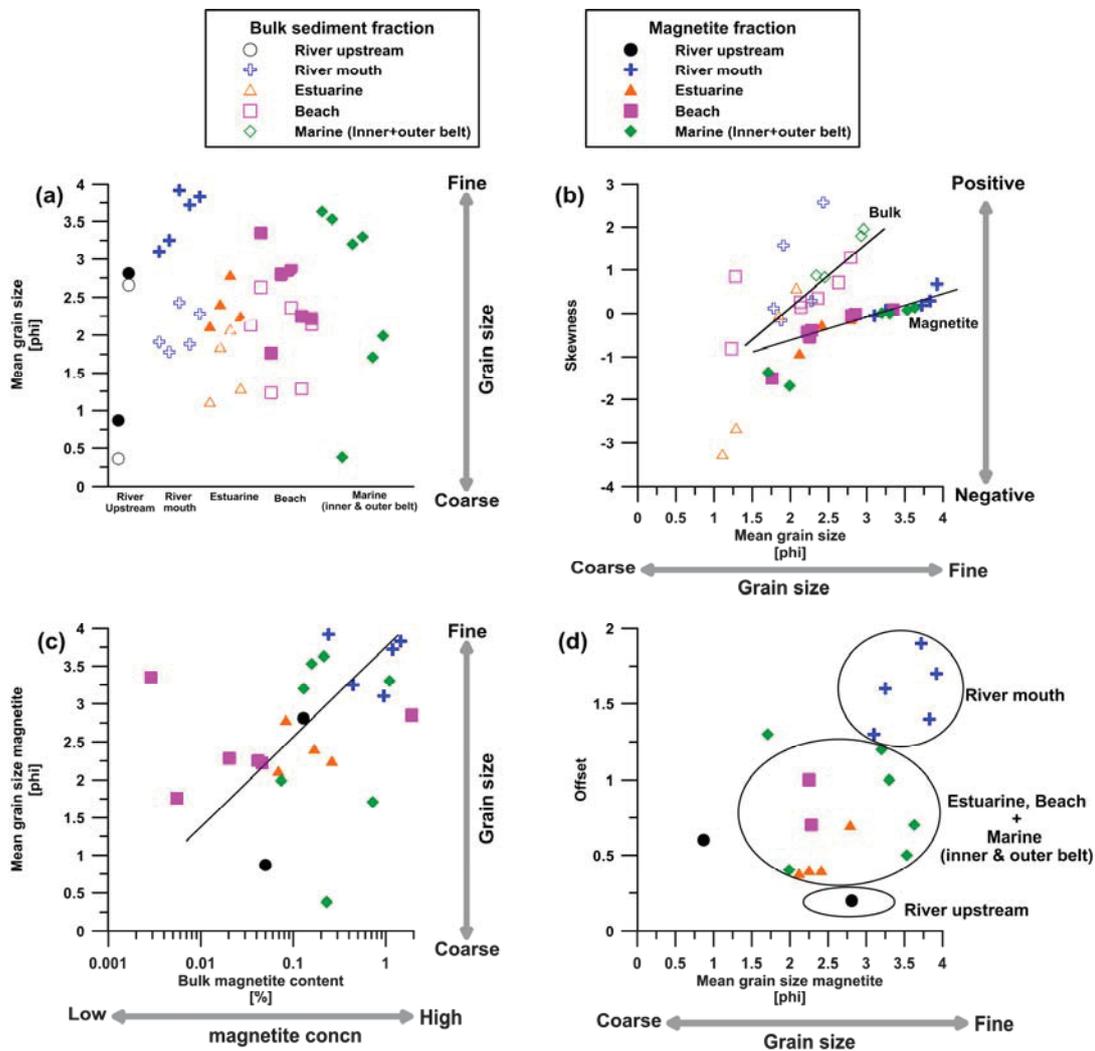


Figure 7: Bivariate scatter plot of statistical parameters (mean, skewness, offset) and magnetic parameters (bulk magnetite content) for sample from various environments.

Numerical values are given in Table. 3. These tables provide details on the statistical parameters used in the study. Overall the mean grain size of magnetite ranges between 1.0 – 4.0 phi scale i.e (Very coarse silt – medium sand). Fig. 7a shows the plot of mean grain size for different depositional environments. We observed a trend in decrease in grain size or increase in phi size of magnetite grains in the samples originating from Wairoa river mouth to marine sands. Marine sands seem to possess finer size magnetite grains and have highest bulk magnetite content; upstream riverbed sediments are coarsest and show lower magnetite concentrations. Fig. 7b shows the bivariate scatter plot of skewness versus mean grain size. This parameter mainly shows the asymmetry of the probability distribution in bulk sediment and magnetite grain size distribution. The bulk sediment grain size distribution appears to be more positively skewed with marine sample had highest skewness compared to magnetite grain size distributions.

Previous studies have shown that various depositional environments could be characterized based on distribution of their statistical parameters. For example magnetite rich sands from Wairoa River mouth showed finer grain sizes (3.2 – 4.0, phi scale, i.e very coarse silt – very fine sand) and larger offset in grain sizes between as compared to the upstream samples (1.0 – 2.8 , Fine - Medium sand) which had lower offsets although similar grain size. We observe that the river mouth samples are much finer and possesses higher offset samples compared to river upstream samples. Magnetite grains from estuarine, and marine sand (inner and outer) had mixed grain sizes ranging between 2.2- 3.7 phi scale i.e very fine – fine sand (Figure 7d). Estuarine, beach and marine sands falls into one group. It seems to be possible to characterize the environments based on their offset and mean grain sizes into three groups a) river mouth samples which possesses higher offset (1.25 – 2) and fines grain sizes, b) estuarine, beach and marine samples: intermediate having average offset (0.2 - 1.1) and c) Wairoa river upstream samples having lowest offset i.e 0.1 phi (Figure 7d).

4.2 Results of the numerical simulations

For the quantification of influence of increasing amounts of heavy minerals in sediment beds on sediment erosion and hence placer enrichment four suites of numerical sediment beds were tested on their erosion behavior under predefined boundary flow velocities ($U = 10$ cm/s, 20 cm/s, 30 cm/s and 40 cm/s). Therefore, three numerical sediment beds of randomly distributed mixtures containing heavy magnetite and light quartz particles of the similar grain size were generated (Table 4). Therein, the amount of magnetite with respect to quartz particles in the sediment beds was changed in each experiment (Experiment 1 - 3). In addition, Experiment 4 was created of magnetite and larger quartz grains (Table 4) for the quantification of grain size related effects occurring in heavy and light mineral

composed sediment beds. The extracted amounts of transported particles horizontal and vertical of each Experiment are presented in Tables 4 and 5. The results derived at 30 cm/s flow speed are presented as an example case in the Figure 8 and 9.

4.2.1 Horizontal and vertical transport rates

Comparing the results in horizontal of all analysed experiments, the results showed that particle transport in x-direction was initiated at 10 cm/s. The amount of particle transport distances extracted from the top of all processed experiments at 30 cm/s flow speeds (Figure 8), showed generally higher amounts of quartz transport with respect to the decreasing magnetite contents in the beds. In particular, when comparing the results of the low, high, and medium quartz content experiments i.e., Experiment 1, 2 and 3, quartz transport increased. Therefore, the sediment bed of Experiment 1 (low quartz content) showed the lowest amounts of quartz particle transport and Experiment 2 (high quartz content) showed the highest amount of quartz particle transport. Values ranged from $6.60\text{E-}05$ m (Experiment 1) to $1.71\text{E-}04$ m (Experiment 2) at 30 cm/s flow speed. Consequently, transport of magnetite particles extracted at the sediment surface was generally lower as compared to those of the quartz minerals. Therefore, sediment transport at the surface of the bed is clearly related to the amount of heavier magnetite particles in the sediment beds.

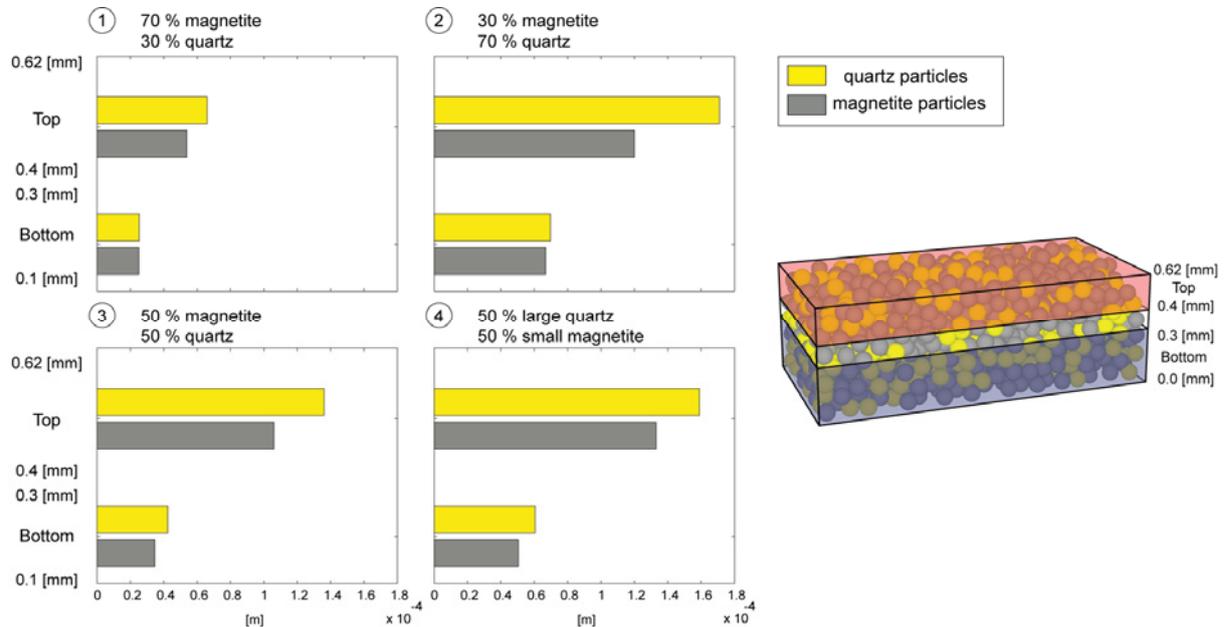


Figure 8: Horizontal particle transport extracted from the top and the bottom of the numerical sediment beds. The transport rates of quartz particles are illustrated in yellow color, whereas the transport rates of the magnetite particles are illustrated in gray colors. All presented transport distances were extracted at 30 cm/s flow speed.

The amount of particle transport in the deeper parts of the bed differs to those measured at the sediment surface, by showing lower amounts of quartz and magnetite transport with increasing quartz content in the beds. However, similar to the measurements derived from the top of the sediment bed more quartz was transported as compared to magnetite. This becomes clear, when comparing the amount of particle transport extracted in the deeper parts of the sediment bed of Experiment 1 (low quartz content) with those of Experiment 2 (high quartz content), whereby an increase of quartz transport and hence an increase of magnetite transport was observed. The corresponding values of magnetite transport ranged from $2.51E-05$ m (Experiment 1) to $6.68E-05$ m (Experiment 2) at 30 cm/s flow speed. It is interesting to note that Experiment 1 having the lowest quartz content showed the lowest amounts of quartz transport towards depth. Whereby, quartz transport, within the higher quartz concentrated Experiment 2 and Experiment 3 increase with depth. In addition, Experiment 4, which was composed of magnetite and larger numerical quartz grains, followed the trend described in Experiment 1. Consequently higher amounts of quartz particles were transported at the top of the sediment bed as compared to magnetite particles. Similar to Experiment 1 quartz transport was higher either at the sediment surface or in the deeper parts of the bed.

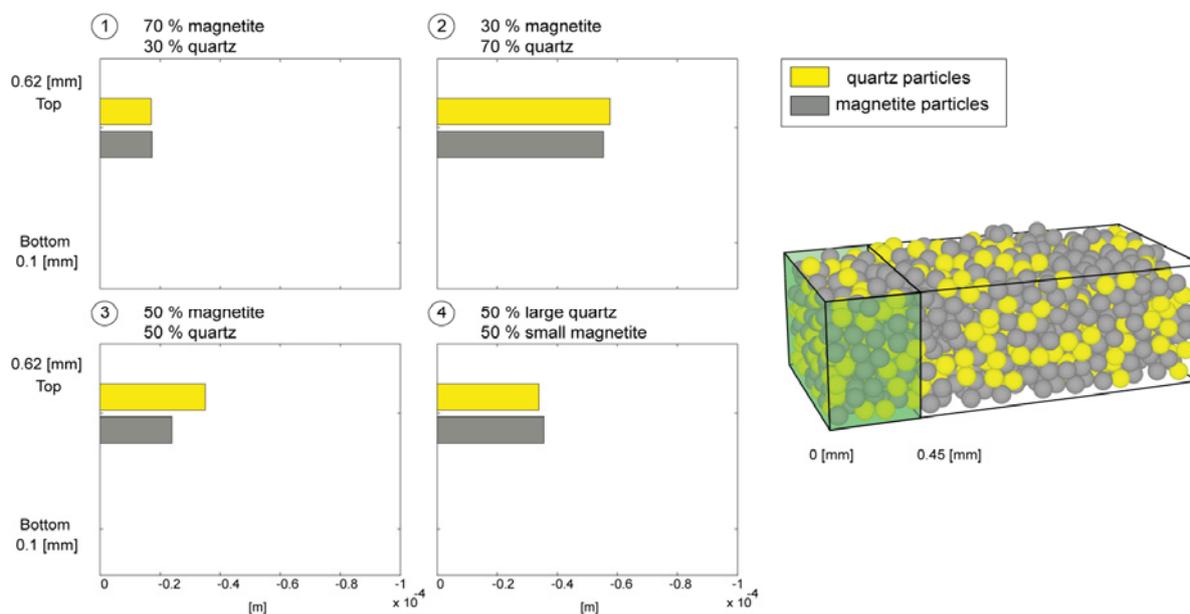


Figure 9: Vertical amount of particles transported in the numerical sediment beds. Transported quartz particles are illustrated in yellow color, whereas transported magnetite particles are illustrated in gray colors. All data was extracted at 30 cm/s flow speed.

The vertical transport rates extracted from all experiments at 30 cm/s flow speeds are presented in Figure 9. The results show, that, different transport amounts in vertical direction with respect to the

amount of magnetite and quartz particles mixed into the bed, were observed. When comparing the results of the low, high and medium quartz content experiments quartz transport increased, and magnetite transport decreased with increasing quartz contents in the beds. Values of quartz transport ranged from $-1.70\text{E-}05$ m (Experiment 1) to $-5.76\text{E-}05$ m (Experiment 3) at 30 cm/s flow speed. Consequently the results show in a low quartz concentrated bed, magnetite was transported faster in the deeper parts of the bed compared to quartz. However, with increasing quartz content in the bed this trend is decreasing. Similar to the results of Experiment 4 an equivalent trend to Experiment 1 was observed, where more of magnetite particles were transported into the deeper parts of the bed as compared to quartz particles.

5. Discussion

5.1 Interpretation and comparisons of log-probability distribution curves of bulk and magnetite grains and its implications for characterizing sediment transport and depositional environment

Generally the grain size distributions of sediments composed of two or more populations are produced due to variable energy and transport conditions. *Visher* (1969) plotted cumulative distribution on log probability scale to relate the modes of each grain size to the various transport modes and depositional processes. He demonstrated that the truncation points for traction, saltation and suspension population provides information on depositional environment including sources and energy conditions. Thus the transport and deposition of magnetite grains in any of the environment depends on the dynamics of the flow conditions. Consequently, in any given flow conditions the magnetite grains will be transported as traction, saltation or suspension population over the bed and depending upon the energy conditions. It is generally observed that the magnetite grains being smaller in size and denser tends to settle faster on the bed as compared with coarser (lighter) minerals. In the present study, the three modes of transport for magnetite fraction and bulk sediment fraction for the samples representing various depositional environments are studied in detail. The magnetite distribution curves were generated from bulk sediment distribution curves by measurement of magnetic susceptibility on each sieved fractions. Around 22 representative distribution curves (log-probability and cumulative percent) of bulk sediment and magnetite properties (size, shapes of the curves and percentage of each grain size population) have been interpreted and compared to gain information on enrichment of magnetite in variable hydrodynamic environments (Figure 3 & 4). The distribution curves for magnetite in majority of the samples from different depositional environments showed that magnetite grains are mainly transported as bedload and also saltation with minor load moving as traction and suspension

population (Figure 3 & 4). The variability in mean grain size and dispersion of magnetite grains from different environments suggests that it is likely that small portion of magnetite grains moving within grain layer populations (saltation or suspension). Further they tends to fall on to the bed and remains deposited followed by burial resulting in formation of enrichment zones.

The following sections describes the relation of magnetite grain transport (size, shape, percentage) and hydrodynamic environments. (a) river upstream, (b) river mouth, (c) estuarine (d) beach and (e) marine.

Wairoa river upstream and mouth

In river upstream environment, the flow is unidirectional and sediments transport is mostly dependent on intensities of currents velocities. Hence the whole sediment load is carried downstream as one major population i.e. predominantly as suspension load. As soon as the flow velocities are reduced, the heavy mineral grains within the bulk sediment composition settle down and are deposited in the river bed. So, heavy minerals being finer and denser sink into the bed and form heavy mineral enriched zones. In general, our river sediments are coarser as our beach sediments. This is understood due to its proximity to the source. Mostly the coarser grains population moves as traction (rolling & sliding). In our studied upstream samples it was observed that the sediment were mainly transported as saltation and suspension population which suggests that high energies in the flow carried the sediment load in this two populations and therefore traction population is not much clearly visible and lacks in few samples.

The similarity in log probability plots of magnetite distribution for Wairoa River upstream and mouth samples suggests that the magnetite grains are mainly in fine-medium grain size range. Although the higher magnetite concentration was found to occur in very fine sand, saltation population was dominant (Figure. 3a-c). The Wairoa River upstream samples had lowest offset compared to samples from other environments. These suggest that higher energies in the river upstream enhances the transport of magnetite grains rather than settling. As observed in most of the magnetite distribution curves, highest concentration was found to occur in very fine sand ranges in the river upstream samples and also possessed lowest mean grain size (coarsest) and highest dispersion. Whereas the river mouth samples showed highest mean grain sizes (finer) and low (consistent) dispersion (Table. 2). This could be explained through the continuous inflow of sediments in mixed grain sizes into river due to the proximity of the source rocks. It is also possible that variability in current intensities of river run offs which would transport the magnetite grains mainly as saltation population together with the bulk sediment load. The truncation point of the saltation population is variable and found to occur

between 0.5 to 4.0 phi i.e very fine to coarse sand (Figure 3 d-f). This is probably due to fluctuations occurring within the flow. This causes the magnetite grains within river environment to move out of the traction (bedload) population and enters the saltation mode during its transport. The curves for samples (WA- 4 & WA -6) seem to lack the traction population. This could be attributed to sudden changes in the flow velocities within the river run off (Figure 3a-c). The bulk sediment grain size distribution of river upstream samples appears to be similar to that of river mouth samples. They mainly contain low amount of traction population i.e from 0.03 – 0.48 %. The truncation points in the river mouth samples is much different than upstream samples, this is possibly due to the interaction of tides and river run offs (currents) at the Wairoa river mouth, which generates the grain size distribution curves of various shapes and percentages.

Estuarine environment

In estuaries, due to intense interaction between waves and tidal currents grain size distribution curves of different sizes, shapes and populations are produced. The distribution curve for the samples from estuary appears to be different compared to other environments (Figure. 3 g-i). The samples were well sorted and showed three distinct populations. Magnetite distributions in different fractions are similar to other samples. These samples represent tidal and non-tidal channel environment within the estuary in water depths of 4 – 10 m but flow energy (tides) are able to drag or lift the magnetite grain fraction into saltation and suspension. Most of this population comes from sediment load brought by Wairoa River and delivered to the southern basin of Tauranga Harbour. The tidal channel sample showed that the saltation population has a range between 1.0 to 3 phi and its truncation point is at 1.5 (Figure. 3g), while the non tidal channel sample has range between 0.0 to 4.0 phi and its truncation point is at 0.5 phi (Fig 3i). Within tidal channel, traction population for this samples showed well sorted three distinct populations and possesses wide range (-1.5 to 1.5) phi and also higher percentage (0.005 to 11.4 %) compared to distributions from other environments. This could be due to the strong interaction of the traction population with high bottom current flow velocities within tidal channels. The higher percentages of the traction population within estuarine samples suggests that the transport of magnetite is mainly driven by bottom current velocities produced due to bi-direction flows generated as a result of ebb and flood currents / tides.

Beach samples

Analysis of log probability curves on beach samples showed that the magnetite is mostly transported as saltation population and has highest mean grain size (2.2–3.3 phi) i.e very fine – fine sand (Figure 3 j-l). The lowest offset between the grain sizes of the bulk and magnetite grains could be attributed to

the similarity in their grain sizes. For example in sample (CM-20m), the offset is nearly zero, this suggests that the magnetite grains mostly remain deposited along with other lighter grains and only higher energy events such as storm surges could entrain or transport these grains from the bed (Fig. 4j – l). The traction population in this sample is very low and lacks in a few samples, since these coarse grain sizes are not available in the depositional environment. In the beach environment, especially in the swash zone where the grains move back and forth through crests and troughs, but finally remain in the same position which is termed as null point for the particular grain size. The minerals possessing grain size higher than null point size are transported seawards and the smaller ones are moved towards the shore. Therefore such mechanism causes the heavy mineral grains to remain on beach as a lag deposit which lacks the tail of coarser grain size fraction.

In beach and nearshore environment the transport of sediment is controlled by longshore transport / littoral drift and surf generated waves. The sediments of different grain sizes are suspended and mixed together and hence settling of grains onto the bed takes place depending upon the individual grain property. Higher energies generated by waves and longshore currents tend to sort the mineral grains. The waves throw the sediment into suspension and then the currents move them seawards. Thus beach or nearshore sand are better sorted than river sand and could sometimes result in accumulation of the heavy minerals as lag deposits.

Nearshore marine environment (inner and outer magnetite belt)

Figure 3 m-o illustrates the magnetite distribution for marine samples mostly covering nearshore region which includes surf zone and the higher energies tend to produce higher suspension population in this region. The bulk susceptibility of sediment was much higher compared to other samples (Figure 4 m-o). The samples were moderately sorted in three populations with saltation being dominant (98.2 – 99.86 %). It appears that the percentage of saltation population is highly dependent on wave energies in surf zone. In this zone, higher energy generated due to breaking of incoming waves causes large amount of sediment (light & heavy mineral grains) to move into suspension and hence the mixing between two populations occurs. Magnetite grains being finer and denser mostly remain as saltation population and settle down quickly onto the bed during low energy conditions, while the lighter mineral grains are transported seaward by currents. The break between the traction and saltation population is in the range between 2 – 2.5 ϕ i.e. very fine – fine sand (Figure 4 m-o). This could be attributed to transport of magnetite grains in both the cycles (crest & trough) of the waves and then deposition during low energy condition.

In the samples from outer belts (inner shelf) the break between the traction and saltation population for bulk sediments and magnetite grains varies and is mostly in the range between -0.5 to 1.0 phi (coarse – very coarse sand) and 1.0 to 2 phi (medium - fine sand) respectively. This mostly indicates the calm energy conditions and nature of sediment in this region. The sediments in inner shelf off Tauranga Harbour are mainly medium-coarse grained relict lag deposits of Pleistocene age that were reworked during the last glacials (*Bradshaw et al.*, 1994; *Michels and Healy*, 1999; *Kruger and Healy*, 2006). Therefore such conditions favour deposition of the grain although there is a difference in the settling of light and heavy (magnetite) minerals. It is possible that the magnetite grains (inner and outer belt) smaller than 4 phi are usually in suspension and are transported seawards unless the sediment input increase the transport energy.

5.2 Numerical models and implications for understanding grain entrainment and transport

In estuaries, sediment transport is controlled by the hydrodynamics which is dependent on the combined interaction of river runoff, tides (ebb and flood), and also waves. The sediments in this environment were well sorted and mostly transported as bedload, saltation, and suspension. In addition the magnetic grains were much finer and found to be concentrated in higher amounts as compared to the Wairoa River upstream. This could be due to the influence of bidirectional currents in the estuary generated by tides (ebb & flood) that cause better sorting of the sediments and hence selective deposition of individual heavy mineral grains. Within the beach environment the transport and entrainment is controlled by winnowing and waves (swash zone). In this region, once the grains are in the suspension, they move back and forward due to periodicity of the waves. So finally the grain in the suspension after certain interval settles down or found to be remain in the same position, which is termed as null point. In our study area, we found that the sediments on the beach (dunes and the swash zone sediments of Matakana beach) were mainly composed of heavy and light grains in similar sizes and the offset was almost zero. This reflects the characteristics of a depositional environment, wherein the grains seemed to be deposited in the bed without any further transport or entrainment. This suggests that much higher energies are required for their movement for example periodic storm surges. This phenomenon was observed by a recent numerical modelling study on selective grain entrainment (*Bartzke & Huhn., in rev.*, 2012). We hypothesized that the numerical Experiment 4 consisting of sediment bed of coarser lighter quartz and magnetite grains represents the initial beach conditions when sediment supply to the beach would have been sufficiently rich in coarse light and fine heavy grains (refer Figure 7 and 11). There appears to be higher washout of the quartz grains in this bed configuration as previously observed in flume studies (*Komar*, 2007). Furthermore, Experiment 3 represent the present conditions of the beach, it was found that increase in magnetite content

considerably reduces or even inhibits the movement of the grains within the bed. This in turn reduces the rates of erosion resulting in stabilization of bed (Figure 7 and 11). This findings reveals that it is not always true that not only the coarser particles provides shielding to the fine heavy mineral fraction (Komar, 2007). Therefore we hypothesize that the past conditions on the beach was much different (eroding) compared with present (stabilizing). One could imagine that the bed becomes more stabilized if the present conditions persists. Past, present and future conditions of the beach evolution based on these findings are presented in a conceptual diagram (Figure 11 A, B,C).

Within the marine environments including nearshore and shelf region, a recent study by *Badesab et al.*, 2012 off Tauranga Harbour identified two coast parallel magnetite enrichment belt. They found that highly energetic conditions generated due to surf zone processes in the nearshore region caused well sorting of heavy minerals resulting in the formation of magnetite rich zones in the region, while the outer belt was mainly composed of relict reworked sediments. The samples analysed from the inner belt showed a well defined grain size distribution and the highest magnetite enrichment in the fine fraction. It can be concluded that higher energies caused by waves (surfzone), littoral drift, tides play a key role in the formation of this belt. In the outer belt sample, i.e, inner shelf, the sediment is transported either as a traction or saltation population. It is possible that due to the presence of lower energy regime induced only by bottom currents and much smaller sediment input, inhibited the sorting of mineral grains which mostly remained accumulated in this region.

5.3 Conceptual model explaining magnetite enrichment and transport mechanism

Here we summarize our findings based on the laboratory and numerical experiments in a conceptual model, which explains the mechanisms of magnetite enrichment in sedimentary environments ranging from fluvial to marine settings (Figure 10 and 11). Therefore we describe the enrichment processes of magnetite occurring in six different sub-environments i.e., river upstream, river mouth, estuary, beach, marine (near shore and inner shelf). In the river upstream the majority of the sediment was transported as saltation and suspension load. This could be due to the association of high current velocities within the unidirectional river flow, which limited the sediment accumulation and deposition in the riverbed even though the sediment influx from the proximal source was higher. Within the river mouth magnetite grains were coarser and had a higher concentration as compared to the river upstream. Additional sediment input brought from the river runoff (Wairoa River, Figure 3) and the presence of a lower energy environment favoured magnetite accumulation rather than transport, which resulted in higher deposition of magnetite grains onto the bed forming enriched layers.

In all environments, a general trend of decrease in grain size magnetite was observed. In addition the sediments from the river mouth had coarser magnetite grains and higher concentration, while the sediments in the marine region were much finer although the concentrations were similar.

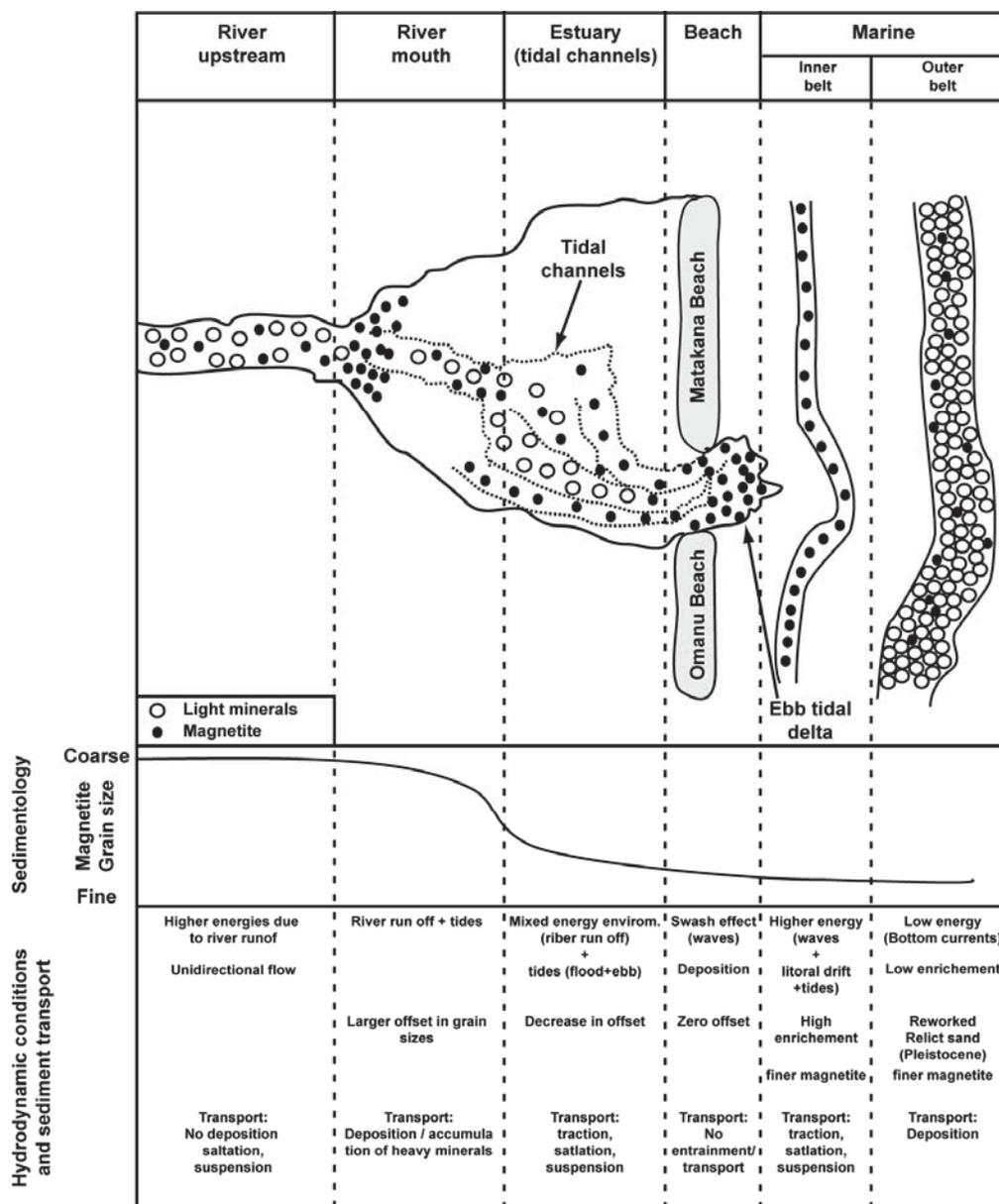


Figure 10: Conceptual model summarizing the findings from the laboratory measurements and numerical models.

Past studies have shown that the grain size of sediment decreases and becomes finer with increasing transport distance from source to sink due to abrasion and collision caused during transport. This concept supports and explains our findings wherein we observed a decrease in magnetite grain size in

samples originating from river mouth (source, coarser) to marine environment (finer, sink). Even though the river mouth, beach and marine (outer belt) environments showed distinct magnetite distributions in terms of their grain sizes and also the concentration, highest amounts of magnetite were seen to be concentrated at the river mouth. The beach environment showed intermediate and the outer belt showed lowest magnetite concentrations. The enrichment in the river mouths is possibly caused due to proximity to the source area.

Our present study showed that in beach environment, the heavy mineral grains provides shielding to lighter mineral grains reducing the rate of erosion and this seems to be true only in a bed consisting of sediments with equivalent grain sizes (refer Experiment 3: Figure 7 and 11).

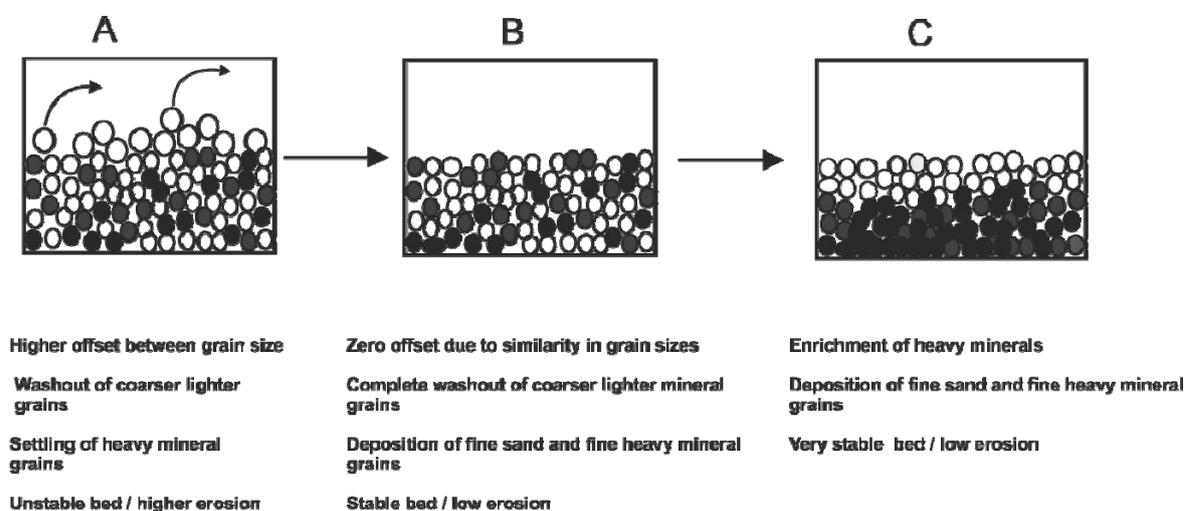


Figure 11: Schematic illustration showing the evolution of the Matakana Beach. A) Past conditions of the beach, containing a mixture of fine and coarse light minerals and fine and heavy minerals. B) Present conditions showing wash out of the coarser lighter mineral and leaving behind the fine sand and fine magnetite behind, in turn increasing the stability of the bed C) Predicted future conditions showing the bed enriched with heavy minerals with a negligible amount of erosion.

In general, our combined study based on laboratory analysis and interpretation of magnetite and bulk sediment distribution curves, statistical methods and 3D high resolution numerical modelling results has provided deep insights into the fundamental mechanism of transport and settling dynamics of magnetite in wide range of depositional environments.

6. Conclusion

The distribution curves of bulk sediment and magnetite grains describe the enrichment and transport processes of magnetite occurring in six different sub-environments i.e., river upstream, river mouth, estuary, beach, marine (near shore and inner shelf). These were analyzed and compared to interpret the transport, deposition, enrichment processes of magnetite and light mineral grain in six sedimentary environments.

The differences in shapes of distribution curves, percentage of each population, offset in grain sizes of bulk and magnetite fraction reflects the variability in grain transport, settling and entrainment dynamics and depositional conditions in each environment.

Magnetite was mostly found in the very fine – fine sand fraction of the total sediment population and highest concentration was found in samples from river mouth and marine environment (inner). Although the majority of the bulk sediments were transported as saltation population, the heavy mineral grains being finer and denser settled down quickly and were trapped between the larger coarser (lighter) grains as the energy of the flow decreases. The smaller velocities of the fluid flow tends to increase offset in grain sizes of light & heavy minerals, which inturn leads to settling of finer and denser minerals as accumulated zones in low energy environment.

The numerical models run to quantify the laboratory findings of three distinct sedimentary environments i.e. river mouth, beach and marine (outer). The results validated the observed processes of magnetite enrichment as observed from laboratory findings. Further it was found that sediments bed consisting of light and heavy mineral grains of equal sizes are highly stabilized as compared to other beds possessing sediments with unequal grain size distributions.

We demonstrate that our present approach of using combined laboratory analysis and numerical modelling possesses potential to investigate the dynamics of magnetic minerals and enrichment processes at grain scale level and could be further applied to any other setting.

Acknowledgement

This work was supported by Deutsche Forschungsgemeinschaft (DFG) through a joint International Research Training Group (Bremen–Waikato) INTERCOAST and MARUM, Center for Marine Environmental Sciences at the University of Bremen, Germany. We would like to thank Liane Brück, Dirk Immenga, Ruggero Capperucci, Serena Fraccascia, Sebastien Boulay and Christopher Daly for providing help during sediment sampling expeditions. The authors would like to thank Lina Podszun,

Jannis Kuhlmann, Linda Wenk and INTERCOAST research students Rike Vöppel, Steffen Wiers, Max Kluger for providing assistance with numerical modelling and laboratory work.

References:

Badesab, F. K., T. v. Dobeneck, K. R. Bryan., H. Müller., R. M. Briggs , T. Frederichs and E. Kwohl (2012), Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand, *Geochemistry, Geophysics, Geosystems.*, 13 (6), doi:10.1029/2012GC004125

Baba, J and Komar, P.D., (1981), Measurements and analysis of settling velocities of natural quartz sand grains, *Journal of Sedimentary Petrology.*, 51, 631.

Bloemendal, J., King, J.W., Hall, F.R. and Doh, S. (1992). Rock Magnetism of Late Neogene and Pleistocene Deep-Sea Sediments: Relationship to Sediment Source, Diagenetic Processes, and Sediment Lithology. *Journal of Geophysical Research.* 97(B4): doi: 10.1029/91JB03068.

Booth, C.A., Walden, J., Neal, A., Smith, J.P., (2005), Use of mineral magnetic concentration data as a particle size proxy: a case study using marine, estuarine and fluvial sediments in the Carmarthen Bay area, South Wales, U.K. *The Science of the Total Environment.*, 347, 241–253.

Bradshaw, B. E., T. R. Healy, C. S Nelson, P. M. Dell., and W.P. De Lange (1994), Holocene sediment lithofacies and dispersal systems on a storm-dominated, back-arc shelf margin: The east Coromandel coast, New Zealand, *Mar. Geol.*, 119, 75–98, doi: 10.1016/0025-3227(94)90142-2.

Bryan, K. R., A. Robinson, and R. M. Briggs (2007), Spatial and temporal variability of titanomagnetite placer deposits on predominantly black sand beach, *Mar. Geol.*, 236, 45–49, doi: 10.1016/j.margeo.2006.09.023.

Cioppa, M. T., N. J. Porter, A. S. Trenhaile, B. Igbokwe, and J. Vickers (2010), Beach sediment magnetism and sources: Lake Erie, Ontario, Canada, *J. Great. Lake. Res.*, 36(4), 674–685, doi:10.1016/j.jglr.2010.07.007.

De Lange, W.P (1991), Wave climate for No 1 Reach, Port of Tauranga, Tauranga Harbour, report, Port of Tauranga Ltd., Hamilton, New Zealand.

- Frihy O. E., and K. M. Dewidar (2003), Patterns of erosion / sedimentation, heavy mineral concentration and grain size to interpret boundaries of littoral sub cells of the Nile delta, Egypt, *Mar. Geol.*, 199, 27–43, doi: 10.1016/S0025-3227(03)00145-2.
- Frihy, O. E and P.D. Komar (1991), Patterns of beach-sand sorting and shoreline erosion on the Nile delta, *Journal of Sedimentary Petrology.*, 37, 514 – 521
- Gallaway, E., A. S. Trenhaile, M. T. Cioppa, and R. G. Hatfield (2012), Magnetic mineral transport and sorting in swash-zone: Northern Lake Erie, Canada, *Sedimentology.*, doi: 10.1111/j.1365-3091.2012.01323.x.
- Gao, S., and Collins, M., (1992), Net sediment transport patterns inferred from grain-size trends, based upon definition of ‘transport vector’, *Sedimentary Geology.*, 80, 47-60.
- Hatfield, R. G., M. T. Cioppa, and A. S. Trenhaile (2010), Sediment sorting and beach erosion along a coastal foreland: Magnetic measurements in Point Pelee National park, Ontario, Canada, *Sed. Geol.*, 231(3-4),63–73. doi:10.1016/j.sedgeo.2010.09.007.
- Hughes, M. G., J. B. Keen and R. G. Joseph (2000), Hydraulic sorting of heavy mineral grains by swash on a medium sand beach, *Journal of Sedimentary Research.*, 70 (5).
- Inman, D. L., (1949), Sorting of sediment in light of fluvial mechanics, *Journal of Sedimentary Petrology.*, 19 , 51-70.
- Komar, P. D., and C. Wang (1984), Processes of selective grain transport and the formation of placers on beaches, *The Journal of Geology*, 92(6), 637–655.
- Krumbein, W.C and Pettijohn, F.J., (1938), *Manual of Sedimentary Petrography*: New York, Appleton-Century, 549 p.
- Kruger, J., and T. R. Healy (2006), Mapping the morphology of dredged ebb tidal delta, Tauranga Harbour, New Zealand, *J. Coast. Res.*, 2(3), 720–727.

Lees, J. A., and J. S. Pethick (1995), Problems associated with quantitative magnetic sourcing of sediments of the Scarborough to Mablethorpe coast, Northeast England, U.K, *Earth Surface Processes and Landforms.*, 20 (9), 795–806, doi: 10.1002/esp.3290200905.

Maher, B.A., Watkins, S.J., Brunskill, G., Alexander, J. and Fieldings, C.R (2008), Sediment provenance in a tropical fluvial and marine context by magnetic fingerprinting of transportable sand fractions, *Sedimentology.*, 5, 841-861.

Mason, C. C and Folk, R.L., (1958), Differentiation of beach dune, and eolian flat environments by size analysis, *Journal of Sedimentary Petrology.*, 28, 211-226.

Mclaren, P.,(1981), An interpretation of trends in grain-size measures, *Journal of Sedimentary Petrology.*, 51, 611-624.

Mclaren, P and Bowles, D (1985), The effects of sediment transport on grain size distributions, *Journal of Sedimentary Petrology.*, 55 (4), 0457-0470.

Michels, K. H., and T. R. Healy (1999), Evaluation of an inner shelf site off Tauranga Harbour, New Zealand, for disposal of muddy-sandy dredged sediments, *J. Coast. Res.*, 15(3), 830–838.

Moss, A. J., (1962), The physical nature of common sandy and pebbly deposits. Part II, *American Journal Science.*, 260, 337 – 373.

Oldfield, F., and L. Yu (1994), The influence of particle size variations on the magnetic properties of sediments from the north-eastern Irish Sea, *Sedimentology.*, 41(6), 1093–1108,doi:10.1111/j.1365-3091-1994.tb01443.x.

Razjigaeva, N. G., and V. V. Naumova (1992), Trace element composition of detrital magnetite from coastal sediments of northwestern Japan Sea for provenance study, *J. Sed. Res.*, 62(5), 802–809, doi: 10.1306/d42679e2-2b26-11d7-8648000102c1865d.

Robinson, S. G., M. A. Maslin and I. N. McCave (1995), Magnetic susceptibility variations in Upper Pleistocene deep-sea sediments of the NE Atlantic: Implications for ice rafting and paleocirculation at the Last Glacial Maximum, *Paleoceanography.*, 10(2), doi: 10.1029/94PA02683

- Rubey, W. W (1933), The size distribution of heavy minerals within a water laid sandstone, *J. Sed. Petrol.*, 3 (1), 3–29, doi: 10.1306/D4268E37-2B26-11D7-8648000102C1865D.
- Sindwoski, K. H., (1958), Diesynoptische Methode des Kornt1ryen-Vetgl~iches Zltr Aussenzug iossiler Sedimentationr~ume: *Geol Jahrb.*, v. 73, p.235-275.
- Slingerland, R. L. (1977), The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands, *J. Sed. Res.*, 47(2), 753–770, doi: 10.1306/212f7243-2b24-11d7-8648000102c1865d.
- Visher, G. S., (1969), Grain size distributions and depositional process, *Journal of Sedimentary Petrology.*, 39(3), 1074-1106.
- Wheeler, A. J., F. Oldfield, and J. D. Orford (1999), Depositional and post-depositional controls on magnetic signals from salt marshes on the north-west coast of Ireland, *Sedimentology.*, 46(3), 545–558, doi: 10.1046/j.1365-3091.1999.00236.x.
- Walden, J., Slattery, MC & Burt, TP (1997), ' Use of mineral magnetic measurements to fingerprint suspended sediment sources: approaches and techniques for data analysis , *Journal of Hydrology.*, 202, 353-372.
- Zhang, W., L. Yu, and S. M. Hutchinson (2001), Diagenesis of magnetic minerals in the intertidal sediments of the Yangtze Estuary, China, and its environmental significance, *The Sci of Total Environ.*, 266(1-3), 169–175, doi: 10.1016/S0048-9697(00)00735-X.
- Zhang, W., Yu, L., Lu, M., Hutchinson, S.M and Feng H (2007), Magnetic approach to normalizing heavy metal concentrations for particle size effects in intertidal sediments in the Yangtze Estuary, China, *Environmental Pollution.*, 147, 238-244.
- Zhang, S., M. T. Cioppa, and Z. Shihong (2010), Spatial variation in particle size and magnetite concentration on Cedar Beach: Implications for grain sorting processes, Western Lake Erie, Canada, *Acta Geologica Sinica.*, 84(6), 1520–1532, doi: 10.1111/j.1755-6724.2010.00345.x.

Table 1: Percentages of population (traction, saltation & suspension) and grain size ranges calculated from magnetite distribution curves of samples from various depositional environments

Depositional Environment	Traction population		Saltation population		Suspension population	
	%	Phi range	%	Phi range	%	Phi range
River upstream (Wairoa River)	0.3 - 2.3	-2.0 to 0.5	58.6 - 62.5	0.5 to 3.0	0.85 - 39	3.0 to 5.5
River mouth (Wairoa River)	0.03 - 0.48	-2.0 to 1.5	68.2 - 99.6	1.5 to 5.0	0.2 - 5.3	5.0 to 7.0
Estuarine (Tauranga Harbour)	0.005 - 11.4	-1.5 to 1.5	87.7 - 98.1	1.5 to 4.0	0.25 - 1.6	4.0 to 5.5
Beach (Matakana Beach)	0.06 - 1.3	0.5 to 1.5	98.2 - 99.8	1.5 to 4.5	0.01 - 0.9	4.5 to 5.5
Marine - nearshore (Inner magnetite enrichment belt)	0.025 - 1.95	-1.0 to 2.5	2.9 - 97.9	2.5 to 4.4	0.01 - 4.7	4.5 to 5.5
Marine – inner shelf (Outer magnetite enrichment belt)	0.99 - 19.8	-1.5 to 2.0	79.9 - 98.9	2.0 to 4.0	0.05 - 0.09	4.0 to 6.5

Table 2: Details of magnetic and statistical parameters (*Krumbein & Pettijohn, 1938*) of analyzed samples

Sample Details	Bulk magnetite content [%]	Mean grain size Bulk fraction [phi]	Dispersion [Bulk fraction]	Mean grain size Magnetite fraction [phi]	Dispersion [Magnetite Fraction]	Offset in grain size [$\Delta\phi$]
Wairoa River upstream						
WU-4	0.049	0.36	1.76	0.87	2.52	0.6
WU-3	0.12	2.66	1.54	2.81	2.17	0.2
WU-6	0.83	-0.46	2.47	-0.67	3.84	0.1
Wairoa River mouth						
WM-3	0.95	1.91	1.04	3.1	0.66	1.3
WM-4	0.44	1.78	0.74	3.25	0.88	1.6
WM-8	0.24	2.43	1.1	3.92	1.21	1.7
WM-12	1.19	1.88	0.83	3.72	0.97	1.9
WM-13	1.44	2.28	1.1	3.83	0.95	1.4
Estuarine (Tauranga Harbour)						
SB-1	0.069	1.11	1.2	2.12	1.24	0.9
SB-2	0.16	1.85	0.53	2.41	0.93	0.4
SB-3	0.083	2.08	0.75	2.79	0.76	0.7
SB-4	0.26	1.29	1.09	2.25	1.04	1.4
Beach (Matakana Beach)						
B1	0.020	2.2	0.56	2.22	1.05	0.7
B2	0.0029	2.63	0.79	3.35	0.55	1.0
B3	0.0055	1.23	0.8	1.76	1.73	0
Marine (Inner magnetite enrichment belt)						
MIB - 1	0.21	2.93	1.13	3.63	0.26	1.0
MIB - 2	0.15	2.96	1.17	3.53	0.24	0.5
MIB - 3	0.12	2.34	1.06	3.2	0.70	1.2
Marine(Outer magnetite enrichment belt)						
MOB - 1	1.10	2.45	0.94	3.3	0.63	1.0
MOB - 2	0.72	0.27	1.81	1.71	1.52	1.3
MOB - 3	0.074	0.65	2.65	1.99	1.47	0.4

Table 3: Properties and configurations of the numerical experiment

Particle properties				
Properties	Exp. 1	Exp. 2	Exp. 3	Exp. 4
Diameter [μm]: quartz	90	90	128.8	90
Diameter [μm]: magnetite	90	90	90	90
Particle number: quartz	381	889	635	350
Particle number: magnetite	889	381	635	350
Normal stiffness [N/m]	1×10^8	1×10^8	1×10^8	1×10^8
Shear stiffness [N/m]	1×10^8	1×10^8	1×10^8	1×10^8
Density ρ quartz [kg/m^3]	2600	2600	2600	2600
Density ρ magnetite [kg/m^3]	5140	5140	5140	5140
Quartz friction μ	0.5	0.5	0.5	0.5
Magnetite friction μ	2	2	2	2
Fluid properties				
Fluid properties	Exp. 1	Exp. 2	Exp. 3	Exp. 4
Fluid density ρ [kg/m^3]	1000	1000	1000	1000
Pore pressure [mbar]	250	250	250	250
Fluid saturation [%]	100	100	100	100
Boundary inflow velocity U [cm/s]		10, 20, 30 and 40		

Table 4: Transported particles in horizontal direction

Experiment 1				
Flow speed [cm/s]	'Quartz' transport [m] (Top)	'Magnetite' transport [m] (Top)	'Quartz' transport [m] (Base)	'Magnetite' transport [m] (Base)
10 cm	3.55E-05	2.37E-05	1.80E-05	1.67E-05
20 cm	5.93E-05	3.90E-05	2.18E-05	2.80E-05
30 cm	6.60E-05	5.38E-05	3.28E-05	3.49E-05
40 cm	7.82E-05	6.72E-05	4.18E-05	4.17E-05

Experiment 2				
Flow speed [cm/s]	'Quartz' transport [m] (Top)	'Magnetite' transport [m] (Top)	'Quartz' transport [m] (Base)	'Magnetite' transport [m] (Base)
10 cm	8.45E-05	6.09E-05	4.92E-05	7.50E-05
20 cm	1.24E-04	8.85E-05	6.82E-05	9.17E-05
30 cm	1.71E-04	1.20E-04	8.97E-05	1.17E-04
40 cm	2.14E-04	1.44E-04	1.02E-04	1.29E-04

Experiment 3				
Flow speed [cm/s]	'Quartz' transport [m] (Top)	'Magnetite' transport [m] (Top)	'Quartz' transport [m] (Base)	'Magnetite' transport [m] (Base)
10 cm	6.01E-05	4.12E-05	3.01E-05	2.47E-05
20 cm				
30 cm	1.36E-04	1.06E-04	5.00E-05	5.77E-05
40 cm				

Experiment 4				
Flow speed [cm/s]	'Quartz' transport [m] (Top)	'Magnetite' transport [m] (Top)	'Quartz' transport [m] (Base)	'Magnetite' transport [m] (Base)
10 cm	7.10E-05	5.25E-05	2.66E-05	3.03E-05
20 cm	1.20E-04	1.10E-04	9.04E-05	6.13E-05
30 cm	1.59E-04	1.33E-04	7.13E-05	7.18E-05
40 cm	1.96E-04	1.45E-04	6.21E-05	8.48E-05

Table 5: Transported particles in vertical direction

Experiment 1		
Flow speed [cm/s]	'Quartz' transport [m]	'Magnetite' transport [m]
10 cm	-7.98E-06	-8.01E-06
20 cm	-1.26E-05	-1.30E-05
30 cm	-1.70E-05	-1.73E-05
40 cm	-2.00E-05	-2.10E-05

Experiment 2		
Flow speed [cm/s]	'Quartz' transport [m]	'Magnetite' transport [m]
10 cm	-2.80E-05	-3.01E-05
20 cm	-4.45E-05	-4.06E-05
30 cm	-5.76E-05	-5.54E-05
40 cm	-6.29E-05	-6.10E-05

Experiment 3		
Flow speed [cm/s]	'Quartz' transport [m]	'Magnetite' transport [m]
10 cm	-1.83E-05	-1.20E-05
20 cm		
30 cm	-3.50E-05	-2.39E-05
40 cm		

Experiment 4		
Flow speed [cm/s]	'Quartz' transport [m]	'Magnetite' transport [m]
10 cm	-1.71E-05	-1.75E-05
20 cm	-2.76E-05	-2.81E-05
30 cm	-3.39E-05	-3.56E-05
40 cm	-3.53E-05	-4.11E-05

Controls on magnetic minerals and grain size distribution in a barrier enclosed estuarine lagoon (Tauranga Harbour, northeastern, New Zealand)

Firoz Badesab^{1,2}, Tilo von Dobeneck¹, Roger M. Briggs², Karin Bryan² and Janna Just¹

1. MARUM - Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Klagenfurter Strasse, 28359, Bremen, Germany
2. Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand

Manuscript for submission to New Zealand Journal of Geology and Geophysics

Abstract

Magnetic minerals are widespread in coastal and shelf environments, and contain information on sediment sources, transport and depositional processes. In complex estuarine environments with different sources of magnetic minerals and variable hydrodynamics, it is important to gain an understanding of the factors controlling their distribution and transport. The magnetic properties and grain sizes of fluvial and estuarine sediments were analyzed to characterize their sediment, distribution and transport in Tauranga Harbour, northeastern New Zealand. Titanomagnetite and titanium rich iron oxides (ilmenite / hemoilmenite) are the dominant minerals within riverine and estuarine sediments of Tauranga Harbour. The sediments from the southern basin are characterized by the highest concentration of multi-domain magnetite and titanomagnetite grains as indicated by higher values of magnetic susceptibility (χ) and saturation isothermal remanent magnetization (SIRM), while the northern basin sediments have much lower values reflecting lower magnetic mineral concentration and relatively high concentration of titanium rich iron oxide minerals. The gradual trend of increasing magnetic mineral concentration and decreasing sediment grain size in riverine sediments draining into the harbour from northwest to southeast region potentially indicate the variability in rate of sediment input, source materials and transport mechanisms. Differences in magnetic properties (concentration and grain size) and bulk sediment grain sizes of the riverine and estuarine sediments suggests that the variability in the terrigenous sediment inputs, distinct local hydrodynamics and regional topography are the major factors controlling the sediment distribution and transport in the study area.

Key words: Magnetic properties, fluvial and estuarine sediments, grain size distribution, sediment sources, transport, Tauranga Harbour, New Zealand

1. Introduction

Magnetic minerals are ubiquitous in sediments and provide valuable information regarding their source, transport and depositional environments. Changes in their composition, grain size and concentration due to various environmental processes such as transport, weathering and diagenesis will affect the magnetic properties of sediments (*Thompson and Oldfield, 1986; Verosub and Roberts, 1995; Maher and Thompson, 1999; Evans and Heller, 2003*). Magnetic measurements provide a simple, fast and non-destructive method of characterizing the sediments in terms of their mineralogy, grain size and concentration (*Thompson and Oldfield, 1986*). Therefore this method has been applied in different environments to characterize the sediment, and can provide important information on sediment provenance, sediment dynamics and post depositional processes (*Bloemendal et al., 1992; Yamazaki and Loka, 1997; Booth et al., 2005, Watkins et al., 2007; Wang et al., 2009*).

In coastal environments, estuaries are geologically and hydrodynamically complex and form a transition between riverine and open ocean environments. The fluvial systems are the major suppliers of sediments to the estuaries. They contain a complex mixture of eroded sediments from different source rocks, agricultural and farming inputs and anthropogenic materials. Various depositional environments possess different grain size distributions due to differential rate of erosion, deposition and transport processes in the basins in which the sediments have accumulated. The transport and depositional processes are in turn strongly dependent on the grain properties, including grain size and density and the prevailing local hydrodynamic conditions. Hence determination of the grain size distribution of sediments could be used to investigate the depositional environment.

Magnetic minerals are often found concentrated within fluvial systems, basins, and tidal channel networks of the estuarine environment. Due to their higher densities, Fe-Ti oxide minerals tend to concentrate as placer deposits within the estuaries. These enrichments depend on the availability of detrital heavy mineral grains and the hydrodynamically induced concentration processes including gravitational sorting and selective entrainment. Thus the variability in magnetic mineral concentration, mineralogy and grain size within an estuarine environment could provide information on the geological and hydrodynamic control on sediment distribution and transport.

The southern basin of Tauranga Harbour being New Zealand's one of the largest natural harbour and biggest export port, has been studied extensively by numerous researchers. Previous studies aimed at understanding the geomorphology, hydrodynamics and sediment dynamics within the southern basin of Tauranga Harbour (*Davies- Colley, 1976; Black, 1983; Healy, 1985; De Lange, 1991; Mathew,*

1997; Kruger and Healy, 2006; Spiers *et al.*, 2009). Recently Badesab *et al.*, 2012 studied the magnetic properties of surficial sediments from the southern basin of Tauranga Harbour and offshore Matakana Island. They identified several discrete magnetite enriched zones within the tidal channel networks and coast parallel magnetite enriched belts off Tauranga Harbour. However there is little data for the northern basin of Tauranga Harbour.

The present study attempts to analyze and compare the magnetic properties and grain size distributions of the fluvial and estuarine sediments from both north and south basins of Tauranga Harbour with an aim to provide a better understanding of the factors controlling the sediment distribution and transport.

2. Study area and Geological setting

The Tauranga Harbour is a mesotidal estuarine lagoon situated on the Bay of Plenty coast on the North Island of New Zealand (**Fig. 1**). It has an area of about 851 km² and is bounded by two Holocene barrier tombolos with Bowentown in the north, Mt Maunganui in the south and the Holocene sand barrier of Matakana Island between them. The sand barrier stretches for about 24 km parallel to the coastline. The inlets to Tauranga Harbour (Katikati entrance in the north, Tauranga entrance in the south) are dominated by tidal currents and at the southern inlet there is a mean tidal range of 1.4 m and mean annual significant wave height of 0.5 m (*De Lange, 1991, Kruger and Healy, 2006*). The Bay of Plenty coastline contains many embayments, tidal estuaries bounded by headlands and sandy beaches. The geology of Tauranga is dominated by volcanic rocks of late Pliocene to Pleistocene age and represents the transition from the Coromandel Volcanic Zone to the presently active Taupo Volcanic Zone (**Fig 2**). The rhyolitic volcanics of the Taupo Volcanic Zone (TVZ) is the major source of sediment for the Bay of Plenty region. The Tauranga Basin is mainly infilled with ignimbrites, rhyolite lavas (Minden Rhyolite), TVZ-derived tephra, andesites (Otago Volcanics and Kaimai Subgroup), and fluvial and estuarine sands and silts. The sediments of Tauranga Harbour consist of Pleistocene marine, fluvial and estuarine materials (*Beanland and Berryman, 1992*). Most of the region is covered by thick layers of tephra of late Pleistocene and Holocene age mainly derived from Taupo Volcanic Zone (*Briggs *et al.*, 1996*). The western and northern part of Tauranga Basin is dominated by Coromandel Volcanic Zone (CVZ- Miocene to Pleistocene, and 18 Ma to 1.9 Ma in age). The southern end of CVZ comprises of both andesitic and rhyolitic rocks probably in equal proportion. The phenocrysts in the andesites are plagioclase, augite, orthopyroxene, occasionally hornblende, titanomagnetite and rare ilmenite.

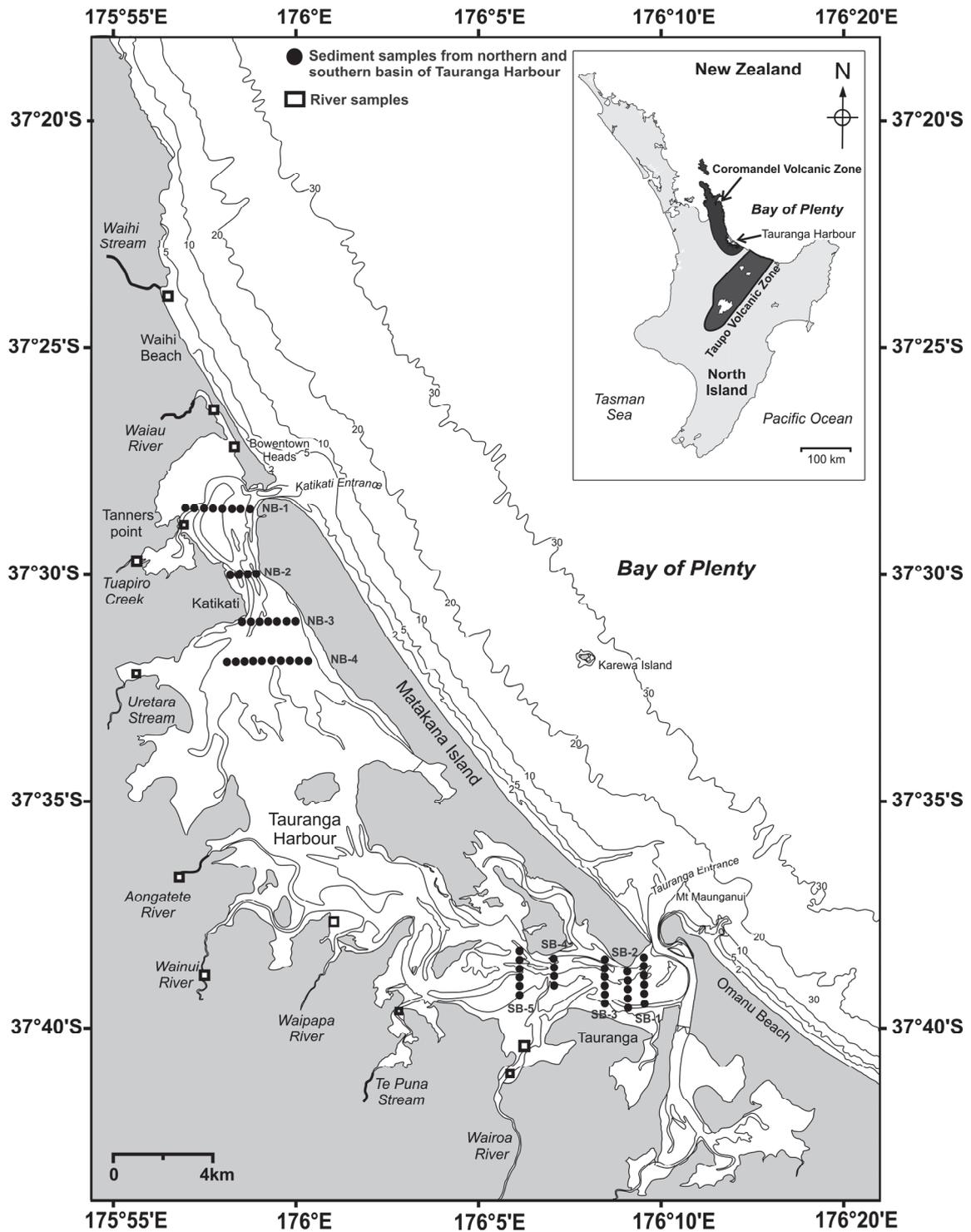


Figure 1: Location of study area and sediment sampling sites NB – 1, NB – 2, NB – 3, NB – 4 represent W –E oriented sediment sampling profiles and SB – 1, SB – 2, SB – 3, SB – 4, SB – 5 represent the N-S oriented sediment sampling profiles within Northern and Southern Basin of Tauranga Harbour.

The rhyolitic ignimbrites and lavas of CVZ contain plagioclase, quartz, orthopyroxene, biotite, hornblende, and both titanomagnetite and ilmenite approximately in equal proportions.

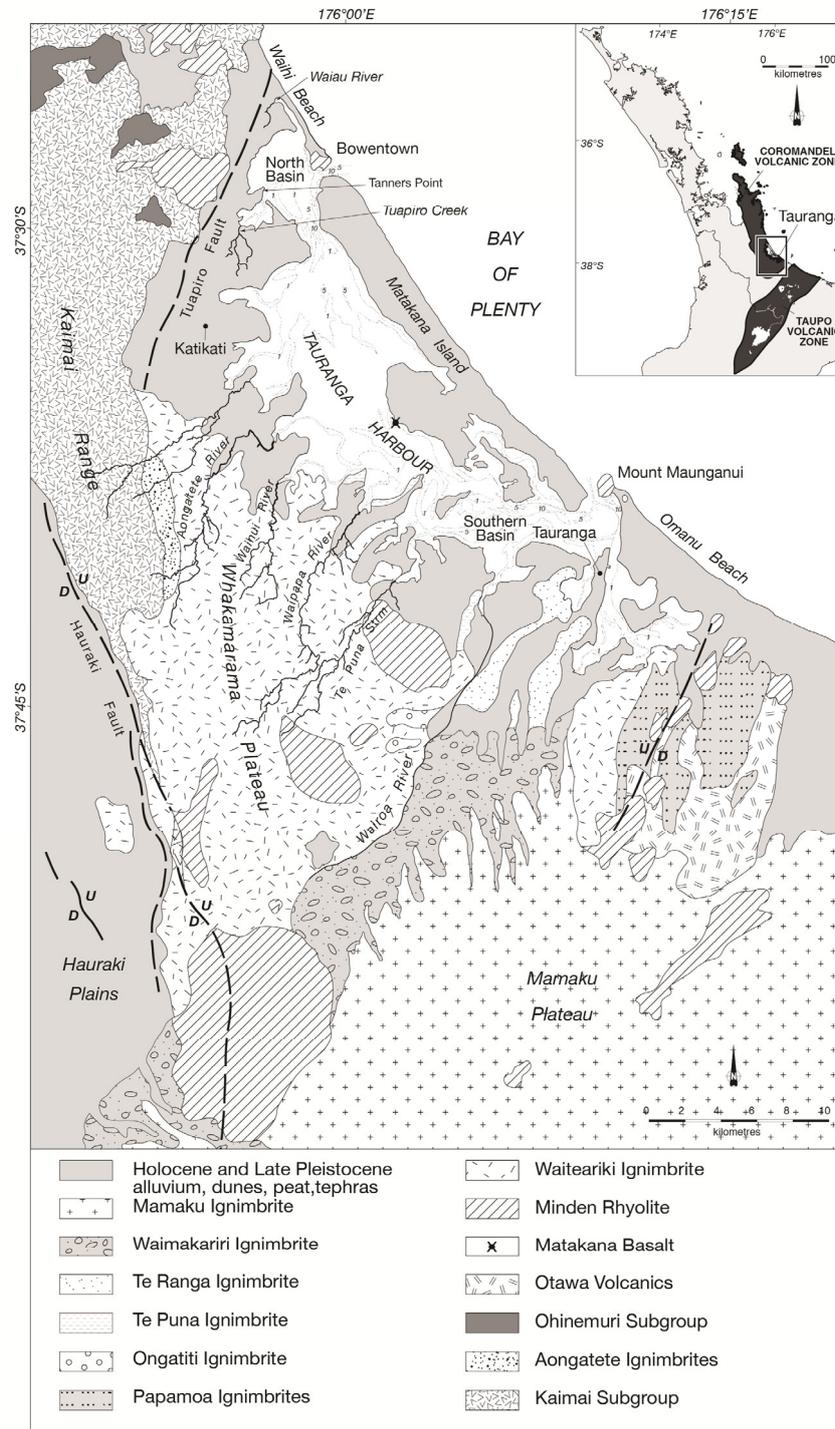


Figure 2: Geological map showing the distribution of main lithologies across Tauranga Harbour.

The eastern and southern part of Tauranga Basin and Mt Maunganui are dominated by rhyolitic volcanics and tephras, mainly derived from the TVZ and contain plagioclase, quartz, orthopyroxene,

rare augite, amphibole (hornblende, cummingtonite) and both titanomagnetite and ilmenite in approximately equal proportions (*Briggs et al.*, 1996). During the Pleistocene interglacial period, fluvial, estuarine and marine sediments were deposited in Tauranga Basin (*Davies – Colley*, 1976 and *Dahm* 1983). The majority of the sand found within the nearshore and inner shelf region outside of Tauranga Harbour are derived from relict deposits (Pleistocene) from the continental shelf which were reworked in the past, i.e. during glacial periods (*Schofield*, 1970, *Kohn and Glasby*, 1978, *Lewis and Pantin*, 1984, *Pillans and Wright*, 1992).

3. Materials and Methods

3.1. Field sampling

A total of 200 samples were collected covering different parts of Tauranga Harbour. Representative samples (n = 54) were collected from various streams and rivers flowing into the Harbour using a clean plastic handheld shovel that enabled retrieval of the top few centimetres of sediment. Estuarine (n = 153) samples from the northern and southern basin of Tauranga Harbour were collected using a Van Veen grab sampler during two separate field surveys in February 2010 and November 2012 onboard research boat *Tai Rangahau*, University of Waikato, Hamilton, New Zealand (Fig. 1).

3.2. Magnetic analyses

The sediment samples were dried at 40 °c, weighed and packed into 6.2 cm³ plastic cubes before the measurements. The low frequency magnetic susceptibility was measured at 0.4 kHz using a Bartington Instrument MS2B magnetic susceptibility meter. Anhysteretic Remanent Magnetization (ARM) was acquired in a 0.04μT dc biasing field superimposed on a peak alternating field (AF) of 100 mT and then further demagnetized in 10 different steps using 2G Enterprise 755R DC SQUID pass-through cryogenic magnetometer at the University of Bremen. Isothermal Remanent Magnetization (IRM) was imparted and remanence was measured at 20 different incremental steps 700 mT. In this study, IRM obtained at 700 mT was referred to as SIRM (saturation IRM). A reverse field of 300 mT was applied in order to calculate $HIRM = (SIRM - IRM_{-300\text{ mT}}) / 2$ and $S\text{-ratio} = (-IRM_{-300\text{ mT}}) / SIRM$

3.3. Grain size analyses of bulk samples

Grain size of bulk surficial sediment samples (riverine and estuarine) were measured using a laser particle sizer (Coulter LS 200). The analyzer categorizes grains in the range of 0.4 – 2000 μm. Samples of about 4 – 5 g were placed into 100 ml beakers into which distilled water and 300 mg of dispersing agent sodium hexametaphosphate (Na₄P₂O₇*10H₂O) was added. The beakers were left

overnight for dispersion. After ultrasonic dispersion, the samples were placed into the analyzer to measure the particle size.

3.4. Heavy liquid extraction and Scanning Electron Microscopy

The heavy minerals were extracted from representative (northern and southern basin) bulk sediment samples using the heavy liquid extraction method proposed by *Franke et al., 2007*. The extracted grains were then dried in air and spread on the carbon sticker for further SEM coupled with Energy dispersive X-ray spectroscopy analysis (EDS). The instrument used was the SUPRA TM 40 high-resolution FESEM based on third generation GEMINI column. Secondary electron (SE) imaging was used at energy levels between 5 and 15 kV. For elemental composition, the EDS (INCA – 300) attached to the instrument was used and the applied energy for this analysis was 15 kV. The elemental spectra were normalized by their oxygen values.

4. Results

4.1. Magnetic properties of riverine and estuarine sediments in Tauranga Harbour

Riverine sediments

We have used the magnetic parameters χ , SIRM and ARM to characterize the sediment samples because they are primarily sensitive to the concentration of ferrimagnetic minerals, and they also respond to magnetic grain size variations and changes in magnetic mineralogy. Magnetic susceptibility measurements on surficial sediments showed large variations between the samples from different rivers draining within Tauranga Harbour. We observed a clear trend of increasing magnetic susceptibility in riverine samples from the northwest to the southeast basins of Tauranga Harbour. The magnetic properties of major rivers flowing into Tauranga Harbour are given in Table 1. The Wairoa River sediments have the highest mean χ values, while the Waihi Stream and Waiau River sediments have the lowest, so that χ generally increases from the northwest to the southeast part of Tauranga Harbour Fig.3. SIRM and ARM values display a similar trend to χ values in the area and can be considered as an indicator of the variation of magnetite concentrations in the samples (Fig. 4b and 4c).

ARM / IRM_{100mT} is generally regarded as an indicator of magnetite grain size, which is proportional to the relative content of single domain (SD) grains (*Muxworthy and Williams, 2006*). Higher values indicate the dominance of finer magnetite grain sizes and lower values indicate coarser magnetic grain sizes. ARM / IRM ratio for river samples varies from 0.005 to 0.10. ARM / IRM ratio increases from

northwestern (Waiau River) towards southeastern part (Wairoa River) with highest / peak values in Uretara Stream, Aongatete River and Wainui River indicating the dominance of finer magnetite grains in these samples (Fig. 4d).

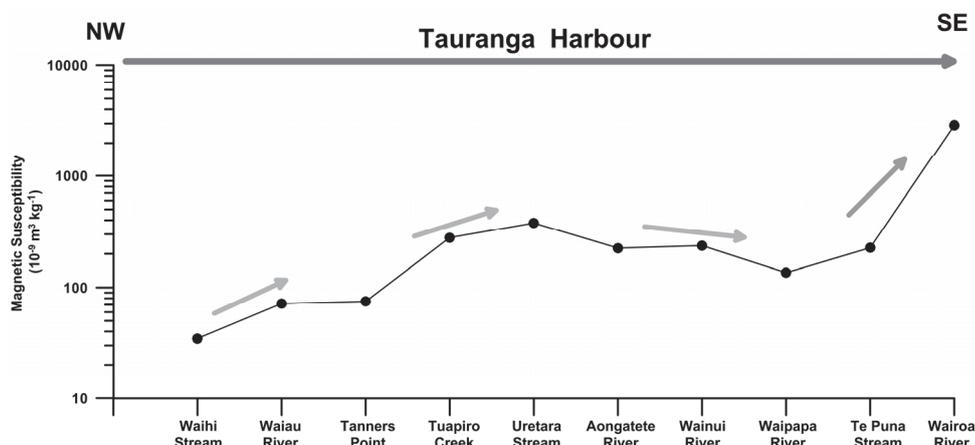


Figure 3: Variation in magnetic mineral concentration as indicated by magnetic susceptibility parameter measured on surficial sediments collected from different rivers draining into Tauranga Harbour. Please note that individual data point indicates the geo-mean values of magnetic susceptibility measurements made on five representative samples from each river.

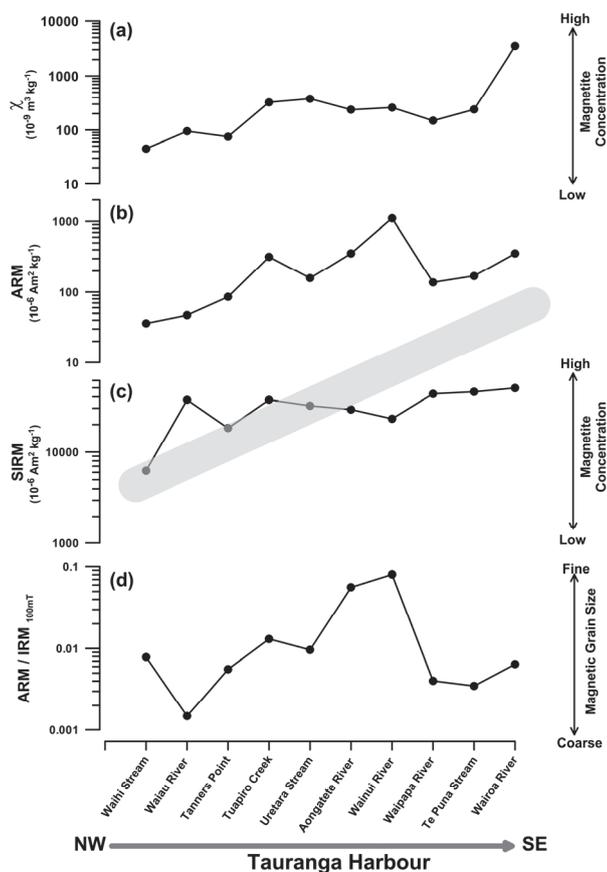


Figure 4: Variation of magnetic parameters (concentration, grain size) in riverine sediments from Tauranga Harbour.

Estuarine sediments

Fig. 5 a–d show bivariate plots between various magnetic parameters in estuarine sediments. These plots can be used to characterize the concentration, mineralogy and grain size of magnetic mineral in sediment samples. Overall within the estuarine environment, the magnetic properties of northern basin samples showed large variation compared with the southern basin (Fig. 5). For example, the highest χ ($7523.95 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$) is observed in the southern basin samples and the lowest ($106.73 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$) in the northern basin. The northern basin samples are characterized by the lowest values of χ , SIRM and S-ratio compared to the southern basin samples, indicating a lower concentration of magnetic minerals. There exists a good correlation between χ , SIRM and ARM among all the samples from southern basin, together with about (> 60%) average S-ratio, suggesting the dominance of ferrimagnetic minerals in these samples with possibly minor contribution of high coercive or titanium-rich iron minerals. (Fig. 5a, b & d). The samples from the northern basin showed lower χ and SIRM values, with equally variable S-ratio suggesting the presence of low concentration of ferrimagnetic minerals and much higher content of either high coercive or titanium-rich minerals compared to southern basin samples (Fig. 5a and 5b). There is a clear trend in ARM / IRM ratio in samples from the southern basin. Higher magnetic susceptibility values are dominated by coarser magnetic grain sizes while no such trend was visible in the samples from northern basin of Tauranga Harbour (Fig. 5c). It is interesting to note that the magnetic properties of northern basin samples are different from those in the southern basin and exhibit variability in terms of their concentration and magnetic grain size.

4.2. Grain size distribution trends in fluvial and estuarine sediments in Tauranga Harbour

Riverine sediments

Surface sediments from different rivers flowing into Tauranga Harbour vary considerably in their grain sizes ranging between 20.44 and 437.40 μm . The representative grain size curves of all the riverine samples are plotted in Fig. 6. The sediment varies from silt to very fine-medium-coarse sand. We observe a clear trend of increase in grain size of the riverine sediment flowing from the northwestern to the southeastern part of Tauranga Harbour, and Uretara Stream seems to mark a sharp boundary in grain size. The median grain sizes of each river is shown in Table 1.

Estuarine sediments

Within the estuary, the grain size distribution curves show an unimodal distribution with varying median grain sizes. The representative grain size curves of all the samples from northern and southern basin of Tauranga Harbour are shown in Fig.7. In the northern basin the median grain size

ranges from 189.20 to 230.70 μm and is mostly fine sand, whereas well sorted fine to medium to coarse sand dominates with median grain size ranging from 190.50 to 544.40 μm .

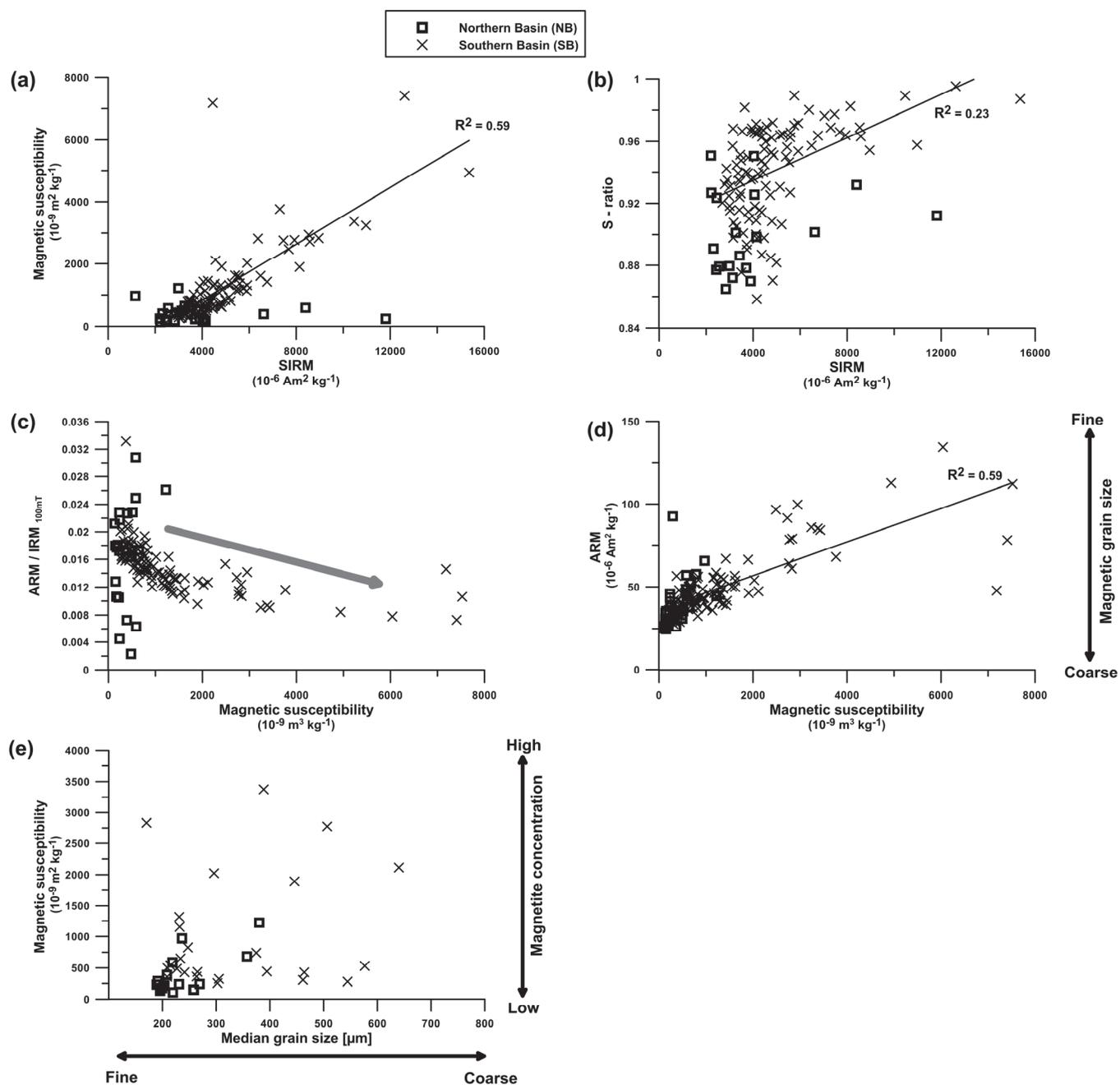


Figure 5: Bivariate scatter plots comparing the magnetic parameters and physical grain size of surficial sediments from northern and southern basin of Tauranga Harbour.

4.3. Major magnetic minerals identified from Scanning Electron Microscopy and EDS analysis

Scanning electron microscopy (SEM) in combination with energy dispersive spectrometry (EDS) were used for identification of dominant minerals in the sediment samples from both basins in Tauranga

Harbour. The SEM images and geochemical composition of selected representative minerals are shown in the Fig. 8 a-f. SEM observations with EDS analyses on heavy mineral grains showed that the most abundant heavy minerals are titanomagnetite and ilmenite. Titanomagnetite is the dominant magnetic mineral in the southern basin while ilmenite is the dominantly found in the northern basin (Fig. 8). Titanomagnetite occurred as opaque, black grains in a variety of shapes mainly rounded to sub rounded to euhedral. Some of the grains showed abrasion features, whereas other showed sharp edges.

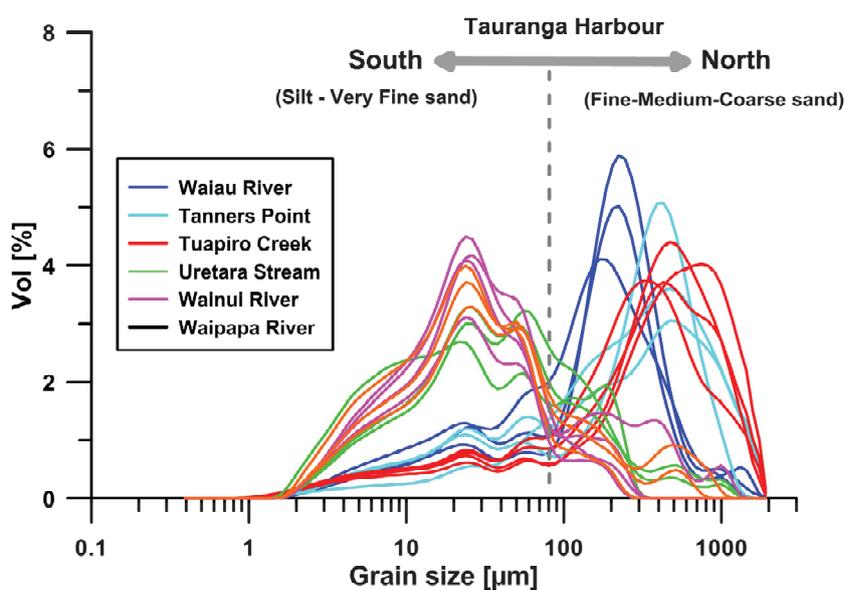


Figure 6: Grain size distribution of riverine sediments flowing into Tauranga Harbour.

5. Discussion

The sediments in an estuarine area comes from the catchments, geology and other environmental factors that affect the properties of magnetic minerals. Different magnetic parameters reflects variations in concentration and grain size of magnetic minerals in sediments. The distribution and abundance of magnetic minerals in sediments is mainly controlled by sediment sources, transport, hydrodynamics, grain size, depositional and post-depositional processes such as diagenesis and authigenesis (Thompson *and* Oldfield, 1986; Maher, 1988; Oldfield *and* Yu, 1994). Our results demonstrates the variability in spatial distribution of magnetic minerals and grain sizes in fluvial and estuarine (northern and southern basin) sediments in Tauranga Harbour and influence of all this controlling factors are discussed below.

5.1 Geological and hydrodynamic controls on magnetic properties of riverine and estuarine sediments

Magnetic properties of sediments within the study area (northern and southern basins) are different in terms of their magnetic mineral concentration and mineralogy. The values of χ , ARM and SIRM are significantly higher in the southern basin sediments than those from the northern basin. The sediments are mainly dominated by titanomagnetite, while titanium rich iron oxides dominates the northern basin with much lower concentration of titanomagnetite as confirmed by magnetic measurements and electron microscopy (Fig. 5 and Fig. 8). The bivariate plots of magnetic data help to interpret the depositional and sedimentary environment. The plots showed that a positive correlation exists between magnetic mineral concentration and magnetic grain size in all the samples of the southern basin, with highest values dominated by coarser magnetic grain sizes (Fig. 5c). In contrast, the samples from the northern basin did not show such a relationship. The rivers, tributaries and streams flowing into the northern basin are more localised and provide much lower sediment load to the basin. Although the catchment geology around this basin is dominated by andesitic rocks which are rich in titanomagnetite, there is no major river system reaching up to the host rocks in the hinterland which could bring the source material to the northern basin. The sediments in the southern basin are mainly sourced from rhyolitic volcanics and tephras, mainly derived from the rhyolitic volcanism of the Taupo Volcanic Zone (TVZ) which contains both titanomagnetite and ilmenite in approximately equal proportions (Briggs *et al.*, 1996) and the majority of the sediments are brought by Wairoa River which is the major river carrying the sedimentation load into the southern basin. Variation in magnetic properties between both the basins sediments seems to be mostly dependent on the accessibility or connection of rivers to the host rock.

The hydrodynamics in the northern basin is calmer and the majority of the sediments in the basin are marine sands brought during flood events. Healy (1980), carried out a fluorescent tracer experiment on Waihi Beach sand to examine the sediment movement along the northern inlet of Tauranga Harbour. He observed that the net littoral drift along Bay of Plenty coast is NW – SE directed and during the flood event most of the nearshore sand from Waihi Beach is transported in a SE direction and then enters the northern basin through the Katikati entrance. Thus most of the sand in the northern basins is sourced from marine environment with minor input from riverine system. Similarly previous investigations by Smale in 1993 showed that majority of the sediments in northern basin of Tauranga Harbour was sourced from the open sea with little contribution from the numerous streams and rivers draining into the basin. Most of the sediment moving out of the basin through the northern (Katikati)

entrance gets mixed with the sediments from the sea and are transported back into the basin during flood events. Studies by *Smale* (1993), showed that the concentration of ilmenite in northern basin sediments was much higher compared to titanomagnetite and mineralogical composition showed similarity with the geology of hinterland suggesting the possible source of sediments. . The sediments in this basin are mainly sourced from marine environment and it is much clear that the low energy depositional environment played a major role in accumulation of sediments. These findings support the observations of *Healy* (1980). It is also not easy to precisely quantify the sediment distribution derived from different sources (marine or riverine), since the major source of sediments to the northern basin in the past would have been mostly through riverine input, but later local hydrodynamic processes such as tides (ebb and flood) must have played a major role in transport and redistribution of sediments. Thus it is very difficult to predict if the sediments were supplied from riverine system or from marine (open sea) sources without detail understanding on the past hydrodynamic environment.

The hydrodynamics at the southern basin of Tauranga Harbour are dominated by tidal currents and waves. The sediment transport is mainly ebb directed. The two main channels in the southern basin (Western and Cutter) which merge at the southern entrance, offer a potential path for sediment transport within the harbour (**Kwoll and Winter, 2011**). Hence most of the sediments are transported out of the southern basin. The hydrodynamics in the northern basin is not very energetic compared to the southern basin, which favours sediment accumulation and deposition rather than further transport. This suggests that variability in hydrodynamics in both the basins affect the sediment distribution.

5.2 Sedimentological and Magnetic characterisation of fluvial sediments within Tauranga Harbour

Although we have demonstrated that the overall the magnetic mineralogy of the sediments is dominated by titanomagnetite, the concentration varies considerably. This possibly reflects the variation in sediment input and the transport mechanism. The sediments collected from different rivers shows differences in their grain size distribution and also a wide variability in their magnetic concentration. Overall the grain size of the fluvial sediments ranges from silt to very fine -medium-coarse sand. The sediments in the rivers (Waiiau River, Tuapiro creek and Uretara Stream) flowing into the northern basin are dominated by fine-medium-coarse sand, while the sediments in the rivers (Wainui River and Waipapa River) are dominated by silty to very fine sand (Fig. 6). This reflects the variability in rate of sediment input from these rivers.

The river sediments from the northern basin are dominated by mixed (fine –medium-coarse) grained sand while the basin sediments are mainly finer (**Fig.6 and Fig. 7**). This suggests that due to low runoff from the rivers, only the fine size grains are transported into the basin while medium and coarse grain sediment remain as accumulated sand in the river catchments. In comparison, the river sediments in the southern basin are dominated by silt to very fine sand, while medium to coarse grain sand are found in the basin. The Wairoa River is the major river flowing into the basin and provides the major sedimentation load to the basin. It drains through numerous catchments dominated by rhyolite lavas and ignimbrites. Due to its high run-off, large amount of mixed (fine-medium-coarse) grained sediments are delivered to the basin, which is then sorted under the influence of basin hydrodynamics. The silt-very fine sediments from the rivers tends to get settled and accumulates alongside the river mouths while the medium to coarse grained sand moves directly into the basin.

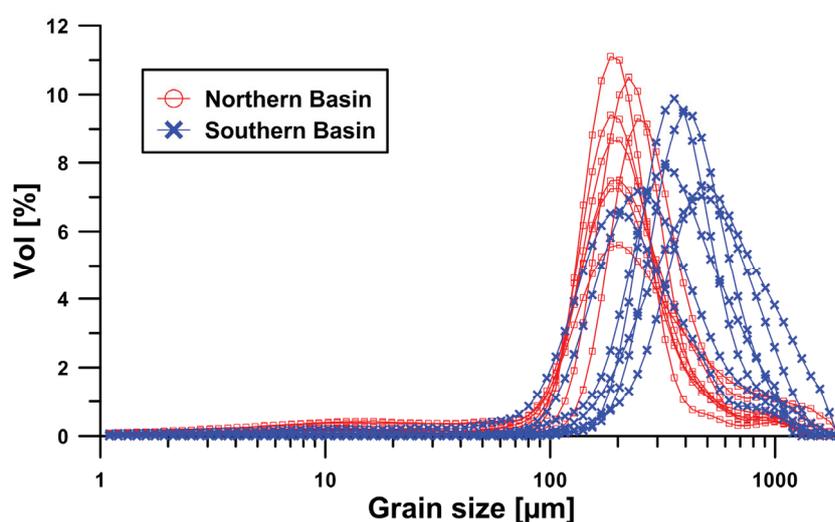


Figure 7: Comparison of grain size distribution in estuarine sediments from northern and southern basin of Tauranga Harbour.

One other possible reason for such variations in river run-offs and sediment inputs within Tauranga Harbour could be due to the topography and distribution of the river systems. Relief is much higher in the southern part compared to the northern part of Tauranga catchment area. This causes the rivers flowing into the southern basin to carry a larger sedimentation load compared to the northern basin. The concentration dependent magnetic parameters (χ , ARM, SIRM) indicates the higher concentration of magnetic minerals in Wairoa River (southern) and lowest in Waihi Stream (northern). Within the riverine systems, magnetic properties data showed a clear trend in increase in magnetic susceptibility in riverine samples from northwest to southeast region in Tauranga Harbour with lower χ , ARM and SIRM values in Waihi Stream (north) and highest values in Wairoa River sediments (Fig. 4 a, b & c).

Although we observe a trend in fining of magnetic grain size indicator parameter ($ARM / IRM_{100 \text{ mT}}$) from NW – SE in riverine sample, the magnetic minerals seems to be similar with dominance of multidomain titanomagnetite. Hence, the major differences are in their magnetic mineral concentration of bulk sediments from each river.

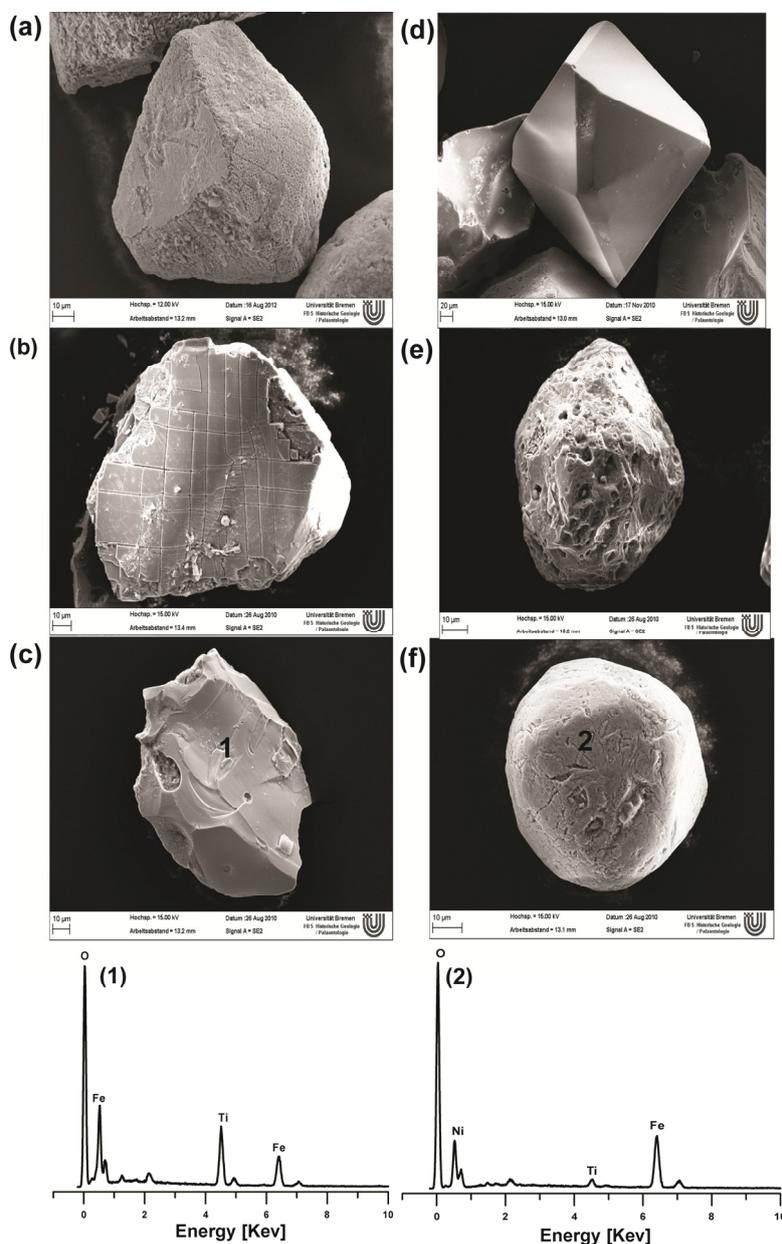


Figure 8: SEM images and EDS element spectra of heavy mineral grains extracted from surface sediments of Tauranga Harbour. (a – c) **northern basin:** titanium rich iron oxide grains possibly ilmenite / Hemoilmenite grains (d – f) **southern basin:** Iron rich oxides mainly magnetite with minor amount of titanium.

5.3. Effect of sediment grain size on magnetic susceptibility values

A plot of magnetic susceptibility versus median grain size of bulk sediment was used to examine the effect of grain size on magnetic mineral concentration (Fig. 5e). Within the northern basin, samples lower susceptibility and finer physical grain sizes ($\sim 150 - 350 \mu\text{m}$) compared to southern basin samples which have higher susceptibilities and coarser physical grain sizes (**Fig. 5c and 5e**). Magnetic susceptibility of bulk sediments seems to be decreasing with decrease in median (physical) grain size, which suggests that coarser size magnetic grains are the major carriers of the magnetic signal and the bulk sediment grain size is not an important factor affecting magnetic susceptibility values in sediments.

5.4. Influence of sediment diagenesis on magnetic properties of surficial sediments

Diagenesis of magnetic minerals is an important factor that influences the magnetic properties of sediments in estuaries and marine sediments (*Karlin and Levi, 1983; Bloemendal et al., 1992; Robert and Turner, 1993*). Various diagenetic processes tend to modify the mineralogy of the magnetic minerals after their deposition onto the sediment bed. Titanomagnetite is unstable under reducing conditions and capable of reductive dissolution under sulfidic conditions leading to transformation from ferrimagnetic to paramagnetic minerals (*Canfield and Berner, 1987; Rowan and Roberts, 2006*). In our study, we analyzed the uppermost few centimetres of surficial sediments dominated by sand. Mostly the variation in magnetic susceptibility of such surficial sands are possibly related to the major factors including terrestrial and marine sediment inputs, hydrodynamics influence and transport processes. Thus it is highly unlikely that sediments are diagenetically influenced as compared to strong reducing diagenesis which is normally observed in long sediment cores.

Conclusion

In this study the magnetic properties helped to characterize the sediments in terms of their relative concentration and grain size of magnetic minerals. Magnetic susceptibility measurements provide a sensitive tracer to measure the magnetic mineral concentration of volcanogenic sediments and track the sediment distribution within Tauranga Harbour. The results of this study on magnetic properties of riverine and estuarine sediments of Tauranga Harbour indicate that the magnetic minerals are dominated by titanomagnetite and ilmenite.

Grain size distributions reflect the occurrence of two major populations, dominance of silty to very fine sand mainly derived from riverine sources and the other by medium-coarse sand which is derived from nearshore or shelf sediments. Variability in terrigenous sediment input delivered to both the

basins through riverine systems and hydrodynamics mostly controlled the sediment distribution and transport. A strong understanding on hydrodynamics of the region is required to gain better understanding on sediment distribution and transport processes within Tauranga Harbour.

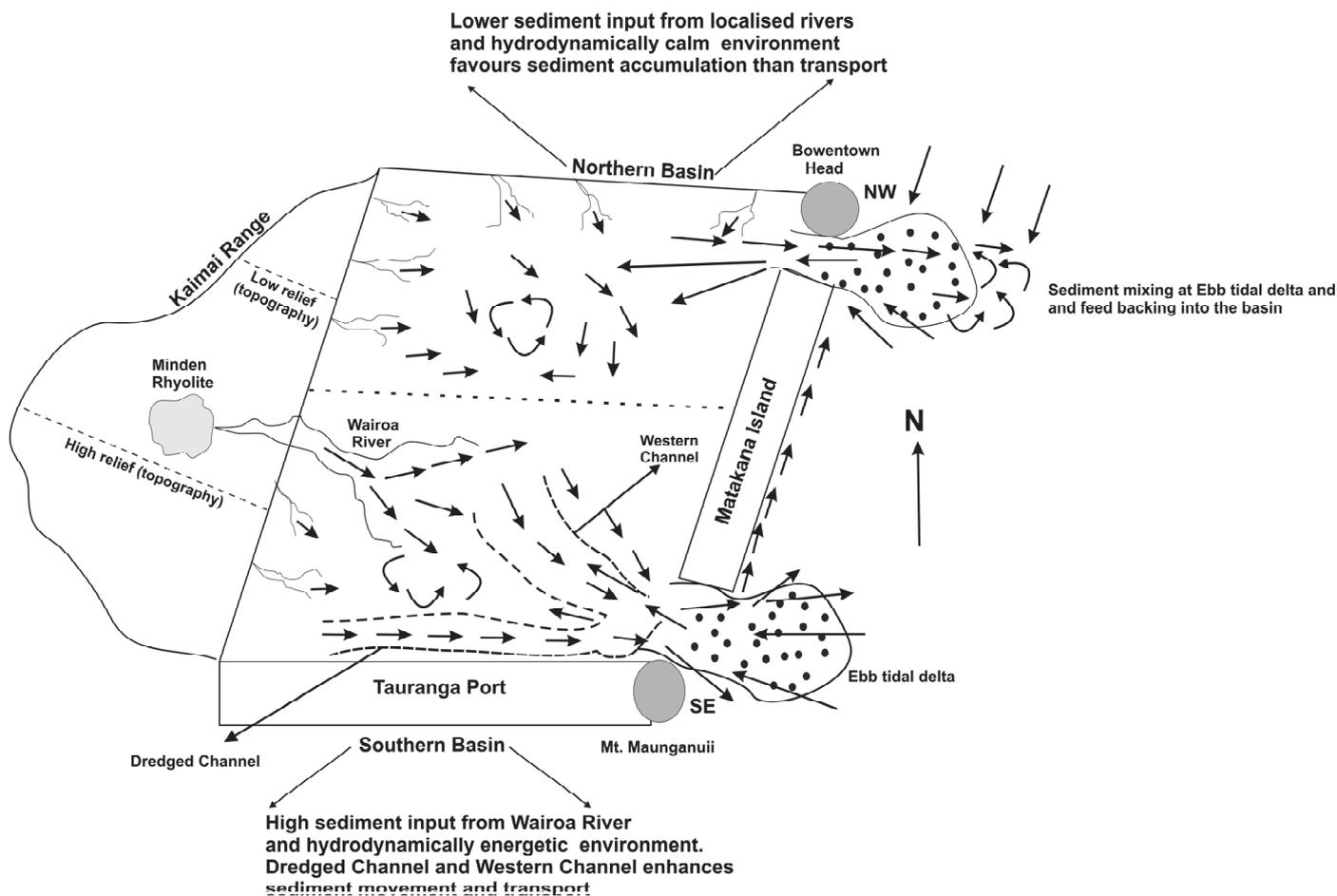


Figure 9: Conceptual diagram explaining the sediment dynamics in an estuarine environment (Tauranga Harbour).

All findings are summarized into a conceptual model (Fig. 9) explaining the sediment distribution, accumulation and transport within Tauranga Harbour. In the northern basin, lower sediment input from localised rivers and hydrodynamically calm environment favours sediment accumulation rather than transport, while in the southern basin, higher input from Wairoa River and presence of natural (Western) and artificial (dredged & entrance) channels influence the generation of highly energetic hydrodynamics which enhances the sediment movement and transport.

Acknowledgement

This work was supported by the Deutsche Forschungsgemeinschaft DFG through the International Research Training Group INTERCOAST and the MARUM Center for Marine Environmental Sciences at the University of Bremen, Germany. We are grateful to Liane Brück, Dirk Immenga, Ruggero Capperucci, Serena Fraccascia, Christopher Daly, Max Kluger, Florian Schmidt, Steffen Wiers and Sebastien Boulay for their assistance during sediment sampling surveys and sample processing in the laboratory. We thank Petra Witte and Julia Butzlaff for their support with electron microscopy. We would like to thank Annette Rodgers, Chris McKinnon and Jacinta Parenzee for providing the laboratory facilities at University of Waikato, Hamilton, New Zealand. Special thanks to Max Oulton for drawing a geological map for Tauranga Harbour. We would like to thank Janna Just, Willem de Lange and Benjamin Baasch for their helpful inputs.

References

- Badesab et al., (2012), Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, *Geochemistry, Geophysics and Geosystems.*, 13 (6),doi: 10.1029/2012GC004125.
- Beanland, S., and K. R. Berryman (1992), Holocene coastal evolution in a continental rift setting; Bay of Plenty, New Zealand, *Quat. Intl.*, 15/16, 151 – 158, doi: 10.1016/1040-6182(92)90043-2.
- Black, K. P. (1983), Sediment transport and tidal inlet hydraulics, PhD thesis, Dep. of Earth. and Ocean Sciences., Univ. of Waikato, Hamilton, New Zealand.
- Briggs et al., (1996), Geology of Tauranga area, Occasional report 22, Department of Earth Sciences, University of Waikato, Hamilton, New Zealand.
- Briggs et al (2005), Ar⁴⁰ / Ar³⁹ ages of silicic volcanic rocks in the Tauranga- Kaimai area, New Zealand: dating the transition between volcanism in the Coromandel Arc and the Taupo Volcanic Zone, *New Zealand Journal of Geology and Geophysics*, 48, 459 – 469.
- Booth, C.A., Walden, J., Neal, A., Smith, J.P (2005), Use of mineral magnetic concentration data as particle size proxy : a case study using marine , estuarine and fluvial sediments in the Carmarthen Bay area, South Wales, U.K. *Sci. Total Environ.* 347, 241-253.

Bloemendal, J., King, J. W., Hall, F.R., Doh, S.J., 1992. Rockmagnetism of Late Neogene and Pleistocene deep-sea sediments: Relationship to sediment source, diagenetic processes, and sediment lithology. *J. Geophys. Res.* 97, 4361 – 4375.

Canfield, D.E., and Berner R.A (1987), Dissolution and pyritization of magnetite in anoxic marine sediments. *Geochim. Cosmochim Acta*, 51, 645 – 659.

Dahm, (1983), The geomorphic development bathymetric stability and sediment dynamics of Tauranga Harbour. University of Waikato, Hamilton, New Zealand, Master Thesis, 230 pp.

Davies-Colley (1976), Sediment dynamics of Tauranga Harbour, M.S. thesis, Dept of Earth and Ocean Sciences, Univ. of Waikato, Hamilton, New Zealand.

De Lange, W. P. (1991), Wave climate for No 1 Reach, Port of Tauranga, Tauranga Harbour, Report to Port of Tauranga Ltd, Hamilton, New Zealand.

Evans, M.E, and Heller, F., (2003), Environmental Magnetism: Principles and Applications of Environmagnetics. Academic Press, San Diego, 299 pp.

Healy, T. R. (1985), Tauranga Harbour Study, Parts II and IV, Field Data Collection Programme and Morphological Study: A report to the Bay of Plenty Harbour Board, New Zealand.

Karlin, R., and Levi, S (1983), Diagenesis of magnetic minerals in recent hemipelagic sediments. *Nature*, 303, 327 – 330.

Kohn, B.P and Glasby, G.P (1978), Tephra distribution and sedimentation rates in the Bay of Plenty, New Zealand, *New Zealand Journal of Geology and Geophysics*, 21(1), 49 – 70.

Kruger, J., and T. R. Healy (2006), Mapping the morphology of dredged ebb tidal delta, Tauranga Harbour, New Zealand, *J. Coast. Res.*, 2, 720–727.

Kwoll, E., and Winter, C (2011), Determination of initial grain size distribution in a tidal inlet by means of numerical modelling, *J. Coastal. Res.*, 64, 1081 – 1085.

Lewis K.B., and Pantin, H.M (1984), Intersection of a marginal basin with a continent: structure and sediments of the Bay of Plenty, New Zealand, *Geological Society , London, Special Publication, 16(1)*, 121 – 135.

Maher, B. A. (1988), Magnetic properties of some synthetic sub-micron magnetites, *Geophys. J.*, *94*, 83–96, doi: 10.1111/j.1365-246X.1988.tb03429.x.

Maher, B. A., R. Thompson, and M. W. Hounslow (1999), *Introduction to Quaternary Climates, Environments and Magnetism*, Cambridge Univ. Press, U.K.

Mathew J (1997), Morphologic changes of tidal deltas and an inner shelf dump ground from large scale dredging and dumping , Tauranga, New Zealand, Hamilton, University of Waikato , Doctoral Thesis, 345p.

Muxworthy, A. R., and W. Williams (2006), Low-temperature viscous magnetization of multidomain magnetite: Evidence for disaccommodation contribution, *J. Magn. Magn. Mater.*, *307*, 113–119, doi: 10.1016/j.jmmm.2006.03.052.

Oldfield, F., and L. Yu (1994), The influence of particle size variations on the magnetic properties of sediments from the north-eastern Irish Sea, *Sedimentology*, *41*, 1093–1108,doi:10.1111/j.1365-3091-1994.tb01443.x.

Pillans, B.J, and Wright I.C (1992), Late Quaternary Tephrostratigraphy from the southern Havre Trough – Bay of Plenty, northeast, New Zealand, *New Zealand Journal of Geology and Geophysics*, *35(2)*, 129 - 143.

Robert, A.P and Turner, G.M (1983), Diagenetic formation of ferrimagnetic iron sulphide minerals in rapidly deposited marine sediments, South Island, New Zealand, *Earth. Planet. Sci. Lett.*, *115*, 257 – 273.

Rowan, C.J., and Roberts A.P (2006), Magnetite dissolution, diachronous greigite formation and secondary magnetization from pyrite oxidation: unravelling complex magnetizations in Neogene marine sediments from New Zealand, *Earth. Planet. Sci. Lett.*, *241*, 119 – 137.

Schofield, J.C (1970), Coastal sands of Northland and Auckland, *New Zealand Journal of Geology and Geophysics*, 13(3), 767 – 824.

Smale, D (1993), Sediment source and movement in Tauranga Harbour and nearshore Bay of Plenty, Institute of Geological and Nuclear Science Report 93/25.

Spiers, K., T. R. Healy, and C. Winter (2009), Ebb-jet dynamics and transient eddy formation at Tauranga Harbour: Implications for entrance channel shoaling, *J. Coast. Res.*, 25, 234–247.

Thompson R., and F. Oldfield (1986), *Environmental Magnetism*, 227 pp., Allen and Unwin, London.

Verosub, K.L., Roberts, A.P., 1995. Environmental magnetism: past, present and future, *J. Geophys Res*, 100, 2175 – 2192.

Wang, Y.H., Yu, Z.G., Li, G.X., Oguchi, T., He, H.J., Shen, H.T (2009), Discrimination in magnetic properties of different-sized sediments from the Changjiang and Huanghe Estuaries of China and its implication for provenance of sediment on the shelf, *Mar. Geol*, 260, 121 – 129.

Watkins, S.J., Maher B.A., Bigg, G.R (2007). Ocean circulation at the Last Glacial Maximum; a combined modelling and magnetic proxy-based study. *Paleoceanography* 22.

Yamazaki T., Loka, N (1997), Environmental rock-magnetism of pelagic clay: implications for Asian eolian input to the North Pacific since the Pliocene. *Paleoceanography* 12, 111-124.

5. Conclusions and perspectives for future research

The major objective of the thesis was to develop the potential of environmental magnetic studies in understanding the coastal zone processes. The distribution, transport and deposition of heavy minerals within estuarine and open coast region of Tauranga Harbour is controlled by variable hydrodynamics in the region and more complex. Within estuary, tides (ebb & flow) and residual currents manages the overall sediment movement, while waves, currents (longshore and crossshore) controls the sediment dynamics on the open coast. In this study, we applied environmental magnetics in combination with sedimentological, hydrodynamic numerical modelling to examine the underlying hydro and sediment dynamics within this lagoonal setting of Tauranga Harbour. Magnetic measurements on the surficial sediments helped to detect the magnetite enriched zones in and off (nearshore and inner shelf) Tauranga Harbour. We made an attempt to examine the link between the distribution of heavy (magnetic) minerals and underlying hydrodynamics. The trends in cross-shore and alongshore distributions of magnetic mineral concentration, magnetic grain size and physical grain size off Tauranga Harbour helped to reconstruct the hydrodynamics of the region including sediment transport paths (direction), surf zone processes and littoral drift system.

The transport dynamics of heavy mineral grains in a range of depositional environment has been studied by combining environmental magnetic studies and 3D numerical models. It is well known that the differences in densities and grain sizes of mineral grains create differential rates of movement and settling of sediments. Our work is based on the hypothesis that the difference in the mean grain sizes of light and heavy minerals (offset) reflects the individual grain settling behaviour, hydrodynamic and depositional environment. The offset was calculated following Stokes law (refer chapter – 3). The magnetic grain size distributions were derived by measuring the magnetic mineral concentration of each sieved fraction within bulk sediment distribution (refer chapter-3). The offset between this two (light and magnetic) mineral distribution calculated for samples from range of depositional environments provided information on the entrainment and transport dynamics of the grains.

The present study has demonstrated the potential of environmental magnetics to reveal and differentiate magnetite enrichment patterns and investigate the formative mechanisms in coastal systems. Although some of the factors controlling the enrichment of heavy (magnetite) minerals at grain scale level have been examined in this work, however the role of several other factors such as morphology, varying rate of sediment inputs influencing distribution and enrichment of heavy minerals in lagoons and coastal systems is not clearly understood and needs to be investigated in

detail. Our approach of using environmental magnetic methods for coastal studies has limitations and can be only be successfully used in sedimentary environments dominated by magnetic minerals (magnetite).

The significance of various parameters used in this study is discussed below:

5.1.1 Environmental magnetic parameters (magnetic mineral concentration and grain size).

Bulk magnetic susceptibility and remanence measurements on surficial sediments revealed the existence of magnetite enriched zones in the study area as discussed in detail in chapter 2. Heavy (magnetic & non-magnetic) minerals represents key indicators of the sedimentary regime and energy conditions of the environments. The link between the magnetic susceptibility and depositional environment is explored. The cross-shore and alongshore variability in magnetic mineral concentration and grain sizes off Tauranga Harbour provides clues on the sediment transport and depositional patterns along the coast. For example alongshore decrease in magnetite concentration away from southern inlet indicates the direction shore parallel transport of sediments along Matakana Coast. A cross-shore decrease in magnetic concentration and grain sizes highlights the importance of the interplay between the local hydrodynamics (surf zone and littoral drift), morphology of the coast and variability in sediment composition (modern or relict sand). The enrichment of magnetite within tidal channel network of Tauranga Harbour suggests that processes concentrating the heavy (magnetic) minerals were mainly controlled by local hydrodynamics (tide induced residual currents). Over all the magnetic parameters utilized in the study increased our understanding on the underlying hydro-sediment dynamics in the region.

5.1.2 Sediment grain size distribution patterns and local hydrodynamics

The grain size distribution characteristics provide information on the sediment types and transport processes. The two different patterns in crossshore and alongshore distribution of sediment grain sizes off Tauranga Harbour highlights the complexity in sediment dynamics induced by combined action of waves and tidal currents and variability in sediment inputs. Shift in sediment grain sizes from fine to medium-coarse grained and decrease in volume of fine sand in crossshore and alongshore directions suggests that periodic changes in wave direction, coastal morphology and bi-directional drift controlled the sediment distribution. The fine sand in the nearshore region (inner belt) represents the modern sand delivered to the coast through northern and southern inlet of Tauranga Harbour. While the medium-coarse grained sand in the inner shelf (outer belt) indicative of the relict sand which were reworked during post-glacial sea level transgression (chapter-2). The coast parallel transport of fine

sand in the nearshore region in combination with highly energetic surf zone processes and reworking of relict sand in the inner shelf resulted in the formation of this magnetite enrichment belts off Tauranga Harbour.

5.1.3 Significance of magnetic and non magnetic grain size distributions and their offsets

Several researchers in the past (*Pettijohn, 1949; Inman, 1949, Bagnold, 1956; Sindowski, 1958*) has utilized the grain size distribution from range of environments to relate it to the depositional processes. In the present study we used the novel approach to derive the magnetite distribution curves from the bulk sediment distribution by performing simple magnetic (concentration) measurements on the each of the sieved fraction. Grain size distributions of bulk sediments and magnetite plotted on log probability scale (*Visher, 1969*), increased our understanding on grain, entrainment, transport (traction, saltation, suspension) and enrichment in various depositional environments. Higher offsets in grain sizes between light and heavy minerals increased the rate of settling of heavy minerals, while the lighter minerals are transported much further into the flow. This resulted in quick deposition of heavy minerals forming enriched zones. Interpretation of grain size distribution curves from range of depositional environments elucidated that the enrichment of magnetite was controlled by two major factors a) proximity of the source, (b) hydrodynamics of the environment. At river mouth, enrichment of magnetite was found to be higher due to higher influx of sediments and low energy environment. The lower velocity in the fluid flows increases the difference in settling of light and heavy minerals, which inturn results in quick settling of heavy mineral fraction on to the bed, compared to the lighter fraction, which further leads to accumulation of heavy minerals into appreciable quantity onto the sediment bed.

5.1.4 Flume tank numerical modelling and its implications for grain entrainment, transport and deposition

The necessary condition for enrichment of magnetite in coastal environments depends on the selective sorting at the grain scale by density and size. The differential entrainment, transport and suspension, mechanism could produce the different patterns of heavy mineral enrichments in wide range of depositional environments. A detail understanding on the processes concentrating the heavy minerals is prerequisite for further quantification of the placer deposits. Previous studies mainly explained the formation mechanism of the placer minerals based only on the differences in the densities of various minerals. The chapter 3 reviews the concentrating processes of heavy minerals in grain scale. The numerical flume tank experimental model was run to quantify the influence of flow velocities on

numerical “sediment” bed in terms of density, grain sizes (offset), and light and magnetic mineral concentration on selective entrainment. The influence of variable fluid flow on grain scale processes in various depositional environments has been accessed. Model results showed that offsets between the grains sizes of light and heavy minerals play an important role in concentrating the heavy minerals onto the bed. Heavy mineral grains being denser and finer have the tendency to settled down much more quickly and hide within the interstices of the bed, while the larger light mineral grains are selectively washed out by entrainment. It was also observed that the lower velocities of the fluid flow enhances the differential rate of transport of light and heavy minerals allowing the higher settling of heavier grains onto the bed. In beach environment (Matakana beach), for example in the sediment bed composed of sediments of equivalent grain sizes i.e zero offsets is more stable and experience negligible amount of erosion. This finding was supported by the model results (chapter-3). The transport rates calculated for heavy and light mineral grains for the beds consisting of variable composition of individual mineral grains with different densities and grain sizes showed that there is always a lag in the transport rates. The transport rates of magnetite decreases with increasing concentration and vice versa. The numerical modeling results increased our understanding on the factors controlling accumulation of heavy minerals in different depositional environments.

5.1.5 Future perspectives

East Coast: The next logical step task for the future research (next IC phase) will be to perform high resolution electromagnetic profiling of the estuarine, nearshore and shelf sediments in and around Tauranga Harbour to map the heavy mineral (magnetite) enriched zones. This will provide better images of the enrichment structures of the belts. Special attention has to be given to map the paleo-tidal inlets along the Matakana coast which were the major sources of heavy minerals to the Matakana Coast in the past as revealed by *Shepherd et al.*, (1997). Further work should also aim to collect the long sediment cores using vibro or gravity coring. This will help to measure the lateral variation in magnetite concentration within these enriched zones. The additional surficial sediment sampling collection inform of crossshore transects should be extended to NW (Whiritoa Beach) and SE (Papamoa Beach). This will help to precisely mark the extension of this enrichment belts (inner and outer, chapter-2) and also to characterize the littoral drift system within the Bay of Plenty region.

Moreover, additional electromagnetic surveying within the southern basin of Tauranga Harbour (tidal & dredged channels) in combination with short coring could increase our understanding on the sediment dispersion patterns within the harbour. This will help to identify and monitor the areas of accretion and erosion. Further, magnetic analyses on these short cores retrieved from dredged area will

help to detect the metal contaminated / polluted sites within the harbour which would need thorough investigation.

West Coast: The present approach of combining field based measurement and electromagnetic profiling should be extended and tested in placer dominated sedimentary environment for example, on black sand (titanomagnetite) dominated beaches situated on west coast of north island, New Zealand. This method would aid to precisely characterize the littoral drift system which plays the major role in distribution and accumulation of heavy minerals forming placers on west coast. Electromagnetic profiling on the placer rich zones would help to quantify the heavy mineral (titanomagnetite) concentration and also delineate the responsible formative mechanisms.

The coastal morphologies also play a key role in controlling the local hydrodynamics and in turn sediment distribution. In the present study, the formative mechanism of magnetite enrichment in a barrier beach (Matakana Beach) has been investigated. It will be interesting to apply the environmental magnetic techniques to investigate the magnetite enrichment and transport mechanisms in various coastal environments including embayed beaches, pocket beaches and open coast beaches.

References:

Bagnold, R. A. (1941), *Physics of blown sand and desert dunes*, Methuen and Co., London, 265p.

Moss, A. J., (1962), The physical nature of common sandy and pebbly deposits. Part II, *American Journal Science.*, 260, 337 – 373.

Pettijohn, F.J., (1949), *Sedimentary Rocks*. Harper and Bros., New York 526p.

Inman, D.L., (1949), Sorting of sediment in light of fluvial mechanics, *Journal of Sedimentary Petrology*, 19, 51-70.

Sindwoski, K. H., (1958), Diesynoptische Methode des Korntypen-Vergleiches zur Auswertung fossiler Sedimentationräume: *Geol Jahrb.*, v. 73, p.235-275.

Visher, G. S., (1969), Grain size distributions and depositional process, *Journal of Sedimentary Petrology.*, 39(3), 1074-1106.

**Appendix 1: Manuscript published in collaboration with National Institute of Oceanography,
Goa, India**

**Sea bed morphology and gas venting features in the continental slope region of Krishna –
Godavari basin, Bay of Bengal: Implications in gas – hydrate exploration, P. Dewangan,**

T. Ramprasad, M.V. Ramana, A. Mazumdar, M. Desa, F.K. Badesab (2010), *Marine and Petroleum
Geology.*, v 27, 7, 1628–1641.

Appendix 2: Papers presented at national and international conferences during the PhD tenure (Oct 2009 – Oct 2012)**Paper 1: Magnetic mineral enrichment and transport mechanisms in and off a mesotidal estuarine lagoon, northeastern, New Zealand****AGU Fall Meeting, Dec – 2012, San Francisco, USA**

Firoz Badesab^{1,2}, Tilo von Dobeneck¹, Karin Bryan², Hendrik Müller², Roger Briggs², Thomas Frederichs¹ and Ewa Kwoł¹

¹MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Germany

²Department of Earth and Ocean Sciences, University of Waikato, Hamilton, New Zealand.

Abstract

This study presents an innovative application of environmental magnetism in combination with sedimentological and numerical methods to detect magnetite enriched zones in and off a mesotidal estuarine lagoon and to investigate their formative mechanisms. Measurements of bulk magnetic susceptibility and grain sizes of surficial sediments collected in and off Tauranga Harbour revealed two areas of magnetite enrichment: (1) within the estuarine channel network of Tauranga Harbour, and (2) the shore parallel nearshore magnetite enrichment belts at water depths of 6-10 m (inner belt) and 10-20 m (outer belt). A strong link between magnetic mineral concentration and magnetic grain size, and the decrease in volume of fine sand along the shore indicates SE – NW directed sediment transport in the nearshore region. Two important mechanisms for magnetite enrichment were found. Firstly, the tide generated residual currents controlled the enrichment of magnetite within the estuarine channel network, and secondly the surf zone processes in combination with highly energetic active shore parallel sediment transport resulted in the formation of the inner belt, while the outer belt is mostly composed of medium-coarse-grained relict non-mobile sands which were reworked during post-glacial sea level transgression. In this study we have developed a new approach to analyze the total sediment grain size and magnetite distribution curves to determine the process based characteristics of each of the sediment grain size populations in response to variable energy conditions in a range of depositional environments (fluvial, riverine, estuarine, beach, marine). Magnetite distribution was calculated by measuring the magnetic mineral concentration in each of the sieved fractions. We compared the grain size and magnetite distributions to gain knowledge on hydraulic behaviour, selective entrainment, and gravitational settling of heavy minerals and lighter fractions in different energy regimes. A 3D

numerical model will be tested to investigate the influence of different flow energy regimes on entrainment, transport and deposition of magnetic and lighter mineral grains, and to interpret the observed changes in grain size and magnetite distribution curves to infer the enrichment mechanisms forming lags in a range of depositional environments. Our study provides new insights into the mechanism of magnetite enrichment in a highly dynamic coastal environment.

Paper 2: Formation of magnetite-enriched zones in a mesotidal estuarine lagoon system: An environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand, Graduate Conference, 18 Oct 2011, University of Waikato, Hamilton, New Zealand.

Firoz Badesab^{1,2}, Tilo von Dobeneck¹, Karin Bryan², Hendrik Müller², Roger Briggs², Thomas Frederichs¹ and Ewa Kwołł¹

¹MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Germany

²Department of Earth and Ocean Sciences, University of Waikato, Hamilton, New Zealand.

Abstract

This study combines environmental magnetic, sedimentological and numerical methods to identify magnetite-enriched placer-like zones and delineate the responsible mechanism for their formation in coastal environments. Magnetic susceptibility and remanence measurements on 221 surficial sediment samples collected in and off the largest bar-built tidal estuary of New Zealand revealed several discrete enrichment zones linked to tide generated bottom currents. These feed into two coast parallel magnetite-enriched shore parallel belts centred at shore distances of about 800 – 1800 and 2000 – 3500 metres, respectively. Magnetic properties data showed that (i) offshore magnetite concentrations are highest at the southern and lowest at northern inlet of Tauranga Harbour. (ii) magnetic grain size shifts from coarser to finer sizes with distance from the coast. A significant correlation was found between magnetic susceptibility and magnetic grain size for all offshore samples where higher values were associated within coarser magnetic crystal size and vice versa. The physical grain size distribution showed two different patterns: the near shore region (< 10 m depth contour) is dominated by fine sand of ~ 150 µm and far shore region (> 10 m depth contour) showed the coarser grain sizes. A two-dimensional non linear hydrodynamic numerical model was setup to evaluate the responsible sediment transport mechanism. It showed that a SE - NW drift generated by residual currents are responsible for the net sediment transport and accumulation of heavy minerals along the Bay of Plenty coast. We therefore conclude that gravitational sorting in tidal channels and in deeper near-shore drift zones rather than selective entrainment in breaker zones is causing the relative enrichment of magnetic minerals in and of this mesotidal lagoonal system. Our study sheds insights into placer deposit formation and demonstrates the eminent potential of environmental magnetics for coastal studies.

Paper 3: Sediment sorting and magnetic properties of barrier beach sediments, Northeastern New Zealand**EGU General Assembly 4 – 8 April 2011, Vienna, Austria.**Firoz Badesab^{1,2}, Hendrik Müller¹, Tilo von Dobeneck¹, Karin Bryan³, Roger Briggs³, Thomas Frederichs¹¹ Faculty of Geosciences, University of Bremen, Germany² Intercoast Graduate College, University of Bremen, Germany³ Dept of Earth and Ocean Science, University of Waikato, Hamilton, New Zealand**Abstract**

Barrier beach systems are some of the most dynamic among all coastal environments. Studies related to beach sediment sorting, transport and distribution are essential to understand their highly transient morphologies. This study presents an innovative application of environmental magnetic and sedimentological proxy parameters in combination with hydrodynamic modelling. The spatial distribution of magnetic minerals in beach sediments has been mapped and mechanisms controlling their distribution have been examined. About 90 surface sediment samples were collected seaward of a Holocene barrier beach (Matakana Island, Bay of Plenty, New Zealand) along four cross-shore profiles at depths of 4-25 m. Magnetic measurements on bulk sediment samples and sieved fractions showed that magnetic properties are dominated by MD magnetite and titanomagnetite. Magnetic mineral concentrations are highest in finest fractions and steadily decrease with larger particle sizes; <125µm fractions of the beach sediment are responsible for the majority of remanence. We hypothesize that selective settling and entrainment is primarily responsible for concentrating these magnetic and other heavy mineral grains within the finer fractions. Similar particle settling velocities of finer heavy and coarser light minerals within the investigated samples suggest that gravitational sorting played an important role. The spatial distributions of magnetic minerals showed that the concentration of magnetic minerals is high at the southern (Profiles 2 and 3) as compared to northern (Profile 1) ends of Matakana Beach. We also observed distinctive patterns of cross shore sorting with highly magnetic minerals and other dense mafic minerals enriching within the inner surf zone and lighter ones accumulating towards the seaward side. Sea bed orbital velocity calculations indicate that the zone of enhanced heavy mineral (magnetic and non-magnetic) concentration within the inner surf zone correlates well with a zone of rapidly increasing bed shear stress. The results clearly show that our integrated approach provides an effective method of characterizing the sediment distribution in a barrier beach system and can be applied elsewhere to investigate the sediment sorting processes along open coast beaches.