Complex inner shelf environments: Observations and modeling of morphodynamics and scour processes

Arthur C. Trembanis

College of William and Mary - Virginia Institute of Marine Science

Follow this and additional works at: https://scholarworks.wm.edu/etd

Part of the Oceanography Commons

Recommended Citation
https://dx.doi.org/doi:10.25773/v5-d7w8-ke49

This Dissertation is brought to you for free and open access by the Theses, Dissertations, & Master Projects at W&M ScholarWorks. It has been accepted for inclusion in Dissertations, Theses, and Masters Projects by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.
COMPLEXINNER SHELLENVIRONMENTS:
OBSERVATIONS AND MODELING OF
MORPHODYNAMICS AND SCOUR PROCESSES

A Dissertation
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Doctor of Philosophy

by
Arthur C. Trembanis
2004
APPROVAL SHEET

This dissertation is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Arthur C. Trembanis

Approved, April 2004

L. Donelson Wright, Ph.D.
Committee Chairman/Co-advisor

Carl T. Friedrichs, Ph.D.
Co-advisor

Linda Schaffner, Ph.D.

Carl H. Hobbs, Ph.D.

Terry M. Hume, Ph.D.
NIWA
Hamilton, New Zealand

Malcolm O. Green, Ph.D.
NIWA
Hamilton, New Zealand

Orrin H. Pilkey, Ph.D.
Duke University
Durham, NC
TABLE OF CONTENTS

ACKNOWLEDGEMENTS.................................................................................................................. ix
LIST OF TABLES .................................................................................................................................. xii
LIST OF FIGURES ............................................................................................................................ xiii
LIST OF VARIABLES ......................................................................................................................... xx
ABSTRACT ........................................................................................................................................ xxvi

CHAPTER 1: INNER SHELF SEDIMENTATION ............................................................................... 1
  1.1 Introduction ............................................................................................................................. 3
  1.2 Structural Organization .......................................................................................................... 7
  1.3 Background ............................................................................................................................ 10
      1.3.1 Inner Shelf Morphodynamics .......................................................................................... 10
      1.3.2 Rippled Scour Depressions ............................................................................................. 11
      1.3.4 RSD Distribution and Morphology ................................................................................ 12
      1.3.5 Formation of RSDs ......................................................................................................... 15
      1.3.6 Self-Maintenance Processes .......................................................................................... 16
      1.3.7 Nature of a Complex System ......................................................................................... 17
      1.3.8 Order, Disorder, Complexity, and Entropy ................................................................. 18
  1.4 Seabed Drag and Wave Friction Factor .................................................................................. 21
  1.5 Estimating Bed Shear Stress .................................................................................................. 25
  1.6 Ripple Dynamics .................................................................................................................... 27
  1.7 Biological Effects .................................................................................................................... 32
  1.8 Scour- Morphodynamics about Seabed Objects .................................................................. 33
  1.9 Summary ................................................................................................................................. 37

CHAPTER 2: THE ROLE OF GEOLOGY IN A COMPLEX INNER SHELF TAIRUA/PAUANUI EMBAYMENT, NEW ZEALAND ................................................................. 58
  PART ONE- FACES ANALYSIS OF A COMPLEX INNER SHELF TAIRUA/PAUANUI EMBAYMENT NEW ZEALAND................................................................. 60
### PART ONE - CASE STUDY FROM TAIRUA/PAUANUI EMBAYMENT, NEW ZEALAND

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>134</td>
</tr>
<tr>
<td>3.21</td>
<td>General and Theoretical Background</td>
<td>135</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Decomposition of Turbulence from Linear Wave Theory</td>
<td>135</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Vortex Ripples and Hummocky Bedforms</td>
<td>136</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Moveable Bed Roughness</td>
<td>137</td>
</tr>
<tr>
<td>3.3</td>
<td>The Field Site</td>
<td>138</td>
</tr>
<tr>
<td>3.4</td>
<td>Field and Analysis Methods</td>
<td>139</td>
</tr>
<tr>
<td>3.5</td>
<td>Bed Conditions and Forcings During the Field Period</td>
<td>141</td>
</tr>
<tr>
<td>3.6</td>
<td>Observed Behavior of bedforms on Rough and Smooth Surfaces</td>
<td>143</td>
</tr>
<tr>
<td>3.7</td>
<td>Direct Observations of Turbulent Friction Over Rough and Smooth Surfaces</td>
<td>145</td>
</tr>
<tr>
<td>3.8</td>
<td>Results from the Inertial Dissipation Method</td>
<td>145</td>
</tr>
<tr>
<td>3.9</td>
<td>Results from Estimating $\tilde{f}_w$ via Equation 1.16</td>
<td>147</td>
</tr>
<tr>
<td>3.10</td>
<td>Results from $w'$ Spectral Analysis and the Importance of Structured Vortices</td>
<td>148</td>
</tr>
<tr>
<td>3.11</td>
<td>Application of Linear Wave Theory (LWT) to Remove Orbital Motions from $w'$</td>
<td>150</td>
</tr>
<tr>
<td>3.12</td>
<td>Model Predictions of $k_b$, $u_{c,w}, f_w$, and $C_d$</td>
<td>152</td>
</tr>
<tr>
<td>3.12.1</td>
<td>Model Predictions of Ripple Roughness $k_b$</td>
<td>152</td>
</tr>
<tr>
<td>3.12.2</td>
<td>Results of Wave-Current and Wave Boundary Layer Model Predictions</td>
<td>154</td>
</tr>
<tr>
<td>3.12.3</td>
<td>Predicted Wave Friction Factor, $f$, Based on Ripple Models</td>
<td>155</td>
</tr>
<tr>
<td>3.12.4</td>
<td>Results from Estimating $C_f$ from the GM Model and a Simple Analytical Approach</td>
<td>155</td>
</tr>
<tr>
<td>3.13</td>
<td>Discussion</td>
<td>156</td>
</tr>
<tr>
<td>3.14</td>
<td>Conclusions</td>
<td>159</td>
</tr>
</tbody>
</table>
PART TWO- CASE STUDY FROM A RAPIDLY TRANSGRESSING BARRIER ISLAND- CEDAR ISLAND, VIRGINIA........................................... 162
3.15 Introduction.......................................................................................... 163
3.16 Site Description................................................................................... 163
3.17 Hydrodynamic Regime........................................................................ 164
3.18 Micromorphological Variability......................................................... 166
3.19 Variability of Bed Stress and Hydraulic Roughness......................... 166
3.20 Results ............................................................................................... 168
3.21 Discussion and Conclusions............................................................... 169

CHAPTER 4: SUSPENDED SEDIMENT TRANSPORT- IMPLICATIONS FOR THE DEVELOPMENT AND MAINTENANCE OF RIPPLED SCOUR DEPRESSIONS ........................................................................................................... 204
4.1 Introduction.......................................................................................... 208
4.2 Methods .............................................................................................. 211
4.2.1 Data............................................................................................... 211
4.2.2 Sorted Bedform Model .................................................................. 214
4.3 Results ............................................................................................... 215
4.3.1 Overview of Suspension Patterns................................................ 216
4.3.2 Suspension Type and Composition ............................................. 217
4.3.3 Burst-Averaged Suspension.......................................................... 220
4.3.4 Fine-Sand Suspension over the Fine-Sand Bed........................... 220
4.3.5 Coarse-Sand Suspension over Fine-Sand Bed......................... 225
4.3.6 Suspension over the RSD ............................................................. 226
4.4 Sorted Bedform Model Test Cases..................................................... 229
4.5 Discussion .......................................................................................... 229
4.5.1 Inhibited Deposition of Fine Sands on Coarse Beds................... 229
4.5.2 Self-organization of Bedforms ..................................................... 235
4.6 Conclusions ...................................................................................... 237

CHAPTER 5: DEVELOPMENT AND ANALYSIS OF AN EMPIRICAL MODEL FOR
SCOUR RELATED BURIAL OF SEABED OBJECTS ........................................ 261

PART ONE- FORECASTING MINE BURIAL- MODEL DEVELOPMENT AND CASE STUDY FROM INDIAN ROCKS BEACH, FLORIDA ...... 264

5.1 Introduction ...................................................................................... 265
5.2 Motivation/Background .................................................................... 265
5.3 Wave Model .................................................................................... 266
5.4 Study Site ......................................................................................... 266
5.5 Methods ........................................................................................... 269
5.6 Results ............................................................................................. 271
5.7 Discussion and Conclusions ............................................................. 274

PART TWO- SCOUR MODEL MODIFICATION AND ASSESSMENT- A CASE STUDY OF THE QUEEN ANNE'S REVENGE SHIPWRECK . 278

5.8 Introduction ...................................................................................... 279
5.9 Methods and Results .......................................................................... 282
  5.9.1 Field Observations ................................................................ 282
  5.9.2 Model Simulations ................................................................ 284
  5.9.3 Wave Conditions ................................................................ 286
  5.9.4 Scour Predictions ................................................................ 288
5.10 Including the Effects of Shallow Stratigraphy ................................... 289
5.11 Discussion and Conclusions ............................................................. 291

CHAPTER 6: INSIGHTS INTO THE MORPHODYNAMIC COMPLEXITY OF THE INNER SHELF ......................................................... 325

MORPHOLOGICAL COMPLEXITY OF THE INNER SHELF- A CRITICAL PHASE TRANSITION MODEL OF RSD DISTRIBUTION AND PERSISTENCE

6.1 Introduction and Motivation ............................................................. 328
6.2 Background ...................................................................................... 332
  6.2.1 Morphologic Complexity of the Inner shelf ......................... 332
  6.2.2 Lenz-Ising Model ............................................................... 333
6.3 Methods and Results ................................................................. 336
   6.3.1 Quantifying Shelf Complexity ........................................... 337
   6.3.2 Model Simulations............................................................. 340

6.4 Discussion ............................................................................... 343
   6.4.1 Implications for Other Shelf Systems .............................. 344
   6.4.2 Issues of Nomenclature................................................... 345

6.5 Conclusions ........................................................................... 347
   6.5.1 Complex Morphological Phase Transitions .................... 347
   6.5.2 Boundary Layer Characteristics .................................... 348
   6.5.3 Bed Roughness ............................................................... 349
   6.5.4 Rippled Scour Depressions .......................................... 350
   6.5.5 Scour about Seabed Objects ........................................ 352

6.6 Future Research .................................................................... 353

APPENDIX ....................................................................................... 366

LITERATURE CITED ............................................................................ 367

VITA ................................................................................................. 392
ACKNOWLEDGMENTS

This project was made possible by the tireless efforts of many of the inhabitants of Middle Earth (VIMS), human (staff), wizard (faculty), and hobbit (student) alike. I am most thankful for the exceptional support of my co-major advisors Drs. Don Wright and Carl Friedrichs. I have benefited both professionally and personally from their expertise and wisdom of all things scientific. To Don I am particularly grateful for his wizard-like wisdom and ability to slay Balrogs that would otherwise block the completion of this work. To Carl I owe my Apple addiction. Thank you for patiently enduring the numerous interruptions to your day, sometimes serious and sometimes of a lighter nature.

To Orrin Pilkey I owe my interest in coastal geology and a host of experiences and opportunities enough to fill several dissertations. Thank you for being my teacher, motivator, and my friend. Thanks for always fighting the good fight. Your uncompromising passion and commitment have been an inspiration to countless researchers and a source of consternation to coastal developers...bravo.

I am deeply indebted to Professor Andy Short at Sydney University who agreed to serve as my Fulbright Advisor and introduced me to the wonders of the Australian coastline and the dangers and rigors of the shore. If it weren’t for Andy I might not have come to VIMS to join the long and distinguished lineage of Don Wright students.

The NZ Foundation for Science Research and Technology (C01X0218), the US National Science Foundation (INT-9987936), and the Office of Naval Research (ONR-N00014-03-1-0298) funded this study. I received additional support from a VIMS fellowship and a generous grant from the Maury Award to which I am most grateful to Captain Maury Werth heir to the Matthew Fontaine Maury legacy. The committee members rendered critical reviews of this document. Dr. D.A. Cacchione is thanked for his interest in this project. I thank Rod Budd, Richard Garlick, Bob Gammisch, Wayne Reisner, Grace Battisto, John Hawken, Andy Hill and Ron Ovenden for their assistance in the field, laboratory analyses and data processing. Special thanks to Mike Stevens (NIWA Greta Point) for his expert assistance and patience with me during the post processing and filtering of the seismic data, the results speak volumes of his skills. I am grateful for the timely and generous use of the GPR data from Dr. Scott Nichol at
Auckland University. The Cedar Island pilot study was supported by the Virginia Institute of Marine Science. George Thomas and Scott Hardaway carried out the analyses of historical shoreline change. I am grateful to R. Gammisch, W. Reisner, T. Nelson, and C. Machen for assistance in the field. The Virginia Institute of Marine Science, and the Office of Naval Research supported the scour model study of the *Queen Anne's Revenge* wreck site. Appreciation for use of and assistance with the Whitehouse/Soulsby model code in this non-military extension of the model is extended to Carl Friedrichs. I also wish to thank the North Carolina Underwater Archaeology Unit and Mark Wilde-Ramsing in particular. Dr. John T. Wells, at UNC-CH is thanked for his knowledge and continued research into the dynamics of the Cape Lookout region. I also wish to acknowledge the direct and ancillary support of the Office of Naval Research, North Carolina SeaGrant, and the U.S. Army Corps of Engineers.

Thanks to Dr. Chris Vincent for assistance and guidance in the analysis of acoustic backscatter sensor data, no one knows ABS systems better.

Drs. Brad Murray and Giovanni Coco provided many thoughtful discussions on the nature of scientific modeling in general and the nature of "rippled scour depressions" in specific. The geomorphic model of sorted bedform was born out of their skill and labor I merely managed to convince then to let me run with it. Grazie mille.

Throughout the authors' graduate career, VIMS staff has been tremendously supportive and encouraging of numerous last moment flighty suggestions. Special gratitude is extended to Kevin Kiley, Gary Anderson, Newt Munson, Mary Ann Bynum, Buddy Matthews, and Tanya Utt of ITNS.

My office mate, Malcolm Scully has been a limitless source of scientific ideas and good humor. Together we have shared the agony and on limited occasion basked in the brief glory attendant with all technical programming ventures.

In a classic case of simultaneous independent discovery both Marjy Friedrichs and Rowan Lockwood must be thanked for having the vision to see the interconnections between the various projects that make up the parts of this work long before anyone else did. If not for their brilliant and logical suggestion I would have been done much much sooner. Thank you.
The arrival of Drs. Courtney K. Harris and Jesse McNinch into the Department of Physical Sciences was of great benefit to this work. They each gave generously of their time and talents. I am indebted to them both for their generosity, friendship, and willingness to be un-official committee members even if they didn’t always know it at the time.

Lawrence Carpenter and Dr. Mark Patterson proved to be limitless sources of humorous and even occasionally enlightening diversions. To Dr. Patterson I am indebted for directing me towards the Lenz-Ising model and infecting me with the LabVIEW programming bug. I am supremely grateful to him for allowing me to tinker with his robots.

Thanks to Carroll and Patty Owens for pleasurable and productive retreats spent housesitting out at Kenilware. Those stints did wonders for my progress and general psyche.

A supreme debt of gratitude is owed to a host of fellow students who generously shared their time and expertise including Katie Farnsworth, Tara Kniskern, Jennifer Miselis, David Fugate, Heidi Romine, Kate Mansfield, and Jo Gascoigne.

Thanks to the Trembanis’ and Hughes’ families for support and encouragement.

Thanks to Grandpa Simonsen for teaching me to appreciate and take ownership of my education and to Papou Trembanis who took the journey that brings me here.

Thanks to my parents, Chris and Celeste, for trips to the shore and encouraging an “insatiable curiosity” for life and learning.

Finally, mackadocious props to my amazing wife Sarah for all that you do, all that you are, and all that you mean to me.
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1 Global Rippled Scour Depression Occurrence</td>
<td>45</td>
</tr>
<tr>
<td>Table 2.1 Textural Analysis of Principle Inner Shelf Sediment Types</td>
<td>103</td>
</tr>
<tr>
<td>Table 2.2 Sub-bottom Acquisition Settings</td>
<td>115</td>
</tr>
<tr>
<td>Table 3.1 Tripod Instrument Sampling Settings</td>
<td>172</td>
</tr>
<tr>
<td>Table 3.2 Estimates of C_d and k_v</td>
<td>190</td>
</tr>
<tr>
<td>Table 3.3 Roughness Properties for Three Bed Types Cedar Island, VA</td>
<td>199</td>
</tr>
<tr>
<td>Table 4.1 Characteristics at Each Tripod Location, Tairua, New Zealand</td>
<td>239</td>
</tr>
<tr>
<td>Table 4.2 Instrument Sampling Details</td>
<td>240</td>
</tr>
<tr>
<td>Table 4.3 Suspended Sediment Behavior, Tairua, New Zealand</td>
<td>241</td>
</tr>
<tr>
<td>Table 4.4 Bedforms Observed at Mangawhai, New Zealand</td>
<td>242</td>
</tr>
<tr>
<td>Table 4.5 Self-Organizing Bedform Model Test Settings</td>
<td>258</td>
</tr>
<tr>
<td>Table 5.1 Mine Deployment Summary</td>
<td>302</td>
</tr>
<tr>
<td>Table 5.2 Summary of Observed and Modeled Mine Burial</td>
<td>306</td>
</tr>
<tr>
<td>Table 5.3 Scour Model Results</td>
<td>322</td>
</tr>
<tr>
<td>Table 5.4 Historical Shipwrecks in the Cape Lookout Region</td>
<td>324</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1 Morphodynamic corridor</td>
<td>39</td>
</tr>
<tr>
<td>Figure 1.2 Interactions among shelf processes</td>
<td>40</td>
</tr>
<tr>
<td>Figure 1.3 Components of the continental shelf</td>
<td>41</td>
</tr>
<tr>
<td>Figure 1.4 Inner shelf transport Processes</td>
<td>42</td>
</tr>
<tr>
<td>Figure 1.5 Map of field sites</td>
<td>43</td>
</tr>
<tr>
<td>Figure 1.6 Map of the East Coast showing U.S. field sites</td>
<td>44</td>
</tr>
<tr>
<td>Figure 1.7 Large Rippled Scour Depression (RSD)</td>
<td>46</td>
</tr>
<tr>
<td>Figure 1.8 Comparison plot of inner shelf profiles</td>
<td>47</td>
</tr>
<tr>
<td>Figure 1.9 Example of a completely ordered system</td>
<td>48</td>
</tr>
<tr>
<td>Figure 1.10 Example of a completely disordered system</td>
<td>49</td>
</tr>
<tr>
<td>Figure 1.11 Example of a complex system</td>
<td>50</td>
</tr>
<tr>
<td>Figure 1.12 Hypothetical complexity index profile</td>
<td>51</td>
</tr>
<tr>
<td>Figure 1.13 Spectral plot of vertical velocity component</td>
<td>52</td>
</tr>
<tr>
<td>Figure 1.14 Plot of non-dimensional ripple wavelength and steepness versus normalized wave orbital diameter</td>
<td>53</td>
</tr>
<tr>
<td>Figure 1.15 Schematic diagram of scour</td>
<td>54</td>
</tr>
<tr>
<td>Figure 1.16 Commonly observed sequence of localized scour</td>
<td>55</td>
</tr>
<tr>
<td>Figure 1.17 Differences in burial: surface area versus scour depth</td>
<td>56</td>
</tr>
<tr>
<td>Figure 1.18 Typical time development curve of scour</td>
<td>57</td>
</tr>
<tr>
<td>Figure 2.1 Photos Tairua and Pauanui beaches, Coromandel Peninsula New Zealand</td>
<td>97</td>
</tr>
<tr>
<td>Figure 2.2 Ground penetrating radar (GPR) profiles: Tairua and Pauanui barriers</td>
<td>98</td>
</tr>
</tbody>
</table>
Figure 2.3 Location of sediment samples .............................................................. 99
Figure 2.4 Adjacent sediment sample comparison ................................................ 100
Figure 2.5 Cross-plot of mean grain size and sorting ............................................ 101
Figure 2.6 Average histogram of sediment samples .......................................... 102
Figure 2.7 Map of bathymetry and sediment facies ........................................... 104
Figure 2.8 Side-scan sonar mosaics of the Tairua/Pauanui inner shelf ................ 105
Figure 2.9 Facies boundaries surrounding the large Rippled Scour Depression (RSD) ................ ................................................................. 106
Figure 2.10 Facies 3 Outcrop related Rippled Scour Depressions (RSD) ............ 107
Figure 2.11 Facies 4- Nearshore shore-normal Rippled Scour Depressions (RSD) ................................................................. 108
Figure 2.12 Facies 5- Offshore shore-parallel Rippled Scour Depression ............ 109
Figure 2.13 Facies 6- Offshore shore-oblique Rippled Scour Depression ............ 110
Figure 2.14 Conceptual diagram of Rippled Scour Depression types ................. 111
Figure 2.15 Peak flood tidal currents ................................................................. 112
Figure 2.16 Tracklines for side-scan sonar, seismic, and bathymetric surveys .... 113
Figure 2.17 Diagram of seismic equipment configuration ................................... 114
Figure 2.18 Cross-section of short-core stratigraphy ......................................... 116
Figure 2.19 Shallow core stratigraphy from site 1 ............................................. 117
Figure 2.20 Shallow core stratigraphy from site 2 ............................................. 118
Figure 2.21 Shallow core stratigraphy from site 3 ............................................. 119
Figure 2.22 Seismic line (Diagonal 2) off Tairua Beach ..................................... 120
Figure 2.23 Seismic line (Diagonal 2) off Tairua Beach with digitized reflectors .. 121
Figure 2.24  Seismic line (Seis 41) off Pauanui Beach ........................................... 122
Figure 2.25  Seismic line (Seis 41) off Pauanui Beach with digitized reflectors .... 123
Figure 2.26  Fence diagram of sub-bottom profile lines ........................................ 124
Figure 2.27  Isopach of Holocene sediment ........................................................... 125
Figure 2.28  Isopach of upper Holocene sediment ................................................ 126
Figure 2.29  Isopach of lower Holocene sediment ................................................ 127
Figure 2.30  Lateral facies adjustments producing interfingering stratigraphic
sequence ................................................................................................................ 128
Figure 3.1  Instrumented tripod deployed on the inner shelf ................................... 171
Figure 3.2  Side-scan sonar image showing Rippled Scour Depression (RSD)....... 173
Figure 3.3  Side-scan sonar and photographic images of small vortex ripples ...... 174
Figure 3.4  Position of cyclone Paula ................................................................. 175
Figure 3.5  Atmospheric and oceanographic conditions during field experiment.... 176
Figure 3.6  Rose diagrams of current vectors in the upper water column .......... 177
Figure 3.7  Smoothed time series of hourly current speeds .................................... 178
Figure 3.8  Altimetry time series ........................................................................... 179
Figure 3.9  Time series of C_d estimated from w' spectra ...................................... 180
Figure 3.10  Time series of f_w estimated via equation 1.16 .................................... 181
Figure 3.11  Power spectra of w' ........................................................................ 182
Figure 3.12  Time series of w' variance ............................................................... 183
Figure 3.13  Ripple heights as predicted from various models ............................... 184
Figure 3.14  Time series of predicted total roughness k_b ..................................... 185
Figure 3.15  Time series of predicted (a) u_\text{corr}, (b) u_\text{w}, (c) \delta_\text{w}, and (d) C_{\text{d100}} ......... 186
Figure 3.16 Time series of $f_w$ estimated via equations 1.4, 1.5, and 1.6 ............... 187
Figure 3.17 Estimates of $C_{010}$ based on application of various $k_w$ and $f_w$ formulae. 188
Figure 3.18 Bottom boundary layer features of the rough and smooth surfaces during storm conditions ................................................................. 189
Figure 3.19 Location of Cedar Island, VA ............................................................ 191
Figure 3.20 Aerial photo of Cedar Island and historical shoreline retreat rates ...... 192
Figure 3.21 Aerial photo of Cedar Island, VA showing overwash ...................... 193
Figure 3.22 Patches of lagoonal peat embedded with oyster shells ................... 194
Figure 3.23 Trackline of side-scan sonar survey ................................................. 195
Figure 3.24 Sonographs from the shoreface off Cedar Island, VA .................... 196
Figure 3.25 Sonographs from Cedar Island, VA ................................................ 197
Figure 3.26 Observed hydrodynamic conditions from Cedar Island tripod ....... 198
Figure 3.27 Bottom boundary layer characteristics estimated via the model of Grant and Madsen (1986) .................................................................. 200
Figure 3.28 Drag coefficient ($C_d$) estimated from model of Grant and Madsen, (1986) ......................................................................................... 201
Figure 3.29 Wave frictions factor ($f_w$) estimated from Swart, (1974) ............. 202
Figure 3.30 Bottom boundary layer features of surfaces encountered off Cedar Island, VA ......................................................................................... 203
Figure 4.1 Waves and currents during the experiment ......................................... 243
Figure 4.2 Three bursts of suspension data ($C_{inf}(z,t)$ from the single-frequency data inversion); different locations at the same time ................................... 244
Figure 4.3 Individual burst average concentration profile from ABS instrument . 245
Figure 4.4 Sample bursts classified by suspension type ........................................... 246
Figure 4.5 Time series of bursts classified by suspension type ................................. 247
Figure 4.6 Fine-sand reference concentration at the fine-sand bed at 22 m depth
(Alice tripod) ........................................................................................................ 248
Figure 4.7 Fine-sand reference concentration at the fine-sand bed at 15 m depth (Bud tripod) .................................................................................................................. 249
Figure 4.8 Fine-sand reference concentration at the fine-sand bed at 22 m depth (Kelly tripod) .............................................................................................. 250
Figure 4.9 $r^2$ for the fit of measured K profile (fine sand) to the constant-K model and to
the linearly increasing-K model........................................................................... 251
Figure 4.10 Cross-plot of $\beta$ and $\beta_{ku}$ ............................................................... 252
Figure 4.11 Observed and model predicted $\beta$ ..................................................... 253
Figure 4.12 Comparison of suspension dynamics over the fine-sand plain
and the RSD ........................................................................................................ 254
Figure 4.13 Comparison of suspension dynamics over the fine-sand plain and the RSD
during an observed sequence of storm, fair-weather and storm conditions .......... 255
Figure 4.14 Conceptual diagrams illustrating suspension dynamics ..................... 256
Figure 4.15 Schematic diagram illustrating variations in suspended
sediment concentrations .................................................................................... 257
Figure 4.16 Results from sorted bedform model using storm conditions ............... 259
Figure 4.17 Results from sorted bedform model using fair-weather conditions ... 260
Figure 5.1 South Korean minesweeper struck by mine, circa 1950 ......................... 294
Figure 5.2 Map of NOAA WaveWatch III model grid locations,
West-Central Florida ................................................................................................... 295

Figure 5.3 Regional geophysical survey of inner shelf Indian Rocks Beach, FL... 296

Figure 5.4 Geophysical data from the Indian Rocks Beach mine burial field site . 297

Figure 5.5 15m gridded swath bathymetry from IRB mine burial field site ......... 298

Figure 5.6 Side-scan sonar mosaic of IRB mine burial field site ...................... 299

Figure 5.7 15m gridded grain size distribution from IRB mine burial field site .... 300

Figure 5.8 Sonograph of seabed mines and quadpod from IRB mine burial field site .......................................................................................................................... 301

Figure 5.9 Comparison between observed and NOAA WW3 model significant wave height.................................................................................................................... 303

Figure 5.10 Oceanographic conditions at Indian Rocks Beach ......................... 304

Figure 5.11 Observed and modeled wave conditions at the IRB field site .......... 305

Figure 5.12 Diver photos of mine and seabed conditions during instrument recovery .......................................................................................................................... 307

Figure 5.13 Comparison between measured and modeled mine burial from second MVCO deployment 2002 ................................................................................................. 308

Figure 5.14 Sequence of hindcast/forecasts of waves and burial for IRB field site 309

Figure 5.15 Graphical user interface (GUI) front panel .................................... 310

Figure 5.16 Queen Anne’s Revenge field site .................................................... 311

Figure 5.17 Three-dimensional surface contour plot of QAR wreck site ........... 312

Figure 5.18 Side-scan sonar mosaic of QAR wreck-site .................................. 313

Figure 5.19 Scour marks associated with shipwrecks ...................................... 314

Figure 5.20 Underwater photographs of the Queen Anne's Revenge wreck site.... 315

xviii
Figure 5.21 Diagrammatic cross-section of substrates and artifact location at QAR wreck-site ................................................................. 316

Figure 5.22 Comparison of near bed orbital velocity from Linear Wave Theory (LWT) and direct measurement ................................................................. 317

Figure 5.23 Oceanographic conditions at the Queen Anne's Revenge wreck-site, Beaufort Inlet, NC under four wave conditions ......................................................... 318

Figure 5.24 Graphical user interface (GUI) of interactive scour model using observations from QAR field study ........................................................................ 319

Figure 5.25 Predicted scour depth for QAR artifacts ................................................................................................................................. 320

Figure 5.26 Variations in scour of with inclusion of resistant sediment horizon .... 321

Figure 5.27 Hypothetical sequence of events leading to present condition of the QAR wreck-site ..................................................................................... 323

Figure 6.1 Lenz-Ising model cellular interactions ............................................................................................................................. 355

Figure 6.2 Idealized morphological phase transition ............................................................................................................................. 356

Figure 6.3 Composite shelf roughness index Tairua/Pauanui New Zealand ......... 357

Figure 6.4 Shelf bathymetry Tairua/Pauanui New Zealand .................................. 358

Figure 6.5 Inner shelf complexity profile ................................................................................................................................. 359

Figure 6.6 Profile of mean roughness index ................................................................................................................................. 360

Figure 6.7 Depth dependent complexity states ............................................................................................................................. 361

Figure 6.8 Depth dependent morphologic regimes ............................................................................................................................. 362

Figure 6.9 Lenz-Ising complexity model simulations ............................................................................................................................. 363

Figure 6.10 Inner shelf morphological regime map ............................................................................................................................. 364

Figure 6.11 Diagram of various shelf processes examined ............................................................................................................................. 365
LIST OF VARIABLES

Variable

$A_m$  Empirical Coefficient

$A_1, A_2, A_3$  Empirical Coefficients

$a_w, A_w$  Wave orbital semi-excursion ($=d_w/2$)

$a_{w,\text{sig}}$  Significant wave orbital semi-excursion

$B$  Instantaneous burial depth

$B_1, B_2, B_3$  Empirical Coefficients

$B_m$  Empirical Coefficient

$B_P$  Years Before Present

$B_D$  Burst duration

$C$  Suspended sediment concentration

$C_d$  Quadratic drag coefficient

$C_{d,\text{cur}}$  Quadratic drag coefficient waves and current

$C_f$  Drag coefficient (Feddersen)

$ar{C}$  Burst averaged concentration

$C_t$  Complexity Index (standard deviation of roughness)

$C_{m}(z_0)$  Mean concentration at elevation $z_0$

$C_o$  Reference concentration

$D$  Diameter of seabed object

$d$  Grain diameter

$d_o$  Near bed wave orbital diameter ($=2^a a_w$)

$d_m$  Mean grain diameter

$d_{50}$  Median grain diameter

$e$  $2.718281828$
E_{\text{ke}} \quad \text{Turbulent kinetic energy}

\text{exp} \quad \text{exponential function (exp(x)=e^x)}

f \quad \text{Frequency (=1/T)}

f_v \quad \text{Vortex shedding frequency}

f_w \quad \text{Wave friction factor}

f' \quad \text{Skin friction wave friction factor}

\bar{f}_w \quad \text{Wave friction factor (Smyth and Hay, 2002)}

\bar{f}_w \quad \text{Friction factor relative index}

g \quad \text{Gravitational acceleration (=9.81 ms}^{-2}\text{)}

h \quad \text{Mean Water Depth}

h_b \quad \text{Local breaker water depth}

H_b \quad \text{Breaking wave height}

H_s \quad \text{Significant wave height}

i \quad \text{Index (i=1:N)}

K \quad \text{Sediment diffusivity}

K_m \quad \text{Momentum diffusivity}

k \quad \text{Wave number (=2\pi/L)}

k_b \quad \text{Total bed roughness}

k_d \quad \text{Nikuradse (Grain) roughness (=30*z_d)}

k_m \quad \text{Moveable bed roughness}

k_r \quad \text{Ripple roughness}

kBP \quad \text{Thousands of years before present}

L \quad \text{Wavelength}

N \quad \text{Limit of index value}

P \quad \text{Pressure}

P_{\text{em}} \quad \text{Empirical Coefficient}

P_{\text{atm}} \quad \text{Pressure of atmosphere}
\[ P(t) \] Instantaneous pressure
\[ q \] Sediment flux
\[ R_e \] Roughness Reynolds number
\[ r \] Range of echo bin from transducer
\[ r_{bed} \] Range from transducer to bed surface
\[ S \] Instantaneous scour depth
\[ S_{inf} \] Final (infinite time) depth of scour
\[ S_{max} \] Maximum scour depth
\[ s \] Relative sediment density
\[ S_s \] Dimensionless fluid-sediment parameter
\[ S_{so} \] Power Spectrum of velocity
\[ t \] Time
\[ T \] Wave Period
\[ T_{co} \] Spectral Average Wave Period
\[ T_p \] Peak Spectral Wave Period
\[ T(t) \] Instantaneous Wave Period
\[ T_x \] Time scale factor
\[ u \] Velocity East-West component
\[ \bar{u} \] Burst average of \( u(t) \)
\[ u' \] Turbulent velocity East-West component
\[ u_b \] Near bottom orbital velocity
\[ u_c \] Mean current velocity
\[ u(t) \] Measured instantaneous velocity East-West component
\[ u_s \] Shear velocity = \( \left( \frac{\tau}{\rho} \right)^{0.5} \)
\[ u_{scw} \] Shear velocity within wave boundary layer
\[ u_{sca} \] Shear velocity above wave boundary layer
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{rw}$</td>
<td>Wave only shear velocity?</td>
</tr>
<tr>
<td>$\vec{u}$</td>
<td>Vector of velocity</td>
</tr>
<tr>
<td>$\vec{u}_c$</td>
<td>Vector of velocity, current component</td>
</tr>
<tr>
<td>$\vec{u}_w$</td>
<td>Vector of velocity, wave component</td>
</tr>
<tr>
<td>$U_{ob}$</td>
<td>Measured near bed orbital velocity</td>
</tr>
<tr>
<td>$U_b$</td>
<td>Estimate of near bed orbital velocity from Linear Wave Theory</td>
</tr>
<tr>
<td>$U_{com}$</td>
<td>Magnitude of the combined horizontal velocity vector</td>
</tr>
<tr>
<td>$U_{crit}$</td>
<td>Critical velocity for initiation of suspension</td>
</tr>
<tr>
<td>$U_c$</td>
<td>Critical velocity for the initiation of motion</td>
</tr>
<tr>
<td>$U_{rms}$</td>
<td>Root mean square wave orbital velocity</td>
</tr>
<tr>
<td>$U_w$</td>
<td>Near bed significant wave orbital velocity</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity North-South component</td>
</tr>
<tr>
<td>$\bar{v}$</td>
<td>Burst average of $v(t)$</td>
</tr>
<tr>
<td>$v(t)$</td>
<td>Measured instantaneous velocity North-South component</td>
</tr>
<tr>
<td>$w$</td>
<td>Vertical velocity</td>
</tr>
<tr>
<td>$w'$</td>
<td>Turbulent vertical velocity</td>
</tr>
<tr>
<td>$w'_{rms}$</td>
<td>Vertical turbulence intensity due to waves</td>
</tr>
<tr>
<td>$X$</td>
<td>Slope of linear fit</td>
</tr>
<tr>
<td>$x$</td>
<td>Coordinate, East-West direction</td>
</tr>
<tr>
<td>$y$</td>
<td>Coordinate, East-West direction</td>
</tr>
<tr>
<td>$z$</td>
<td>Coordinate, vertical direction</td>
</tr>
<tr>
<td>$z_o$</td>
<td>Hydraulic roughness length ($=k_s/30$)</td>
</tr>
<tr>
<td>$z_{oc}$</td>
<td>Apparent roughness height</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Empirical coefficient</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Empirical coefficient</td>
</tr>
<tr>
<td>$\gamma_o$</td>
<td>Suspension coefficient</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$\delta t$</td>
<td>Sampling interval</td>
</tr>
<tr>
<td>$\delta_w$</td>
<td>Thickness of wave boundary layer</td>
</tr>
<tr>
<td>$\delta_{cw}$</td>
<td>Thickness of wave-current boundary layer</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Empirical constant (IDM)</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Non-dimensional parameter</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Ripple height</td>
</tr>
<tr>
<td>$\eta(t)$</td>
<td>Surface displacement</td>
</tr>
<tr>
<td>$\theta_{wc}$</td>
<td>Angle between current and wave propagation</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>Direction of mean current</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>Direction of wave propagation</td>
</tr>
<tr>
<td>$u$</td>
<td>Skin friction Shields parameter</td>
</tr>
<tr>
<td>$\theta''$</td>
<td>Skin friction Shields parameter with stress enhancement factor</td>
</tr>
<tr>
<td>$\theta'_e$</td>
<td>Critical skin friction Shields parameter</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>von Karman's constant (0.41)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Ripple wavelength</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Molecular viscosity of water</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity of water ($=\mu/\rho_w$)</td>
</tr>
<tr>
<td>$\Xi$</td>
<td>Efficiency factor</td>
</tr>
<tr>
<td>$\pi$</td>
<td>3.141592654</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Density of sediment</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Density of water</td>
</tr>
<tr>
<td>$\sigma_w$</td>
<td>Variance of wave orbital velocity</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Bed shear stress</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>Current induced shear stress</td>
</tr>
<tr>
<td>$\tau_{cw}$</td>
<td>Wave-Current induced shear stress</td>
</tr>
</tbody>
</table>

xxiv
\begin{align*}
\tau_{sw} & \quad \text{Surface wind stress} \\
\tau' & \quad \text{Skin friction} \\
\tau_{cr} & \quad \text{Critical shear stress} \\
\tau_{fl} & \quad \text{Form drag} \\
\psi' & \quad \text{Wave mobility number} \\
\phi & \quad \text{Grain size } \log_2 (\text{diameter in mm}) \\
\phi_{sw} & \quad \text{Spectral density of the } w \text{th velocity component} \\
\Omega & \quad \text{Proportionality constant} \\
\omega & \quad \text{Radian wave frequency } (=2\pi/T) \\
\omega_f & \quad \text{Fall velocity}
\end{align*}
ABSTRACT

The inner continental shelf is a complex environmental system marked by sharp variations in bed roughness. Such heterogeneous systems account for 80% of the non-rocky inner shelves worldwide. Interactions among forces (waves, tides, turbulence, and bioturbation) and roughness elements (bed forms, rocks, and anthropogenic objects) exert major controls on sedimentary processes. This study attempts to advance the knowledge and understanding of the morphodynamics of the inner shelf.

This study investigates scour and morphodynamic processes at Tairua, New Zealand; Cedar Island, Virginia; Indian Rocks Beach, Florida; and Beaufort Inlet, North Carolina. Using data from the field, the study develops new conceptual models to characterize and quantify the hydrodynamics and morphology of the seabed. The overall dataset includes side-scan sonograms, sub-bottom profiles, grain-size analyses, suspended sediment concentrations and hydrodynamic measurements.

Analysis of the morphological data yielded a six-type classification of bottom features previously termed Rippled Scour Depressions (RSDs). The observed stratigraphic signature of RSDs does not agree with the previous interpretation of their formation. Striking spatial and temporal variations in seabed roughness produce significant enhancements of hydraulic roughness and turbulence over different substrates resulting in a self-organized, feed-back system of erosion (scour), deposition, and modified bed forms. The study demonstrates that widely used ripple models inadequately predict bed form geometry and behavior, especially during storms.

Improved understanding of scour processes developed in this study leads to a new model of scour and burial of sea-bed objects such as naval mines and archaeological artifacts. When using the model to predict scour and burial, the greatest errors result from the uncertainties in the available forecasts of wave conditions. The model includes vertical variations in sediment characteristics as field observations indicate abrupt changes in substrate substantially alter the scour process.

The overall study makes substantial contributions to the general understanding of RSD behavior by tying together detailed field studies with applicable insights from the area of complexity research. A new conceptual model of complex phase-transition is developed, involving critical process factors (hydrodynamics, underlying geology, and depth), which contribute to the observed spatial complexity and temporal variability of different RSD types.

Arthur Chris Trembanis

SCHOOL OF MARINE SCIENCE

THE COLLEGE OF WILLIAM AND MARY IN VIRGINIA
COMPLEX INNER SHELF ENVIRONMENTS:
OBSERVATIONS AND MODELING OF
MORPHODYNAMICS AND SCOUR PROCESSES
CHAPTER 1

INNER SHELF SEDIMENTATION
1.1 INTRODUCTION

Spatially and temporally variable bed roughness patterns at all scales dominate many inner shelf settings worldwide, yet little is known about the morphodynamic behavior of such systems (Hume et al., 2000; Wright et al., 1999; Wright, 1995). These systems are termed complex both because they are marked by heterogeneity of sedimentary properties sensu Holland et al. (2003) and also because of marked nonlinearity between forcing and response processes (Murray and Thieler, 2004) involved in the formation and maintenance of such systems. Heterogeneous or complex sedimentary systems, such as those examined in this study, represent as much as 80% of the world’s non-rocky inner shelves (Holland et al., 2003). In order to better understand sediment assemblages on such systems, it is necessary to understand how various roughness patterns interact both with hydrodynamics and with each other over a range of spatial/temporal scales. The goal of this dissertation is to examine the morphodynamic behavior of several inner shelf systems around the globe at varying spatial/temporal scales. In order to model medium and long-term coastal behavior it is critical to understand complex bed patterns. Sites in New Zealand (Tairua Beach), Virginia (Cedar Island), Florida (Indian Rocks Beach), and North Carolina (Beaufort Inlet) with strong signals of seabed complexity offer diverse settings to examine phenomena that may operate off many other coastlines worldwide (Figure 1.5 and Figure 1.6).

This study is motivated by a need to understand the processes responsible for the development and maintenance of seabed roughness on inner shelf settings around the world. The focus is an examination of the morphodynamic and scour behavior of complex inner shelf systems from several locations around the world at various
spatial/temporal scales through the use of observations and models. In part one (Chapters 2–4), field studies from Tairua, New Zealand and Cedar Island, Virginia are used to study the effects of varying bed roughness on bottom boundary-layer turbulence, wave friction, and suspended sediment transport. This component involves understanding morphodynamic processes from spatial scales of ripples up to kilometer wide Ripple Scour Depressions (RSDs) and from temporal scales of wave/current turbulence to millennia. Additionally, the influence of underlying geology in initiating complex patterns of bed roughness is examined. The stratigraphic expression and interpretation of spatially complex facies is explored. In part two (Chapter 5) the special case of morphodynamic response due to scour processes induced by seabed objects is explored. First, an empirical model for scour processes related to cylindrical mines is developed and assessed against an intensive field study. The model results are compared against field data collected off of Indian Rocks Beach, Florida. Model sensitivity to variations of inputs including empirical coefficients, forecast errors, and bed roughness are examined with respect to the resulting effects on scour forecasts. Next, the model is modified to include a simple parameterization for the effects of vertical variation in grain size and utilized in a study of shipwreck artifacts. In Chapter 6, insights into morphodynamics and scour processes are integrated into a new complexity model for rippled scour depression behavior based on complexity theory. In addition, general conclusions are drawn from the entire study and future avenues of research are suggested.
The issue of shoreface complexity typically has been neglected in modeling efforts. Traditionally, measurements of boundary-layer processes have been made at one location and then applied to an entire system assuming spatial homogeneity. In formulating research programs, many researchers have consciously avoided field sites with complex roughness patterns (Wright et al., 1999). This study serves to show that shoreface complexity can no longer be ignored.

Insights into these processes may contribute to improved models of sediment transport on the inner shelf. The ultimate objectives are: (1) to understand the macroscopic morphology of complex inner shelves with reference to the role of underlying geology and sediment heterogeneity; (2) to characterize the mesoscale morphodynamics of persistent/self-sustaining shoreface deposits and evaluate the implications of the stratigraphic signature of such features for event-scale depositional interpretation; (3) to examine the effect of variable roughness on seabed drag coefficients, turbulent boundary layer dynamics, and several widely-used bedform models; and (4) to develop and utilize a simple model for seabed scour in predicting and explaining the behavior of seabed objects ranging from military mines to shipwreck artifacts.

Understanding the feedbacks between hydrodynamics and sediment dynamics of the inner shelf is a first step towards gaining the ability to model the medium-term and long-term behavior of dynamic coastal reaches (Carter and Woodroffe, 1994). Such knowledge is also important to the informed management of coastal systems (Hobbs,
2002; Pilkey et al., 1999). Numerous studies of inner-shelf settings around the world (Hume et al., 2000; Schwab et al., 2000; Drake, 1999; Wright et al., 1999; Riggs et al., 1998; Thieler et al., 1995; Cacchione and Drake, 1990; and Green, 1986) are advancing the stance that morphologic complexity is more the norm than the exception.

While our appreciation for the widespread existence of inner shelf complexity is growing, our knowledge of the specific morphodynamic role of inner shelf complexity is incipient (Holland et al., 2003). Recent work by Friedrichs and Wright (1998), Hume et al. (2000), Cacchione et al. (1999), and Ogsten and Sternberg (1999), amongst others indicates that variations in bed roughness are widespread and affect the bottom boundary layer thickness, vertical suspended sediment concentrations, and the bottom drag as felt by mean currents. Yet, many questions remain to be answered including: How do complex patterns of inner shelf sediments form and change? What is the role of underlying geology in developing and maintaining inner shelf complexity? How do morphologic, sedimentologic, and disturbing forces interact to maintain certain shoreface deposit patterns while others are altered? Is the concept of the shoreface profile of equilibrium applicable to a complex energetic inner shelf system? What are the stratigraphic consequences that arise from having dynamic sediment deposits in sharp contact with one another? How do sharp gradients of roughness affect turbulence and sediment transport in the field? How do complex roughness patterns affect seabed drag at various scales as felt by waves and currents? Are presently used analytical and numerical models sufficient at capturing the dynamics of bedforms and sediment transport on complex inner shelves? In what way do shelf processes interact with natural
and man-made objects resting on the seabed? Can the scour behavior of such objects be reliably estimated from simple parameterized models of turbulent scour processes?

This dissertation involves the examination of inner shelf morphodynamics at several spatial/temporal scales (Figure 1.1), the details of which will be discussed in the following chapters.

1.2 STRUCTURAL ORGANIZATION

Overall the dissertation follows a thematic and spatio-temporal progression from largest to smallest scale. Along the way, observations of geology and modern processes are utilized to test and challenge various numerical models. The first chapter is focused on introducing the inner shelf environment along with concepts of morphodynamics, sediment transport, and scour processes. Basic concepts and previous research into inner shelf sedimentation are presented along with the theoretical framework for the remainder of the study.

The second chapter examines the role of geology with respect to the formation and maintenance of spatially complex facies patterns. The first portion of Chapter two involves the analysis of sediment samples, short cores, and repeated side-scan sonar mosaics in order to quantitatively characterize, map, and classify the surface sedimentary facies at the field site. The second portion of Chapter two explores the characteristics of the subsurface sediment deposits, particularly the relationships between surficial facies patterns and the underlying geologic architecture of the inner shelf. In addition, a
conceptual sequence of Holocene deposition is suggested for the embayment to account for the diverse spatial and vertical sedimentary patterns.

The third chapter assesses the coupled morphodynamic links between mobile bedforms and bottom boundary layer hydrodynamics at two field sites marked by sharp spatial gradients in seabed roughness. In this chapter, high-resolution measurements of bottom boundary layer dynamics are used to explore the impact of variable roughness on turbulence, current, and wave friction and how variations in hydrodynamic conditions in turn affect bedform configuration. The results of the observational experiment are used to test several widely used bedform models and friction formulae. The second part of Chapter three involves the analysis of a field and numerical study conducted on the inner shelf off of Cedar Island, Virginia (Figure 1.6). At Cedar Island, the roughness variation is due in part to bedform variation as well as the spatially frequent outcropping of lagoonal mud and peat deposits. Here, the direct impact of mobile ripples and patches of exposed substrate on boundary layer characteristics are explored.

Chapter 4 builds upon the work from the previous chapter by examining the influence of variable seabed roughness on suspended sediment transport. Variations in the type, magnitude, and direction of suspended sediment transport have critical implications to the maintenance and dynamics of commonly observed ripple scour depressions. Observations from the previously presented field studies are used as the inputs to a recently developed behavioral model for sorted bedforms.
In Chapter 5, the focus is turned from rippled scour depressions to the processes and modeling of scour associated with objects lying exposed on the seafloor. In part one a simple empirical model for scour around seabed objects is introduced and evaluated with a field experiment of military mine burial off of the west coast of Florida. The sensitivity to both input conditions as well as adjustments of the model parameters are explored. The model is seen to be quite sensitive to wave parameters and grain size variability. In part two, the model is modified to include the influence of variable vertical sedimentary characteristics as were noted in Chapter 2. The modified model is then evaluated with an observational dataset collect from the site of the Queen Anne's Revenge Shipwreck (Figure 1.6).

The last chapter presents a new conceptual model for the distribution and persistence of complex self-organizing morphologic features based on analysis of roughness patterns and morphodynamic processes documented in the previous chapters. The new complexity theory for shelf morphology is developed from the Lenz-Ising statistical physics model of ferromagnetic behavior. In addition, Chapter 6 presents a summary of the entire dissertation coalescing the previous chapters into a set of interrelated insights of morphodynamics and scour behavior associated with inner shelf morphologic complexity. The combined lessons of variable bedform evolution, seabed scour, and boundary layer dynamics are woven together illustrating the advances in our understanding of these processes. Furthermore, suggestions for future research to address the large gaps still present in our understanding and modeling of these processes is also suggested.
Figure 1.2, illustrates the inter-relationships between processes examined in this study.

1.3 BACKGROUND

1.3.1 INNER SHELF MORPHODYNAMICS

The inner shelf is an important transition region for physical, biological, and geological processes, one that forms a critical link between the nearshore and the outer continental shelf. Field observations and theory refinements by numerous investigators over the past decade have significantly advanced understanding of inner shelf sediment transport processes. The inner shelf is the portion of the shelf immediately seaward of the surf zone where surface and bottom boundary layers completely overlap and waves are the dominant source of bed agitation (Figure 1.3) (Wright, 1995). The inner shelf is a morphodynamic system influenced by coupled physical, geological, chemical, and biological processes (Figure 1.4). Processes and phenomena of the inner shelf exhibit strong spatial/temporal variability, making this a complex four-dimensional region of study. Within this relatively shallow setting, frictional forces are important in connecting hydrodynamics to the behavior of seabed forms of varying scale. In a strongly bidirectional manner, the bottom boundary layer structure depends heavily on the morphology of the seabed which in turn is shaped by gradients in the hydrodynamics (Wright, 1995).
1.3.2 RIPPLED SCOUR DEPRESSIONS

Rippled scour depressions (RSDs) are patches of coarse sand and gravel supporting large ripples within depressions surmounted by adjacent beds of fine sand (Hume et al., 2003, Cacchione et al., 1984). These furrow-like patterns are distinct from sand ribbons in which the fine sand exists in a subordinate position to the coarser material (Hunter et al., 1988). Understanding the processes responsible for the formation and maintenance of these features is important for many areas of inner shelf research including modeling of sediment transport (Green et al., 2004), determining sediment budgets (Thieler et al., 2001), developing facies models (Hume et al., 2000), benthic habitat classification (Cochrane and Lafferty, 2002), predicting the fate of maritime artifacts (Trembanis and McNinch, 2003), and interpretation of the rock record (Riggs et al., 1998; Leckie, 1988).

RSDs form in complex environments such as the inner continental shelf. They generally comprise shallow depressions floored with poorly sorted coarse gravely sands supporting large long-crested symmetrical wave-generated ripples. The depressions are about 0.5 m lower than the surrounding fine sand plain (i.e. have negative relief). RSDs play an important role in nearshore hydrodynamics and sediment transport and for these reasons it is important to identify them in cores and the rock record. One of the features of RSDs that could confound paleo-environmental interpretation is the paradoxical association of the fine sand plain and mixed sand gravel facies adjacent to each other on the seabed that appear to form and coexist under the same embayment scale oceanographic conditions.
1.3.4 RSD DISTRIBUTION AND MORPHOLOGY

RSDs have been observed on many of the world’s inner shelf settings including, but not limited to, the North Aleutian Shelf (Marlow et al., 1998; Schwab and Molnia, 1987), the Gulf of Maine (Barnhardt et al., 1998), California (Eittreim et al., 2002; Hunter et al., 1988; Cacchione et al., 1984), North Carolina (Thieler et al., 2001; Reed and Wells, 2000; Riggs et al., 1998; Thieler et al., 1995; MacIntyre and Pilkey, 1969), France (Cirac et al., 2000), Puerto Rico (Schwab et al., 1996), Nova Scotia (Amos et al., 1999; Forbes and Boyd, 1986), South Africa (Flemming, 1980), New York (Schwab et al., 2000), Australia (Short 2002; Field and Roy, 1984), New Zealand (Hume et al., 2003; Trembanis et al., 2001; Hume et al., 2000; Black and Oldman, 1999; Hilton, M., 1995; Bradshaw et al., 1994; Black and Healy, 1988;), and Martha’s Vineyard, Massachusetts (Goff et al., 2003) Table 1.1. RSDs have emerged as a blanket term, first proposed by Cacchione et al. (1984). Subsequent authors (Hume et al., 2003; Thieler et al., 1995) have questioned the assumed genetic implications the name conveys; yet it persists in the literature as a general term. A host of other names have been used to describe these features including, lineations (Marlow et al., 1999), gravel ripples (Forbes and Boyd, 1986), furrows (Hunter et al., 1988), coarse-sediment bands (Black and Oldman, 1999; Hunter et al., 1988) sand ribbons (Flemming, 1980), sand cover with tears (Hume et al., 2000), bedforms (Schwab and Molnia, 1987; Swift and Ferland, 1978), and recently self-organizing sorted bedforms (Murray and Thieler, 2004). From this non-exhaustive list one can conclude that not only is there a lack consensus on the genetic processes responsible for these features but even their nomenclature is in dispute. Recently, Hume
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
genetically different types, suggesting that RSD is a loose blanket term with many distinctive subclasses.

Few long-term repeated studies of RSDs have been conducted (Murray and Thieler, 2004). Some authors have documented significant mobility of RSDs on inter-annual timescales (Goff et al., 2003; Thieler et al., 2001), while others such as Hume et al. (2003, 2000) and Hunter et al. (1988) have noted that behavior of these features is highly scale dependent, with certain smaller scale features exhibiting pronounced changes in shape and position, while larger RSD patterns were surprisingly robust, maintaining their positions (within survey accuracy) over several years (see Chapter 2 for a detailed treatment of this phenomenon).

Recently, Barnhardt et al. (1998) suggested a new mapping scheme for dealing with complex ‘patchy’ distributions of surficial facies. This new approach of using composite map units to represent small-scale variability at scales of 1:100,000 would otherwise be impossible with traditional mapping techniques. The authors were able to combine bathymetry, side-scan sonar, seismic profiles, grab samples, and cores into integrated surficial geologic maps. While their study provides a useful protocol for the identification and mapping of RSDs which were frequently encountered in the study site (inner shelf of Maine), it does not give detailed insight into the sediment dynamics responsible for the formation and behavior of these heterogeneous patterns. Yet, the ability to meaningfully map these features is a critical component in the successful modeling of sediment transport processes.
1.3.5 FORMATION OF RSDs

Various theories for the origin of RSDs have been proposed including: alongshore current derived transverse bedforms (Swift and Ferland, 1978); in situ lag deposits from localized wave induced scour (Black and Oldman, 1999; Hunter et al., 1988); storm generated downwelling currents (Cacchione et al., 1984); scour around exposed bedrock (Hume et al., 2003; Cacchione et al., 1984); rip-currents (Reimnitz, 1967); and, recently, turbulence enhanced hindered settling (Murray and Thieler, 2004; Green et al., 2004). To embrace the various scour depression types encountered in their study, Hume et al. (2003) (see Chapter 2) suggested that several of these processes in addition to storm related wave climate evolution along with underlying geology contributed in varying combinations in the formation of the facies identified.

Cacchione et al. (1984) suggested that storm generated cross-shore downwelling aided by local steering due to exposed rock ledges was responsible for the formation of the RSDs they observed. Recently, however, Murray and Thieler (2004) questioned the validity of this explanation due to the large distance between the rock outcrops and the features themselves. The authors instead argue for a self-organizing process in which slight perturbations in grain size lead to positively reinforcing feedbacks in ripple development, sediment sorting, and turbulence enhancement. Few direct measurements of hydrodynamics and sediment transport, however, have been conducted immediately on top and adjacent to scour depressions. For instance, the suggestion by Cacchione et al.
(1984) of cross-shore directed scour and suspension were inferred from measurements at 90m whereas the scour depressions themselves were observed along the 60 m isobath.

Swift and Ferland (1978) suggested that the nearly shore-normal scour depressions they found in the middle Atlantic Bight were transverse bedforms generated by alongshore currents. Cacchione et al. (1984) questioned this interpretation based on the irregular spacing of the features, their lack of asymmetry, and the fact that, unlike bedforms, these features exhibit negative rather than positive relief. Recently, Murray and Thieler (2004) further argued against the conclusions of Swift and Ferland (1978), noting that the bedform model the authors suggested provided no mechanism for the marked size sorting associated with these features.

1.3.6 SELF-MAINTENANCE PROCESSES

One of the central issues surrounding RSDs is their seeming persistence within regions of active sediment transport. Previous researchers have posited the existence of some form of a self-maintaining process at work to preserve the features (Hume et al., 2003). Early attempts to explain the maintenance of such features (Cacchione, et al., 1984; Swift and Ferland, 1978) focused on the role of bottom currents for their formation. Cacchione et al. (1984) suggested that episodic cleansing from storm induced downwelling currents served to maintain the features. Recent theories suggest that deposition of fine sand is inhibited (or reduced) over the regions of coarse sediment relative to the regions of fine sediment (Murray and Thieler, 2004; Green et al., 2004; Traykovski and Goff, 2003; and Black and Oldman, 1999). Schwab and Molnia (1987) rejected this
explanation, namely that the coarse depressed lineations of their study were maintained due to inhibited deposition over the coarse material, surrounded by regions of deposited fine sediment. They cited as evidence the absence of a source location for new fine sediment to the coast. However, the authors did not explain why new material would be required instead of a sorting process that redistributed fine and coarse material in situ. They also suggested that the features are short lived owing to the observation that few fish trawling gouges are preserved on the seabed and that in some instances distinct overlapping depressions were found. Recently, Murray et al. (2002) and Murray and Thieler (2004) have made initial attempts to model the origin and behavior of “sorted beds” similar to those found off of Wrightsville Beach using a rules based behavioral modeling approach.

Aside from acoustic mapping and scaled down laboratory modeling efforts, little is known about the combined wave-current dynamics associated with such complex features in the field (Murray and Thieler, 2004). It is likely that the distribution of the coarse beds is largely dependent upon underlying and adjacent geologic features that may have initially helped form the deposits (see Chapter 2 part 2) (Riggs et al., 1998; Thieler et al., 1995).

1.3.7 NATURE OF A COMPLEX SYSTEM

In the following chapters, the inner shelf will be referred to as morphologically “complex.” While in some cases the use of this term is synonymous for spatially heterogeneity (Chapter 2), it is also more broadly indicative of a “complex system,” one
that has many components interacting in interesting non-linear ways (Chapters 3 and 4). Researchers within the field of complexity (e.g. Axelrod and Cohen, 2001; Rasband, 1990; Bak et al., 1987) suggest that a system is complex if it possesses several of the following characteristics: 1) heterogeneity – the individual components differ significantly; 2) dynamics – the characteristics of the system change over temporal and spatial scales as the environment changes; 3) non-linearity – the dynamics that describe how the system changes over time are highly non-linear and often chaotic; 4) feedbacks – changes to the system are the result of interactive feedbacks between components; and 5) self-organization – interactions between the components develop into defined groups or structures, in-turn these structures influence how the system evolves over time.

1.3.8 ORDER, DISORDER, COMPLEXITY, AND ENTROPY

Nature abounds with both ordered and disordered systems. The order or disorder of a system can be expressed both spatially and temporally. To illustrate these concepts, imagine an idealized ordered sedimentary system in which an expansive, homogeneous, fine-sand plain lies adjacent to an uninterrupted field of coarse-sand and gravel (Figure 1.9). Other examples of ordered systems such as that shown in Figure 1.9 include the structured arrangement of water molecules within ice or the predictable rhythm of the tides. Next, imagine a totally random arrangement of sediment (Figure 1.10), perhaps the disorganized scatter of shells on the beach or the stochastic occurrence of storms. A system, such as that illustrated in Figure 1.10, would be called disordered.
Now, let us examine a system in which the arrangement of sediment is neither totally random nor completely ordered (Figure 1.11). Clearly ordered patterns of various size patches are observed nested in and amongst disordered zones. Unlike a fully ordered system, the patterns within a complex system not simply at discrete scales but rather, at many different scales. This pattern is said to be “complex.” Nature is replete with complex systems, from the organization of rainforests to the behavior of the stock-market each of which are dynamic systems that are neither completely ordered nor disordered (Sole’ and Goodwin, 2000; Rasband, 1990; Bak et al., 1987).

One final concept to introduce is that of entropy. Entropy is a measure of the disorder of a physical system. Another way to think of entropy is to equate it with diversity or heterogeneity. The entropy of a given system can be defined by means of a probabilistic description of its states. The entropy of a system is maximized when it is at its most disordered state, and thus all configurations have the same probability. Thus entropy and disorder grow in concert together. According to the Second Law of Thermodynamics, the entropy of a system will tend to increase over time unless energy is introduced in the form of work to organize the system (Sole’ and Goodwin, 2000).

The concept of entropy as applied to geomorphologic phenomena is not new. Leopold and Langbein (1962) introduced the concept of entropy into the evaluation of fluvial morphology. By extension from thermodynamics, they postulated that a geomorphologic system evolves to maximize the entropy in which the energy dissipation
rate is uniformly distributed and the system does the least amount of work Langbein and Leopold (1964).

If we consider the entropy of the idealized systems discussed above, we see that an ordered system has a low value of entropy (Figure 1.9), while a disordered system has high value of entropy (Figure 1.10). The structural arrangement of the ordered system (Figure 1.9) makes it possible to infer the pattern in adjacent parts of the system by considering only a small subset. In other words, the system is predictably regular. In a simple analogy, one could easily produce the pattern of a checkerboard having seen only a small portion of the whole.

At the other end of the entropy spectrum is a disordered system (Figure 1.10). In a highly disordered system, all of the components or the system are randomly distributed such that there is no discernable pattern. Although this pattern is random, the high entropy of the system means that the same statistical features are reproduced within various subsets of the whole. While it is not possible to infer the exact pattern from one cell to another as in the case of the ordered system, we can infer an equal distribution of possible states in a highly entropic system.

In order to meaningfully study complex systems it is necessary to utilize some established metric of complexity or develop a reasonable measurement of complexity a priori. From the discussion above it is clear that entropy is not a meaningful measure of complexity as it increases with disorder. Thus a measure of complexity by entropy alone
would suggest that the disordered system (Figure 1.10) is the most complex configuration. A properly defined metric of complexity would instead have a minimum at both the ordered (Figure 1.9) and disordered (Figure 1.10) ends of the spectrum with a maximum at some intermediate “complex” level between the two states (Figure 1.11). A hypothetical plot of complexity index versus system state (disordered/complex/ordered) is illustrated in Figure 1.12. The particular index of morphologic complexity that has been used in this study is described in Chapter 6.

1.4 SEABED DRAG AND WAVE FRICTION FACTOR

The effects of bed roughness on benthic boundary layer flow have long been recognized as important because roughness strongly influences the fluid motions close to the bed (Dade et al., 2001). Bedforms influence how the total bed shear stress, \( \tau \), is partitioned into form drag, \( \tau_{fd} \), and skin friction, \( \tau' \), responsible for sediment suspension and transport (Wright, 1995). The bed shear stress, \( \tau \), is related to a characteristic shear velocity, \( u_* \) by the formula:

\[
\frac{u_*}{u} = \left( \frac{\tau}{\rho_w u_*^2} \right)^{0.5}
\]

where \( \rho_w \) is water density (Soulsby, 1997).

In wave-current boundary layers, bed stress may be described in terms of two distinct components: the characteristic magnitude of instantaneous bed stress, \( \tau_{cw} = \rho_w u_*^2 \), and the magnitude of the wave-averaged bed stress, \( \tau_c = \rho_w u_*^2 \). The former quantity suspends sediment within the thin wave-current boundary layer just
above the bed, whereas the mean-current profile above the wave-current boundary layer responds to the wave-averaged bed stress. Bed stress is crucial not only to sediment suspension and transport but also to modulating the near-bottom currents over the inner shelf. For the case of the Middle Atlantic Bight inner shelf where surface (air-sea) and bottom boundary layers strongly overlap, Lentz et al. (1999) showed that the along shelf momentum balance is well approximated by a balance between surface wind stress, $\tau_{sw}$, and current-sensed bed stress, $\tau_{bc}$, i.e., $\tau_{sw} \approx -\tau_{bc}$. In settings where stratification is minimal, the assumptions of Lentz et al. (1999) will apply.

In the simple case of neutrally stratified steady flows in the absence of waves, the current shear velocity, $u_c$, is related to the log-layer velocity profile by the von Karman-Prandtl equation

$$u_c(z) = \frac{u_{zc}}{K} \ln \left( \frac{z}{z_{oc}} \right)$$

in which $u_c(z)$ is the mean current at height $z$, $K$ is von Karman’s constant (0.41), and $z_{oc}$ is the intercept expressing apparent roughness. In classic laboratory analyses of fully rough turbulent flow, the log-profile zero intercept, $z_o$, is related to the height, $k_b$, of the effective roughness elements by $z_o = k_b/30$. The effective roughness, $k_b$, is considered by traditional models to consist of three potentially time-varying components (e.g. Nielsen, 1983): grain roughness, $k_d$, ripple roughness, $k_r$, and movable bed roughness, $k_m$. In other words, $k_b = k_d + k_r + k_m$. Another type of more subtle large-scale roughness, hummocky bedforms, may also be important, but generally these features have not been included in predictive models for wave-current interaction. The apparent roughness, $z_{oc}$, as determined from the best fit of equation (1.2) to velocity profiles above wave–current
boundary layers, is typically much greater than $k_b/30$ because of the presence of the wave–current boundary layer and potentially, because of sediment-induced stratification effects during high-energy events. Because $z_{oc}$ is directly dependent on $k_b$ and hence on the heights of roughness elements such as ripples, sand waves, sediment particles, or irregular surfaces, variations in roughness thereby create gradients in $\tau_{cw}$, $u_{rc}$, and, potentially, sediment flux.

On the inner shelf, waves and mean currents interact and estimations of bed stress and roughness are more complicated. To examine the effects of wave–current boundary layers on mean-current velocity profiles as well as to estimate the total wave–current stresses applied to the bed to resuspend sediment, previous efforts (e.g. Wright et al., 1999; Kim et al., 1997) have often used the model of Grant and Madsen (1986, 1979) to obtain estimates of $u_{rcw}$, $u_{rc}$, and wave-current boundary layer thickness, $\delta_{cw} = \frac{2k_b u_{rcw}}{\omega}$, where $\omega$ is the radian wave frequency. By matching velocity at $z = \delta_{cw}$, apparent roughness, $z_{oc}$, is related to “true” (i.e. without wave effects) bottom roughness, $z_o$, by

$$\frac{z_{oc}}{z_o} = \left(\frac{\delta_{cw}}{z_o}\right)^{\frac{u_{rcw}}{u_{rc}}}$$  \hspace{1cm} (1.3)

The key parameter here is $z_o$, which is likely to exhibit pronounced spatial variations over complex inner shelf surfaces and thereby produce variations in eddy viscosity.

Several expressions for the wave friction factor, $f_w$, exist in the literature. The wave friction factor, $f_w$, as evaluated by Swart (1974) is
\[ f_w = \exp \left[ 5.213 \left( \frac{k_b}{a_w} \right)^{0.194} - 5.977 \right] \quad (1.4) \]

where \( a_w = \frac{U_w}{\omega} \) is the wave orbital excursion amplitude at the bed. Madsen (1994) suggested a slightly different formulation of the wave friction factor

\[ f_w = \exp \left[ 5.61 \left( \frac{a_w}{k_b} \right)^{-0.109} - 7.3 \right] \quad (1.5) \]

Smyth and Hay (2002) have recently proposed a formulation for \( f_w \) applicable for sandy nearshore beds where

\[ f_w = 0.247 \left( \frac{a_w}{k_b} \right)^{0.623} \quad (1.6) \]

Another useful way of expressing the relationship between the near bed current, bottom roughness and bottom stress is with a quadratic drag coefficient, \( C_d \), such that the instantaneous bottom stress is given by

\[ \tau(t) = \rho_w C_d |\bar{u}(t)| \bar{u}(t) \quad (1.7) \]

where \( \bar{u}(t) = \bar{u}_w(t) + \bar{u}_c(t) \) is instantaneous velocity at some height close to the sea bed (Feddersen et al., 2000; Grant and Madsen, 1979), and \( \bar{u}_w(t) \) and \( \bar{u}_c(t) \) are the wave and current components of total instantaneous velocity. When averaging over multiple wave cycles, the amplitude of the bottom wave orbital velocity, \( U_{rms} \), is estimated from the root-mean-squared (rms) value of near-bed flows. It is straightforward to evaluate equation (1.7) to leading order for the case of \( U_{rms} \gg u_c \), where \( u_c \) is the speed of the near-bed mean current. In the current bottom boundary layer not far above the top of the wave boundary layer, it follows for the asymptotic situation of strong waves
perpendicular to a weak current that:

\[ \tau_{cw} = \rho_w C_d U_{rms}^2 \]  \hspace{1cm} (1.8)

\[ \tau_c = \rho_w C_d U_{rms} u_c \]  \hspace{1cm} (1.9)

\[ u*_{cw} = \sqrt{C_d U_{rms}} \]  \hspace{1cm} (1.10) and

\[ u*_{c} = \sqrt{C_d (U_{rms} u_c)^{\frac{3}{2}}} \]  \hspace{1cm} (1.11)

In equations (1.7–1.11), \( C_d = \frac{f_w}{2} \), where \( f_w \) is the wave friction factor described by (1.4) to (1.6). It is also possible to impose a quadratic relationship between the mean current and mean stress by defining

\[ \tau_c = \rho_w C_{dcurr} U_c^2 \]  \hspace{1cm} (1.12)

\[ u*_{c} = \sqrt{C_{dcurr} U_c} \]  \hspace{1cm} (1.13)

which gives

\[ C_{dcurr} = \left( \frac{U_{rms}}{U_c} \right) C_d \]  \hspace{1cm} (1.14)

From the perspective of quadratic drag on the mean current, waves enhance \( C_{dcurr} \) in equation (1.14) in a manner analogous to the effect of waves on \( z_{oc} \) in equation (1.3).

1.5 ESTIMATING BED SHEAR STRESS

In the log-layer of fully-turbulent boundary layers, there is, at first order, a balance between shear production of turbulence and viscous dissipation over the inertial subrange of wave numbers \( k \) (Kim et al., 2000). Within the inertial subrange, energy is cascaded from low to high frequencies and decreases at a rate proportional to \( k^{-5/3} \). In such cases, the spectral density, \( \phi_{uvw} \), of the vertical velocity component (which is the component that
exhibits the least contamination from waves) is related to dissipation, $\epsilon$, by $\phi_{\text{wave}} = 0.68e^{2/3}k^{-5/3}$ at all wave numbers in the inertial subrange of the wave number energy spectrum. Assuming that the $-5/3$ slope is supported by data, one can then obtain an independent estimate of shear velocity from the inertial dissipation method using (Green, 1992; Stapleton and Huntley, 1995)

$$u_c = (Kz)^{5/3} \left( \frac{\phi_{\text{wave}}(k)k^{5/3}}{0.68} \right)^{5/2} \tag{1.15}$$

In applying (1.15), $k$ is estimated from observations by converting the spectrum of vertical velocity fluctuations ($\phi_{\text{wave}}$) in terms of frequency into wave number assuming Taylor's frozen turbulence theory such that $k = 2\pi f / U_{\text{com}}$ where $U_{\text{com}}$ is the magnitude of the combined horizontal velocity vectors (see Stapleton and Huntley, 1995, for details).

Another approach to expressing boundary layer turbulence and estimating bed stress, applied successfully to acoustic Doppler velocimeter (ADV) data dominated by tidal currents by Kim et al. (2000), involves the estimation of total kinetic energy (TKE). Although Stapleton and Huntley (1995) proposed a modification to this method that involves removal of wave-induced oscillations, the currents in these data (Chapter 3) were very weak in comparison with wave orbital motions and this introduced large uncertainty in the results obtained via the TKE method. However, in a recent analysis of wave-dominated nearshore boundary layers, Smyth and Hay (2002) utilized the ratio of vertical turbulence intensity within the wave boundary layer, $w'_{\text{rms}}$, to orbital velocity, $U_{\text{rms}}$, to estimate the wave friction factor, $f_w$, following
1.6 RIPPLE DYNAMICS

Sand ripples on the shoreface and inner shelf are important sources of seabed roughness to waves and currents (Ardhuin et al., 2002; Grant and Madsen, 1982) and play a key role in the nature and magnitude of sediment resuspension (Traykovski et al., 1999; Li et al., 1996; Drake and Cacchione, 1989). Several field and laboratory studies have been conducted in attempts to develop empirical formulae between ripple geometry (e.g. height, length, steepness) and flow conditions (Wiberg and Harris, 1994; Wikramanayake, 1993; Dingler, 1984; Grant and Madsen, 1982; Nielsen, 1981; Miller and Komar, 1980). Under the typically irregular flow conditions encountered in the field, the ability of these models to accurately predict observed ripple geometry has been shown to be rather poor (Doucette, J., 2002; Traykovski et al., 1999; Li et al., 1996; and Osborne and Vincent, 1993). In part, the reason for the poor agreement between field data and model estimates is that ripple geometries encountered in the field are often relict products of forcings from past events and not instantaneous hydrodynamic conditions. Both Traykovski et al. (1999) and Li and Amos (1999) observed significant hysteresis in ripple development on the shelf.

In addition to non-equilibrium evolution, spatially varying grain size is another important issue affecting ripple dynamics. Grain size and ripple dimensions on the inner shelf often exhibit large variations over spatial domains both greater than 1 km (e.g. Hume et al., 2000; Black and Oldman, 1999; Barnhardt et al., 1998; and Field and Roy,
1984) and less than 1 km (e.g. Ardhuin et al., 2002; Thieler et al., 1995; Hunter et al., 1988; and Schwab and Molnia, 1987), often in correlation with sorted bedforms (or “rippled scour depressions”) that have wavelengths much longer than the ripples themselves (Green et al., 2004; Traykovski and Goff, 2003). According to Holland et al. (2003), heterogeneous patches of contrasting sediment and dynamic temporal changes in grain size are often the norm along rippled inner shelf environments.

A recent review of ripple studies by Doucette and O'Donoghue (2002) concluded that the present understanding of ripple dynamics is poor and more research especially in irregular flow regime settings is needed to improve predictive models. The theoretical background on several widely used ripple models analysed in this study are presented below.

When ripples dominate the bed roughness, the ripple roughness height, $k_r$, depends directly on ripple height, $\eta$, and inversely on ripple spacing, $\lambda$. Nielsen (1981) concluded that

$$k_r = \frac{8\eta^2}{\lambda}$$

(1.17)

whereas Madsen and Wikramanayake (1991) obtained the simpler relation, $k_r = 4\eta$. Recently, Smyth and Hay (2002) suggested a formulation which is more sensitive to ripple steepness, but applicable over only a very small range of ripple dimensions:

$$k_r = 1.18 \times 10^6 \left(\frac{\eta}{\lambda}\right)^{3.75} \eta$$

(1.18)
Caution should be used when applying this formula, as reasonable results exist only for very small ripples. When ripple dimensions such as those encountered in this study ($\eta \sim 0.10$ m; $\lambda \sim 1$ m) are used, equation (1.18) returns extreme overestimates of $k_r$ ($k_r = 20.9$ m). Under conditions where ripples are subtle or are replaced by a movable plane bed, other forms of bed roughness, notably grain roughness, $k_d (-d_{50})$ and movable bed roughness, $k_m$, are added to or replace ripple roughness. The total effective roughness, $k_b$, is then simply $k_b = k_d + k_r + k_m$. Another type of roughness, not yet dealt with by existing predictive models but probably of considerable importance in many shelf settings, is hummocky topography, which often prevails under the same conditions for which a plane moveable bed is predicted.

Most models predict the dimensions of wave ripples and movable bed roughness as functions of either the skin friction Shields parameter, $\theta'$, which, for the wave dominated case, is

$$\theta' = \frac{0.5 f_w U_w^2}{gd_{50}(s-1)} \quad (1.19)$$

or the wave mobility number $\psi'$, which is

$$\psi' = \frac{U_w^2}{gd_{50}(s-1)} \quad (1.20)$$

In equations (1.19) and (1.20), $U_w$ is significant wave orbital velocity at the top of the wave boundary layer = $\sqrt{2} U_{rms}$, $f_w$ is the skin friction factor (computed on the basis of equation (1.4) with grain size roughness, $k_d = d_{50}$, replacing ripple roughness; typically $f_w = (0.01)$, $d_{50}$ is the median grain diameter of the bed sediment, $g$ is the acceleration of gravity, and $s$ is the critical shear stress for bed detachment.
gravity, and $s$ is sediment density relative to the density of seawater. In terms of $\psi'$, Nielsen (1981) found that

$$ \eta = a_w \left[ 21 \left( \frac{\psi'}{f_w} \right)^{1.85} \right] \quad \text{for } \psi' > 10 \quad \text{and} \quad \eta = a_w (0.275 - 0.022 \psi'^{0.5}) \quad \text{for } \psi' \leq 10$$

(1.21)

Based on field data, Nielsen (1981) found the following expression of ripple wave-length in terms of $\psi'$:

$$ \lambda = a_w \exp \left( \frac{693 - 0.37 \ln \psi'}{1000 + 0.75 \ln \psi'} \right) \quad \text{for } \psi' > 10 $$

(1.22)

An alternative model offered by Wikramanayake (1993) utilizes the non-dimensional parameter, $\zeta$, which is related to $\psi'$ via

$$ \zeta = \frac{4 \nu U_w^2}{d_{50} [(s - 1) gd_{50}]^3} $$

(1.23)

in which $\nu$ is kinematic molecular viscosity. For cases where $\zeta < 2$, Wikramanayake (1993) predicts ripple dimensions from

$$ \eta = 0.30 a_w \psi'^{-0.39} \quad \text{and} \quad \lambda = 1.96 a_w \psi'^{-0.28} $$

(1.24)

Under more energetic conditions, when $\zeta \geq 2$, the relationships become

$$ \eta = 0.45 a_w \psi'^{-0.99} \quad \text{and} \quad \lambda = 2.71 a_w \psi'^{-0.75} $$

(1.25)

Combining analyses of field and laboratory data, Wiberg and Harris (1994), proposed an updated ripple classification scheme and predictive model for ripple geometry based on scales dominated either by $d_o$ (orbital ripples), $d$ (anorbital ripples), or a combination of the two (sub-orbital ripples). The model of Wiberg and Harris (1994) parameterizes ripple steepness ($\eta/\lambda$) in terms of $d_o/\eta$ as follows.
where $A_1 = 0.095$, $A_2 = 0.442$ and $A_3 = 2.28$ are empirical coefficients from the second-order polynomial fit to the data used by Wiberg and Harris (1994). The above formula is transitive in nature and thus requires an iterative solution for $\eta$.

The solution for ripple wavelength proposed by Wiberg and Harris is:

$$
\lambda = \begin{cases} 
0.17 & \frac{d_o}{\eta} \leq 10 \\
\exp\left[-A_1 \ln^2\left(\frac{d_o}{\eta}\right) + A_2 \ln\left(\frac{d_o}{\eta}\right) - A_3\right] & \frac{d_o}{\eta} > 10
\end{cases}, \tag{1.26}
$$

(1.26)

where $A_1 = 0.095$, $A_2 = 0.442$ and $A_3 = 2.28$ are empirical coefficients from the second-order polynomial fit to the data used by Wiberg and Harris (1994). The above formula is transitive in nature and thus requires an iterative solution for $\eta$.

The solution for ripple wavelength proposed by Wiberg and Harris is:

$$
\lambda = \begin{cases} 
0.62d_o & \frac{d_o}{\eta_{ano}} < 20 \\
\lambda_{aoo} = f\left(\frac{d_o}{\eta_{ano}}\right) & 20 \leq \frac{d_o}{\eta_{ano}} \leq 100 \\
535d & \frac{d_o}{\eta_{ano}} > 100
\end{cases}, \tag{1.27}
$$

(1.27)

where $\lambda_{orb}$, $\lambda_{sub}$, and $\lambda_{ano}$ delineate the regions of orbital (2-D vortex ripples), sub-orbital, and anorbital (3-D) ripples based on the classification of Wiberg and Harris (1994). In equation (1.27), $\frac{d_o}{\eta_{ano}}$ is given by the solution of equation (1.26) by setting $\lambda = \lambda_{ano}$.

In equation (1.27),

$$
f\left(\frac{d_o}{\eta_{ano}}\right) = -\ln\left(\frac{\lambda_{orb}}{\lambda_{ano}}\right) \ln\left(0.01\frac{d_o}{\eta_{ano}}\right) \ln 5 \tag{1.28}
$$

(1.28)

Recently, Malarkey and Davies (2003) have suggested a non-iterative procedure for the Wiberg and Harris model based on a quadratic solution for $d_o/\eta$ written as:

$$
\frac{d_o}{\eta} = \exp\left[B_2 - \sqrt{B_3 - B_1 \ln\left(\frac{d_o}{\eta}\right)}\right] \tag{1.29}
$$

(1.29)

where $B_i = 1/A_i$, $B_2 = 1/2(1 + A_2)B_1$, and $B_1 = B_2^2 - A_3B_1$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
This solution allows equation (1.27) to be expressed in terms of \( \frac{d_o}{\lambda} \) with the form:

\[
\frac{d_o}{\lambda} = \begin{cases} 
\frac{1}{0.62} & \frac{d_o}{\eta_{ano}} < 20 \\
\frac{d_o - e^{f\left(\frac{d_o}{\eta_{ano}}\right)}}{535d} & 20 \leq \frac{d_o}{\eta_{ano}} \leq 100 \\
\frac{d_o}{\eta_{ano}} & \frac{d_o}{\eta_{ano}} > 100
\end{cases}
\]  

(1.30)

where \( \frac{d_o}{\eta_{ano}} \) is determined from the solution of equation (1.29) based on \( \frac{d_o}{\lambda} \) for the anorbital case \( \frac{d_o}{\lambda} = \frac{d_o}{(535d)} \). The above procedure for the Wiberg and Harris (1994) ripple geometry model is semi-iterative in that a two-stage calculation beginning with the assumed anorbital condition is necessary as opposed to a fully iterative solution. Nonetheless, the computational savings especially for large three-dimensional models by using this implementation may be worthwhile.

1.7 BIOLOGICAL EFFECTS

The activities of organisms, particularly benthic flora and fauna, on the seabed can affect the hydrodynamics and bed micromorphology. Biological effects include the build-up of fecal mounds and feeding tracks that can double the roughness length of a stationary smooth bed (Nowell et al., 1981). Additionally, exo-polymers can serve to bind the surface sediment, and in doing so, increase the critical shear stress threshold of the bed material (Dade et al., 2001). The influence of biogenic roughness is especially pronounced during relatively calm hydrodynamic conditions. Biogenic roughness typically is wiped-out by energetic events but redevelops quickly and acts to rework relict physical bedforms left from the storm (Wright, 1995). During fair-weather conditions...
conditions, bioturbation may serve as the leading process in the reworking and molding of relict bedforms from previous storm events (Richardson et al., 2001; Li and Amos, 1999). Variations in biogenic roughness caused by changes in hydrodynamic flow conditions were observed by Wright et al. (1997). The present study focuses on energetic events when biological effects are likely to be significantly reduced relative to physical processes. Therefore, the role of biogenic processes in complex roughness will not be dealt with in this study.

1.8 SCOUR- MORPHODYNAMICS ABOUT SEABED OBJECTS

Scour is the morphodynamic response of the seabed as a result of the presence of an object or structure (Soulsby, 1998). Scour is important for a variety of marine situations including bridge piers, dock pilings, breakwaters, oil platforms, offshore pipelines, marine artifacts, heterogeneous seabed bedforms, and naval mines (Whitehouse, 1998) (Figure 1.15a).

The presence of an object on the seabed produces local flow acceleration due to continuity and thus drives a flux of local sediment and concomitant bed adjustments (Whitehouse, 1998). Another manifestation of scour is an increase in bed shear stress and turbulence as structured vortices are generated and released from around the object. Numerous vortex types have been identified and studied including wake vortices and horseshoe vortices (Figure 1.15b). Scour can be classified both in terms of spatial extent and hydrodynamics. Three spatial classes of scour are: “local scour” which is in the immediate vicinity of the object (on the order of meters), “global scour” composed of
wide depressions around large or multiple objects (on the order of 10s of meters), and “overall seabed movement” associated with large scale (100s -- 1000s of meters) patterns of erosion, deposition and bedform movement (Whitehouse, 1998). In terms of hydrodynamic intensity, scour is classified as either clear-water when the ambient flow (bed shear stress) is below threshold velocity or live-bed when ambient flow is above threshold velocity and the entire bed is active. In the former, the amplification of flow about the object induces transport locally but elsewhere the bed is immobile. In the latter case, sediment is being transported by flow everywhere, but especially near the object, where turbulence and bed shear stress are enhanced. In this study, local scour involving both clear-water and live-bed conditions of free settling objects is studied.

Once an object is exposed on the seabed, scour is initiated around the lateral ends of the object because of converging accelerated flow. This convergence leads to progressive erosion of the sediment from under the ends of the object, forming an expanding scour pit and shrinking the support pedestal. The object then will settle into its scour pit in a series of rocking and rolling motions until it is no longer protruding above the ambient seabed or until flow conditions subside and backfilling (deposition) ensues. In non-steady flows, periods of excavation (scour) will normally be interrupted by episodes of backfilling (deposition) (Richardson and Traykovski, 2002; Fredsoe, 1978). A possible sequence for scour around a free settling horizontal object, such as those examined in this study, is illustrated in Figure 1.16.

Extensive laboratory and occasional field research has been carried out over the
last 30 years in an effort to meaningfully estimate the rate and maximum depth of scour associated with a host of marine structures (Whitehouse, 1998). The approach to estimating scour in this study is to apply and build upon the well-established relations for scour around seabed objects as developed in the academic literature (Friedrichs, 2001; Whitehouse, 1998; Soulsby, 1997). Soulsby’s work provides the basis for determining bed shear stress and critical threshold for initiation of motion for non-cohesive sediment. Whitehouse (1998) introduced a discretization procedure for incorporating time variable forces including both waves and tides. For energetic scour, these relations predict

\[
S(t) = S_\infty \left(1 - \exp\left(\frac{t}{T_x}\right)^{P_m}\right),
\]

where \(S_\infty\) is the final depth of scour, \(t\) is time, and \(T_x\) is a time-scale factor that in turn, is a function of dimensionless numbers characterizing the environmental forcing, \(D\) is the diameter of the object, and \(P_m\) is empirically based on the geometry of the object in question and the shape of the scour rate curve (Figure 1.18). 

\(S_\infty\) is determined from the formula

\[
S_\infty = \begin{cases} 
0 & U < 0.75U_{cr} \\
1.15D(2U - 1.5U_{cr})/U_{cr} & 0.75U_{cr} < U < 1.25U_{cr} \\
1.15D & U > 1.25U_{cr}
\end{cases},
\]

where \(U\) is the flow velocity (currents, waves, or a combination) above the object (observed or estimated from linear wave theory), and \(U_{cr}\) is the critical velocity for the initiation of motion of non-cohesive sand given by Soulsby (1997) as a function of sand size and density. Following Whitehouse, the timescale factor in equation (1.31) is given by

\[
T_x = A_m g^{B_m} D^2 \int_{g(s-1)}d^3 f^{-1/2}
\]
where $A_m = 0.095$ and $B_m = -2.02$ are empirical coefficients presented in Whitehouse (1998). $\theta'$ is Shields parameter (equation 1.19), $g$ is the acceleration of gravity, $s$ is the weight of sand relative to water, and $d$ is grain size.

Mine surface area exposure is related to, but distinct from, depth of scour. Based on the observations of Richardson and Traykovski (2002) at the Martha’s Vineyard Coastal Observatory (MVCO), a cylindrical object on a sandy inner shelf buries by repeatedly falling into its own scour pit (Figure 1.16). Thus, the depth of burial of an object relative to the undisturbed far-field bed is given approximately by the maximum depth of scour, $S_{\text{max}}$, experienced to that point by the object (Figure 1.17). Another important result of Richardson and Traykovski is that growing waves can partially unbury a previously buried object. Thus it is necessary to define instantaneous burial depth, $B$, as

$$B = S_{\text{max}} \left( 1 - \Xi \left( \frac{S}{S_{\text{max}}} \right) \right), \quad (1.34)$$

where $\Xi$ is a factor (between 0 and 1) that parameterizes the efficiency with which scour re-exposes the object while the object simultaneously settles into its scour pit. Finally, percent burial by surface area is calculated by relating $B$ to the exposed surface area of a circle submerged to depth $B$. A 100% maximum and 10% minimum limit are imposed because no more than 100% of a mine can be buried, and initial observations from previous field experiments at MVCO indicate at least 10% of a cylindrical seabed object is always in contact with the bed (Figure 1.17).
1.9 SUMMARY

The inner shelf is a complex, heterogeneous, morphodynamic system that provides a critical link between the nearshore and the continental shelf. Marked spatial and temporal variations in seabed texture and composition as well as sharp gradients in forcing conditions (waves and currents) typify many inner shelf systems worldwide. Waves, currents, and seabed roughness form a tight, highly non-linear feedback loop within the bottom boundary layer that can significantly affect the exchanges of physically (momentum and mass) and biologically (e.g. nutrients and larvae) important quantities. Numerical models for ripple roughness, largely developed in the laboratory, need to be assessed with field observations under non-steady irregular flow in mixed grain environments. Increasing our present understanding of the coupled links between variable bed roughness and hydrodynamics is a crucial step in order to model short and long-term morphologic behavior of the inner shelf.

Rippled scour depressions are common features across the inner shelf in locations throughout the world, yet questions still remain about the processes responsible for their origin and maintenance. It is clear from the literature that RSDs are not moribund relict deposits but rather active, perhaps palimpsest, features engaged in complex dynamic equilibrium between morphology and hydrodynamics. While more measurements and modeling studies regarding the morphodynamic behavior of these phenomena are required, many of the theories put forward previously to explain the occurrence and maintenance of RSDs may be correct only for isolated instances.
Scour is a particular and important class of morphodynamic response of seabed morphology to the presence of an object. Understanding and predicting the rate and magnitude of scour around objects is important both for both pure science endeavors and numerous applied situations. Simple but robust empirical models of scour behavior developed from extensive past studies may prove useful for explaining and predicting the short-term fate of numerous seabed objects and should be tested against detailed field studies.

This study includes observational and numerical investigations of ripple behavior, suspended sediment transport, rippled scour depression dynamics, and scour associated with various seabed objects. The following chapters detail several independent but related studies built upon the theoretical foundation presented above that variously examine the morphodynamics and scour processes of wave dominated inner shelf sedimentary systems.
Figure 1.1 Diagram showing temporal and spatial length scales and research issues in this study.
Figure 1.2 Schematic indicating complex interactions between studied processes
Figure 1.3 Components of the Continental Shelf. After Wright, 1995.
Figure 1.4 Conceptual Diagram of Inner Shelf Transport Processes. After Nittrouer and Wright (1994)
Cedar Island, VA (Chapter 3)

Indian Rocks Beach, FL (Chapter 5)

Queen Anne's Revenge Shipwreck Beaufort, NC (Chapter 5)

Tairua/Pauanui New Zealand (Chapters 2, 3, 4, and 6)

Figure 1.5 World map showing location of field sites
Figure 1.6 Map of the East Coast showing location of U.S. field sites.
<table>
<thead>
<tr>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onslow Bay, NC</td>
<td>McIntyre and Pilkey, 1969</td>
</tr>
<tr>
<td>Western Mexico</td>
<td>Reimnitz et al., 1976</td>
</tr>
<tr>
<td>Middle Atlantic Bight</td>
<td>Swift and Freeland, 1978</td>
</tr>
<tr>
<td>Bristol Bay, Alaska</td>
<td>Schwab and Molnia, 1987; Marlow et al., 1999</td>
</tr>
<tr>
<td>Central California</td>
<td>Cacchione et al., 1984</td>
</tr>
<tr>
<td>SE Australia</td>
<td>Field and Roy, 1984</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>Schwab et al., 1997</td>
</tr>
<tr>
<td>Gulf of Maine</td>
<td>Barnhardt et al., 1998</td>
</tr>
<tr>
<td>Long Island, NY</td>
<td>Schwab et al., 2000</td>
</tr>
<tr>
<td>Monterey Bay, CA</td>
<td>Hunter et al., 1988; Eittreim et al., 1997</td>
</tr>
<tr>
<td>Scotian Shelf</td>
<td>Forbes and Boyd, 1986; Amos et al., 1999</td>
</tr>
<tr>
<td>Southeast Africa</td>
<td>Flemming, 1980</td>
</tr>
<tr>
<td>Martha’s Vineyard, MA</td>
<td>Goff et al., 2003</td>
</tr>
<tr>
<td>Beaufort Inlet region, NC</td>
<td>Reed and Wells, 2000; McNinch et al., 2001</td>
</tr>
<tr>
<td>Wrightsville Beach, NC</td>
<td>Thieler et al., 1995; Thieler et al., 2001</td>
</tr>
<tr>
<td>Hauraki Gulf, NZ</td>
<td>Hihon, 1995; Black and Oldman, 1999; Hume et al., 2000</td>
</tr>
<tr>
<td>Coromandel Peninsula, NZ</td>
<td>Bradshaw et al., 1994; Trembanis et al., 2001; Hume et al., 2003</td>
</tr>
<tr>
<td>Aquitaine Coast, France</td>
<td>Cirac et al., 2000</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>Morang and McMaster, 1980</td>
</tr>
<tr>
<td>Indian Rocks, FL</td>
<td>Howd et al., 2001</td>
</tr>
</tbody>
</table>

Table 1.1 Summary of studies in which Rippled Scour Depression features have been encountered. Adapted and updated from Cacchione et al. (1984) and Leckie (1988).
Figure 1.7 Perspective Image of Large Rippled Scour Depression examined in this study (Chapter 2-4).
Figure 1.8 Comparison Plot of Inner Shelf Profiles: Pauanui Beach, New Zealand; Tairua Beach, New Zealand; Duck, NC; Cedar Island, VA; Eel River, CA; and New South Wales (NSW), Australia.
Figure 1.9 Example of a completely well-ordered sedimentary system.
Figure 1.10 Example of a completely disordered (random) sedimentary system.
Figure 1.11 Example of a complex sedimentary system.
Figure 1.12 Hypothetical complexity index profile.
Figure 1.9 Spectral Plot of Vertical Velocity Component, Illustrating -5/3 Slope within Inertial Subrange.
Figure 1.14 Plot of non-dimensional ripple wavelength (red), height (blue), and steepness versus normalized wave orbital diameter based on the ripple geometry model of Wiberg and Harris (1994).
Figure 1.15 (a) Schematic Diagram of Scour (b) Scour Related Turbulent Flow Structures (after McNinch et al., 2000)
Time 0: initial exposure of object

Time 1: scour around ends of object

Time 2: object begins settling into scour hole realignment to local flow

Time 3: continued settling until object no longer obstructs flow

Time 4: scour hole fills during quiescent time with subsequent re-exposure

After McNinch et al., 2000

Figure 1.16 Commonly Observed Sequence of Localized Scour.
Figure 1.17 Examples of Seabed Object Orientations and Differences in Burial related to Surface Area versus Scour Depth
Figure 1.18 Typical Time Development Curve of Scour. After Whitehouse, 1998
CHAPTER 2

THE ROLE OF GEOLOGY IN A COMPLEX INNER SHELF TAIRUA/PAUANUI EMBAYMENT, NEW ZEALAND
OVERVIEW

In this chapter, the surface (part one) and sub-surface (part two) characteristics of a complex heterogeneous inner shelf sedimentary systems are explored. Part one presents a morphogenetic classification of features commonly termed either rippled scour depressions (RSDs) or sorted bedforms. Seabed mapping by side-scan sonar on the inner shelf in water depths of 6–45 m has revealed complex facies. Particularly striking are shallow depressions (<0.5 m deep) in the sandy seafloor floored with coarse rippled sediment. Paradoxically, facies boundaries between unconsolidated sediments can be sharp despite the fact that the inner shelf environment is one of shoaling energetic waves with dynamic sediment transport and mobile bedforms. Furthermore, many sharp facies boundaries were found to maintain their location at annual time scales despite large storms. Based on observations, it is concluded that sand supplies are insufficient to bury the rippled coarse sediments and/or that the coarse patches are maintained with the assistance of turbulent induced resuspension over the rough bed, four morphogenetically unique types of RSDs are identified. The complex seabed facies are stable at spatial and temporal scales over which numerical models are most useful and thus might be represented by temporally varying spatially stable roughness in models.

In part two, the shallow stratigraphic signatures of these features are examined, and a series of cautionary insights applicable to paleoenvironmental reconstruction is suggested. Matching the stratigraphy of shallow cores to the characteristics of overlying surficial sediments and oceanographic conditions in a heterogeneous sedimentary environment will aid in the recognition of RSDs in the stratigraphic record and assist paleoenvironmental interpretation of these deposits. An important observation is that the stratigraphic signature of RSDs, does not reflect the commonly assumed calm/storm sequences of changes to oceanographic conditions. Rather the fine/coarse sequences reflect present-day morphodynamics associated with the seabed boundary layer.
PART ONE-
FACIES ANALYSIS OF A COMPLEX INNER SHELF

Portions of this chapter were published in the proceedings of the Coastal Sediments 2003 Conference with authors:
Hume, T., Trembanis, A. C., Stephens, S., Hill, A., and Liefting, R.
2.1 INTRODUCTION

Over the last few decades, detailed swath mapping of the world's inner shelf environments by sonar methods has shown that facies distributions are more heterogeneous and complex than previously considered from grab-samples, drop-camera, and diver observations. Numerous studies (e.g. Thieler et al., 2001; Hume et al., 2000; Schwab et al., 2000; Manighetti and Carter, 1999; Amos 1996; Carter and Lewis, 1995; Hequette and Hill, 1995; Hilton, 1995; Thieler et al., 1995; Bradshaw et al., 1994; Black and Healy, 1988; Hunter et al., 1988; Leckie, 1988; Mearns et al., 1988; Schwab and Molnia, 1987; Cacchione at al., 1984; Field and Roy, 1984) have identified fine sand plains juxtaposed alongside rippled gravely sands and outcrops of pre-Holocene consolidated 'basement' material in a spatially variable patchwork mosaic.

Paradoxically, facies boundaries between unconsolidated sediments can be sharp despite the fact that the inner shelf environment is one of shoaling energetic waves with dynamic bedforms (diagnostic of sediment mobility and sand transport). Furthermore, in a recent study of an energetic inner shelf by Hume et al. (2003) it was found that facies boundaries maintained their location at annual time scales despite large storm events. This seeming persistence at large spatial scales raises questions about how the patterns are constructed and maintained, how the patterns might be interpreted in terms of embayment-scale sand movement, and how numerical models that simulate fluid flow and sediment transport might be adapted to deal with this complexity.
This chapter focuses on the results of detailed side-scan sonar mapping that revealed spatially variable but temporally stable facies patterns. Facies are described and given a morphogenetic classification based on the environmental conditions under which they formed. The implications of temporally variable spatially stable roughness patterns for numerical modeling are explored.

2.2 STUDY AREA DESCRIPTION

In order to examine the role that shoreface complexity plays in inner shelf morphodynamics, we chose a field site with pronounced sediment heterogeneity. The site is the inner shelf of the Tairua/Pauanui embayment off the Coromandel Peninsula of New Zealand's North Island (Figure 2.1). The beaches of Tairua and Pauanui, are on either side of the inlet. Tairua is 1.2 km long, steep, reflective, and comprised of 0.4 mm median diameter sand. Pauanui is 2.7 km long and dissipative, composed of 0.2 mm median diameter sand. The shoreface profile is steeper off Tairua than Pauanui (Figure 1.8) but upwardly convex off both beaches to about 20 – 25 m depth beyond which the slope flattens to <0.01 degrees. Offshore from the beaches to about 45 m depth the shoreface seabed is comprised of very fine sand with patches of rock reef and the rippled gravely sand substrate of RSDs that occur in depths of 14 to 35 m.

High-resolution side-scan sonar surveys of the inner shelf off of Tairua show highly complex, and spatially variable roughness patterns. These patterns involve alternations among small and large wave ripples, relatively smooth fine-sand plains, and mega-rippled coarse shell-hash deposits, along with variously exposed rock reef hard-
bottom (Figures 2.4, 2.7 and 2.8). Complex patterns of inner shelf sediment facies have been observed in numerous shelf settings including Duck, North Carolina (Friedrichs and Wright, 1998; Madsen et al., 1993; Wright, 1993;), northern California (Wright et al., 1999; Cacchione et al., 1984;), and southeastern North Carolina (Riggs et al., 1998; Thieler et al., 1994).

How representative is the present field site relative to other inner shelf systems worldwide? According to the recent literature, (Trembanis et al., in press; Murray and Thieler, 2004; Green et al., 2004; Short, 2002; Hume et al., 2000; Schwab et al., 2000; Drake, 1999; Wright et al., 1999; Thieler et al., 1995; Cacchione and Drake, 1990; and Green, 1986) such complex systems are common worldwide. The idea that the inner shelf is a physically homogeneous, comprised of abundant smooth fine-sand is therefore, inconsistent with field data. Instead, most inner shelf systems, like the present field site, appear to be composed of highly variable bedforms with diverse sediment texture, supporting abundant communities of benthic organisms (Holland et al., 2003; Wright et al., 1987). Whereas the specific mix of morphological complexities and physical processes varies geographically, the Tairua/Pauanui embayment, with its strong signal of complexity, provides a useful study site for many similar systems found worldwide.

The present study-site can be placed within the spectrum of other inner shelf settings by comparing its shoreface profile to other more commonly studied systems such as Duck, North Carolina (a relatively stable storm-dominated system), Cedar Island, Virginia (a rapidly retreating barrier island), Eel River, Northern California (a stable
steep shoreface with large episodic fluvial flood deposits), and the southeastern coast of Australia (a stable energetic, sediment rich system). Figure 1.8 shows a comparison of the profile among these four settings. The steepest portion of the Tairua/Pauanui profile, over which the tripods were placed, compares favorably in slope to the shoreface of New South Wales, Australia (Wright, 1995). The shoreface at Tairua is convex upward between depths of 8 and 25 m, beyond which it flattens. Bed sediments are primarily unimodal fine sand (mean grain size 0.22 mm), with outcrops of poorly-sorted coarse sand (mean grain size 0.75 mm) in RSD deposits.

2.3 GEOLOGIC AND OCEANOGRAPHIC SETTING

The Tairua/Pauanui embayment is located along the southern sector of the east Coromandel Coast of the North Island of New Zealand, an active margin between the Australian and Pacific plates. The Coromandel coast is steep and rocky and indented by numerous small embayments, pocket beaches, and tidal inlets that front a relatively narrow continental shelf. The area serves as a popular summer beach resort (Bell, 1994, Bradshaw et al., 1991). The oldest dated artifacts indicating the inception of Polynesian colonization of New Zealand in the 13th century (pearl shell lures) were found in a shell midden layer in the dune at Tairua, making this an extremely important cultural site (Schmidt and Higham, 1998). Physiographically, the Coromandel peninsula is an uplifted horst block composed mainly of weathered andesite, dacite, and rhyolite overlying an indurated Jurassic basement (Bell, 1994; Homer and Moore, 1992; Bradshaw et al., 1991). The region exhibits a steep, rocky coastline with a relatively
narrow (20 – 30 km) continental shelf (Bradshaw et al., 1994). The remnant plug of a rhyolite dome (Mt. Paku), approximately 7000–8000 kBP years old lies in the central portion of the embayment at the entrance to the Tairua Harbor estuary (Homer and Moore, 1992; Rutherford, 1978). The catchment for the Tairua Estuary system is one of the largest on the Coromandel at ~280 km² (Bell, 1994; Bradshaw et al., 1994).

Connecting Paku to the headland to the north, Tairua Beach has been described morphologically as a tombolo (Bell, 1994), though it would be more accurate to refer to it as a baymouth barrier, much like Palm Beach north of Sydney, Australia. To the south of the estuary inlet is the barrier spit system of Pauanui. Abrahamson (1987) identified two main classes of sediment off the Coromandel: “marine” and “fluvial” sands. While both sediments are marine deposits at the present time, the classification is meant to differentiate them on the basis of initial depositional environment. The marine sands are composed of quartz (25 – 45%), feldspar (30 – 45%), volcanic glass (10%), and shell fragments and heavy minerals (<10%). The fluvial sediments are composed of feldspar (40%), volcanic glass (10%), heavy minerals (10%), and quartz (<15%). Bradshaw et al. (1991) defined seven sediment classes based on statistical classification of textural data from samples obtained throughout the Coromandel.

Both Tairua and Pauanui are barriers built during the Holocene post-glacial marine transgression that came to a relative still-stand approximately 6.5 kBP (Bradshaw et al., 1994). Recent ground penetrating radar surveys of the two barriers suggest stark differences in the structure of the Holocene deposits of the two beaches (Hume and Nichol personal communications). At Pauanui Beach, a series of prograding dunes have
built seaward during the Holocene. In contrast, the data from Tairua suggest vertical stacking of the sediments (Figure 2.2). Bradshaw et al. (1994) characterized the Holocene sediment lithofacies of the entire east Coromandel coast as an accommodation-dominated regime in which autochthonous siliciclastic sediments were reworked through erosional shoreface retreat pushing fine-grained sands shoreward while leaving coarser sands as erosional-lag deposits.

The estuary plays a major role as the source of the limited new detrital material entering the inner shelf system. In general, the estuary is a trap for sediment both worked ashore by waves and currents and carried down from the hinterland. The processes responsible for estuary infilling within an embayed system are reported in Green and MacDonald (2001). The contribution of allochthonous sediment to the system is meager and episodic based on long-term gauging station data from the upper reaches of the Tairua catchment basin (Bell, 1994). Human alterations to the landscape, particularly post-European settlement logging and mining activities, destabilized much of the upland and led to increased sedimentation rates (Hume and Gibb, 1987).

The tides in the region are semidiurnal; the spring tidal range is 1.6 m placing this system on the high end of the micro-tidal regime (Bell, 1994; Hayes, 1979). Tidal currents are generally weak (< 10 cm s\(^{-1}\) at 100 cm above the bed), except at the mouths of tidal inlets and in the vicinity of offshore islands. The Coromandel coast is a lee shore (dominant wind direction west to southwest) that has been classified by Carter and Heath (1975) as a storm-dominated coast. The wave climate is a mix of locally generated sea...
waves and distantly generated swell. Highest swell is associated with cyclones that leave
the tropics and pass to the east of New Zealand. Average significant wave height is 0.9
m (swell associated with tropical cyclones up to 7 m) and average period is 5.8 s (up to
13 s) (Gorman et al., 2004).

2.4 METHODS AND DATA

Field investigations included swath mapping by echo sounder and high-resolution
side-scan sonar along with ground-truthing by seabed sampling, SCUBA, and drop-
camera video. Ground penetrating radar and seismic surveys of the sand barriers and
offshore were acquired. Instrumented tripods were deployed on the shoreface (see
Chapters 3 and 4 for a full treatment of tripod data). Numerical modeling of waves and
currents was undertaken. The swath mapping and ground-truthing provide the primary
database for this study and are described below. All the data were registered in the same
geographic coordinate system (Universal Transverse Mercator–UTM) and imported into
a geographic information system (GIS) to relate acoustic patterns to seabed morphology
and texture.

2.4.1 SEABED MAPPING

A C-Max side-scan sonar system was towed at ~2-3 m s⁻¹ along a pre-determined
box grid, with shore parallel vessel tracks 350 m apart (Figure 2.16). The side-scan was
operated at low frequency (300 kHz), with a range of 200 m to either side of the vessel,
giving ~50 m overlap between adjacent lines. Tracks were shore-parallel to enhance the
reflections from wave-generated bedforms. The seabed was mapped to about 5 km
offshore and to about 35-40 m depth. The embayment was mapped in September 2000 and again in September 2001. Select areas and several drift lines were run in 2000 using a Marine Sonic Technology side-scan sonar tow-fish operating at 300 kHz and 900 kHz respectively (Trembanis et al., 2001). During the September 2001 survey, part of the area, a 1600 m by 2600 m ‘box’ (Figure 2.9), was surveyed at higher resolution by side-scan (600 kHz) and echosounder. An ECHOTRAC depth sounding system with heave compensation was run at the same time as the side-scan. Horizontal positions were logged about every 5 m along the vessel track using DGPS and are accurate to ±2 m. The digital side-scan record was processed to remove water column (bottom-tracked), corrected for beam angle and layback, then finally mosaiced. The facies boundaries were digitized “on-screen” in GIS.

The side-scan sonar was ground-truthed by sediment samples, diver observations, and a drop-camera deployed while the vessel drifted over 200–1000 m-long stretches of the seabed. Sediment samples were collected by diver and grab from about 50 sites (Figure 2.3). Additional samples were taken from the estuary and two beaches. Short (~0.5 m long) diver-rammed cores of 8 cm diameter were taken from the seabed at 9 sites to study the shallow sedimentary structure of contacts between the fine sand and coarse rippled sand facies. The cores were split, described, photographed, and sub-sampled for grain size analysis. Gravel, sand, and mud proportions in the sediments were determined by wet sieving. Grain size was determined by dry sieving following washing and drying. Representative samples of fine and coarse sediment were submitted to acid dissolution to
determine the percent carbonate composition by weight. Summary of grain size analysis is shown in Table 2.1, Figure 2.5, and Figure 2.6.

2.4.2 MODELING CURRENTS

Tidal currents were simulated using the Danish Hydraulics Institute two-dimensional model MIKE21 (DHI water and environment, 2002). Tides were forced at the open boundaries using the largest 13 tidal components output from the New Zealand tidal model (Walters et al., 2001; Walters, 1992), and showed good correlation with observed water levels recorded at tide gauges in the embayment. The fine grid model has a cell size of 45 m by 45 m.

2.4.3 INSTRUMENT DEPLOYMENTS

Three instrumented tripods were deployed in 15-22 m water depth (Figure 1.7) for 37 days that included two storms. The tripods provide information on bedform development and suspension dynamics. Two tripods were deployed at 22 m depth, one located within a coarse-sand rippled scour depression and the other nearby on the relatively featureless fine-sand plain. A further tripod was located on the fine-sand plain at 15 m depth. Each tripod had a pressure sensor for measuring waves, current meters for measuring turbulence, mean currents and wave-orbital velocities, and also a multi-frequency acoustic backscatter sensor. A detailed analysis of tripod measurements is presented in Chapters 3 and 4.
2.5 RESULTS

2.5.1 FACIES TYPES

Seabed mapping revealed complex patterns of sediment type and bed morphology within the embayment (Figures 2.7 and 2.8). Particularly striking are shallow depressions on the seabed that are floored with poorly sorted, coarse, gravely sands with long-crested, symmetrical, wave orbital ripples. On the sonargraphs the depressions are darker (stronger-backscatter) than the surrounding light-colored (weaker-backscatter) fine sand and are mostly sharply bounded. The bathymetric record, shadow effects on the side-scan and diver observations all indicate that the depressions are flat floored and lower than the surrounding seabed (i.e. have negative relief). These features are termed “rippled scour depressions” (RSDs) following the genetic term coined by Cacchione at al. (1984). However, adopting this term does not imply a similar origin for the various features reported here. Six major facies types are identified and described below on the basis of the sediment type, morphology, bedforms, and environment of deposition (Figures 2.7 and 2.10–2.14).

Facies 1: Fine-sand plain  Much of the area comprises a sandy seabed of well sorted to moderately well sorted, very fine sand (diameter range 0.07–0.12 mm) (Figure 2.4). The fine-sand plain is flat and featureless on the side-scan record, but diver observations revealed small symmetrical wave orbital ripples ($\eta = 3\text{–}5 \text{ cm}$, $\lambda = 15\text{–}20 \text{ cm}$), shallow pits, depressions, and humps in places that are possibly the remnants of hummocky bedforms (see Chapters 3 and 4) subsequently reworked by waves and bioturbation.
Facies 2: Bedrock outcrops  Outcrops of basement rock and rubble reef occur at the headlands, Shoe Island, and around the ‘roller patch’ reef in the southeast portion of the study area (Figure 2.8).

Facies 3: Outcrop related RSDs  Bands of poorly sorted gravely sands with large ripples flank most of the reef areas, including the shallow area in the wave shadow of Shoe Island. The grain size and ripple size increases closer to reef outcrop Figure 2.10.

Facies 4: Nearshore shore-normal RSDs  Finger-like ribbons of coarse rippled sands occur in shallow depressions (<0.5 m deep) running perpendicular to shore just seaward of the nearshore bar and in water depths 6-16 m. They progressively widen offshore from several meters width to 15-20 m (Figure 2.11). The spacing between successive ribbons ranges from 5-25 m. The ribbons occur in dense swarms and frequently coalesce into larger features in deeper water (Figure 2.12). The sediment comprises a poorly sorted, gravely, coarse-sand (median size 1 mm) with large symmetrical wave orbital ripples (η = 35 cm, λ = 130 cm). The boundaries with the adjacent sand plain are sharp to diffuse. These features only show up clearly on the 900 kHz side-scan record and appear to be ephemeral as indicated from repeated surveys. They have only been observed off the northern end of Tairua Beach (Figure 2.11).

Facies 5: Offshore shore-parallel RSDs  In water depths of 18-26 m, where the convex upward bulging shoreface begins to flatten offshore, coarse rippled sands occur in shallow depressions that run parallel with the trend of the beach. Close to islands and
rock reefs these large features become more complicated in outline and they merge with Facies 3. At the largest scale, the patches are over 400 m wide and up to 2 km long. The depressions are 40-50 cm deep relative to the surrounding fine-sand plains, with which they can have very sharp contacts. The sediment is a poorly sorted, gravely, coarse sand (mean size 0.6-2.0 mm) with large symmetrical wave orbital ripples ($\eta = 15-30$ cm, $\lambda = 70-100$ cm). The ripples are oriented to the locally observed wave field (Figure 2.12).

**Facies 6: Offshore shore-oblique RSDs** In deeper water (>35 m) in the northeast of the surveyed area, coarse rippled sands occur in topographic lows that run oblique to the trend of the shore and seabed contours. The alongshore spacing of the features is between 250-500 m. The sediment is comprised of a poorly sorted, gravely, coarse sand (mean size 0.6-2.0 mm) with large symmetrical wave orbital ripples ($\eta = 15-30$ cm, $\lambda = 70-100$ cm). The depressions progressively widen offshore from several meters width to 50-100 m wide offshore. Close to Shoe Island they become more complicated in outline where they merge with Facies 3. The morphology and other side-scan surveys in the area (Hume et al., 1995 and Bradshaw et al., 1994) suggest that these RDSs are associated with large, low amplitude sand ridges (Figure 2.13).

Figure 2.14 is a schematic diagram illustrating the idealized features of the RSD types identified in this study.
2.5.2 SEABED STABILITY AT THE FACIES SCALE

The overall pattern and distribution of the facies remained essentially unchanged (positionally stable) from one survey to the next (Figure 2.8 and 2.9). Furthermore, within the limits of positional accuracy from one survey to the next, many of the sharp boundaries of the RSDs, particularly those delineating Facies 5 (Offshore shore-parallel RSDs) and Facies 6 (Offshore shore oblique RSDs) remain largely unchanged with only minor modifications of no more than a few meters at the boundaries between surveys. However, the sharpness of the boundaries does appear to vary slightly from a sharp edge to a more diffuse outline perhaps as the lips of the depressions change in shape (e.g. lateral position adjustments). Changes in the sharpness of facies boundaries were also reported by Thieler et al. (2001). The finding of spatial stability with respect to Facies 5 and 6 is similar to that of Hunter et al. (1988) who reported that in Monterey Bay shore-parallel bands of rippled coarse sand in 10-20 m depth maintained the same overall patterns between surveys spanning three years. This stability is surprising given the fact that the bed is disturbed by numerous storms throughout the year. In contrast, the shape and position of Facies 4 (Nearshore shore-normal RSDs) is more ephemeral such that the features are seen to disappear and reappear from one survey to the next. Similar transient RSD behavior has been observed near the Martha’s Vineyard Coastal Observatory (L. Mayer, personal communication).

2.5.3 TIDAL CURRENTS
Depth averaged tidal currents simulated by the model and measured by the tripods are weak for most of the time except in the vicinity of the tidal inlet and estuary and, to a lesser extent, around the islands and reef areas (Figure 2.15). Away from the inlet, peak ebb, and flood currents for spring tides rarely exceed 10 cm s⁻¹.

2.6 DISCUSSION

To understand the factors controlling the distribution and apparent stability of facies on the inner shelf of the Tairua/Pauanui, embayment a close look at the oceanographic and geological setting associated with the RSDs is required. There are two issues here: first, how the RSDs are formed, and secondly, how are they maintained. Of course the answer may be the same to both questions, depending on the temporal and spatial scales considered. For instance, all RSDs were characterized by large wave orbital ripples. While this means the rippled bed is formed by waves, it does not necessarily mean that RSD features owe their origin to waves alone. Other studies of heterogeneous inner shelf environments (Hume et al., 2000; Schwab et al., 2000; Amos 1996; Hilton 1995; Thieler et al., 1995; Bradshaw et al., 1994; Black and Healy 1988; Hunter et al., 1988; Leckie 1988; Mearns et al., 1988; Schwab and Molnia 1987; Cacchione et al., 1984; Field and Roy 1984; Reimnitz et al., 1976) have suggested various explanations for RSDs described in the theoretical background to the study, including (1) tidal currents, (2) seaward flowing rips, (3) down-welling bottom currents as part of the currents generated by storm winds, (4) currents including Langmuir currents, that are generated in part by wave action, and (5) underlying geological structure. The hypothesis of this study of the Tairua/Pauanui embayment is that several
types of RSDs exist, each formed by varying combinations of processes. While there is no direct information on how these features form, their oceanographic and geological associations allow us to explore some options. Regardless of their origin, once formed, the coarse patches are maintained with the assistance of turbulent induced resuspension over the rough bed.

2.6.1 FORMATION OF RSDs

Previous studies have suggested that tidal currents are primarily responsible for forming RSDs in cases where elongated depressions are aligned with strong currents (e.g. Carter and Eade, 1995; Forbes and Boyd, 1986; Stride, 1963). At Cape Rodney, on the New Zealand coast, RSDs were observed to scale with large tidally generated phase eddies (Hume et al., 2000). In the Tairua/Pauanui embayment, tidal currents are weak and well below threshold velocities (Figure 2.15) and, by themselves, could not form RSDs. A possible mechanism for the formation of RSDs due to the combined interaction of wave stirring with a weak advective mean current is explored in Chapter 4. Suggestions for the formation of the various RSDs encountered in this study are offered below.

Facies 3: Outcrop related RSDs The bands of poorly sorted gravely sands with large ripples that flank most of the reef areas are probably the result of waves and tidal currents being steered and intensified in the vicinity of bathymetric irregularities. The evidence for this is the association with the reef and the way the grain size and ripple size increases close to reef outcrop that rises irregularly above the general level of the adjacent fine
sand plain. The tidal current simulations (Figure 2.15) show that currents are steered and increase in speed in the vicinity of rock outcrops. These rock outcrops likely act as scour agents causing increased velocities of flow and enhanced turbulence as in the case of other objects protruding above the ambient bed (see Chapter 5).

**Facies 4: Nearshore shore-normal RSDs** These features form just seaward of the nearshore bar where the sand cover is several meters thick (e.g. Fig. 2.27) so they are unrelated to the underlying geological structure of the Holocene ravinement surface. They differ in this respect to the features reported by Storlazzi and Field (2000) off the sediment-starved Monterey Peninsula where sediment-filled, shore-normal palaeochannels occur in the underlying bedrock. However, their shore-normal orientation, proximity to the surf zone, and the prevalence of rips that extend at least 150 m offshore and to depths of 5 m (Bogle et al., 2001), suggest they may be related to seaward flowing rips generated during storms. Their ephemeral nature is not surprising given that there is considerable wave action, sediment transport, and sand bank movement in the vicinity. Changes in location are consistent with a rip current origin because rip channels migrate laterally along Tairua Beach (Bogle et al., 2001).

However, the individual spacing of these features is not consistent with rip current spacing. Furthermore it is not clear how rip currents, which decrease in energy seaward, would produce features that grow larger and wider in the seaward direction. The occurrence of these features at the steepest part of the upwardly-convex portion of the shoreface suggests that wave focusing may play a role in their formation, as was suggested for similar bands of coarse-sand off the East Gippsland coast of Australia of by
Black and Oldman (1999). It may be that some combination of rip currents and waves such that wave focusing may serve to increase the suspension of the fines with enhanced advective transport due to the presence of rip currents.

Facies 5: Offshore shore-parallel RSDs These deposits are unlike the shore-normal bands found in many inner shelf areas in that they trend parallel to the shore. Similar shore-parallel features have been reported by Hunter et al. (1988) in southern Monterey Bay in depths of 10-20 m and within 1 km of the shore where the wave environment is similar to Tairua. The Tairua features lie in somewhat deeper water (20-25 m and 1.5-2 km offshore). Interestingly, they occur almost continuously across the face of the Tairua and Pauanui beaches along inflection point where the upwardly-convex shoreface begins to flatten out and become upwardly-concave (Figures 1.8 and 2.7). The sediment cover is thin in some, but not all, places along this isobath. The frequently observed occurrence of RSDs within distinct bathymetric intervals is explored in Chapter 6, where a phase transition model is used to suggest the existence of zones of optimal RSD association.

Analysis of seismic data in part two of this chapter suggests that underlying geological structure does not strongly influence the alignment of Facies 5 RSDs. However, in environments that are more sand depauperate, where only a thin veneer of sediment is present, the underlying geological structure is thought to be important (e.g. Thieler et al., 2001; Schwab et al., 2000). The manner in which these RSDs align with the seaward edge of headlands and along the break in slope at the toe of the shoreface suggests that coastal morphology and bathymetric irregularities (reefs) on the seabed may
be a factor in the formation of this facies. Tidal currents, while more or less aligned with the features, are too weak to initiate sediment transport on their own and thus create the RSDs, yet analysis of suspended sediment data (Chapter 4) and modeling efforts (Chapters 4 and 6) suggest that mean currents may play a significant role in the long-term evolution and stability of RSDs. While there is no certainty of their origin, it would appear that shoreface morphology, wind generated currents during storms, and waves all play a role.

**Facies 6: Offshore shore-oblique RSDs** These features occur in deeper water (>30 m) in the northeast of the surveyed area. The morphology of these RSDs and other side-scan surveys in the area (Hume et al., 1995; Bradshaw et al., 1994) suggest they are related to a large field of sand ridges that occurs offshore to the north and south of the study area. Similar features, associated with low amplitude, long wavelength sand ridges, have been observed elsewhere (e.g. Thieler et al., 2001; Hume et al., 2000; Manighetti and Carter, 1999; Amos et al., 1996; Hilton, 1995; Field and Roy, 1983). These features previously have been thought to form during late stages of storm decay under down-welling bottom currents (e.g. Amos et al., 1996; Cacchione et al., 1984). An alternative hypothesis is that these features formed as part of a subtle sorting feedback mechanism recently postulated by Thieler and Murray (2004). The morphology and composition of the Facies 6 features encountered in this study are consistent with those predicted from application of Murray and Thieler's self-organizing model to conditions encountered at this field site. Application of the self-organization model by Murray and Thieler (2004) suggests that these RSDs or "sorted bedforms" are the product of wave stirring of
sediment and advection by tidal currents oriented orthogonal to the shape of the features. Simulations of the sorted bedform model using observed forcing conditions are presented in Chapter 4.

2.6.2 INCORPORATING VARYING ROUGHNESS INTO NUMERICAL MODELS

The findings of spatially variable but temporally stable complex sedimentary facies are of interest from a modeling standpoint. On the surface they suggest that spatially varying and time constant roughness is an appropriate parameterization for numerical models in situations like Tairua.

To achieve accurate simulations of currents and sediment transport in numerical models it is important that the topography and roughness are accurately parameterized in the models (Doucette and O’Donoghue, 2003). Topography is relief with a horizontal scale that is similar or greater than the wavelength of the waves. It includes rock outcrop, ridges, banks, troughs, and shoals (several 10’s to 100’s of meters scale). It acts to deform the waves by the processes of refraction and diffraction, steering and constricting flows. Topography can be accurately determined for model purposes by echo sounding or swath bathymetry. Roughness, on the other hand, is relief with horizontal scales smaller than the wavelength of the wavetrain. Roughness includes bedforms with wavelengths of several meters and smaller, down to seabed texture (grains). Roughness affects waves and current flows through surface friction, which dissipates energy reducing the height of the waves and the strength of the currents. In modeling, roughness may be parameterized as either constant (uniform roughness) or
spatially varying (non-uniform) over the model area, depending on the purpose of the model and the spatial precision required. An appropriate roughness is chosen following calibration against field measurements of flow conditions (waves and currents).

Quantifying spatially varying roughness is difficult because it necessitates mapping micro-topographic features including ripples, humps, pits/depressions, biological features and the sediment texture (grain size). Nevertheless, for detailed numerical models, spatially varying roughness can be parameterized for each model cell from maps constructed from seabed surveys using side-scan sonar, diver and video observations, and sediment sampling. Having done, this the question then arises about how relevant this ‘map of roughness’ is over long time scales.

Surveys at Tairua suggest that even in energetic environments the complex seabed facies distributions and roughness are stable at spatial scales of models (cell size 30-50 m) and at the time scales over which numerical models are most useful (tides, events, months, years), and that non-uniform roughness will better represent the natural situation in models. However, there may also be a need to incorporate time-varying roughness into models, for short intervals and on certain substrates. Evidence from other studies (Green and Black, 1999) and tripod deployments in this study (Trembanis et al. in press; Green et al., 2004; Chapters 3 and 4), suggest that the sandy substrate may change as ripples on the fine sand plain evolve into hummocks during storm events. Therefore, models may be improved by changing the roughness on the fine sand and RSD facies during storm events while maintaining their respective positions laterally.
2.7 CONCLUSIONS

This study of dynamic geological and sedimentary processes in a sandy coastal embayment shows that, rather surprisingly, spatially variable but temporally stable complex sediment facies patterns can exist on a wave dominated shoreface. Several different types of RSDs form under various conditions. Once RSDs form, and where sand supplies are insufficient to bury the rippled coarse sediments, the coarse patches are maintained with the assistance of enhanced turbulence over the rough bed. The complex seabed facies distributions and roughness are stable at spatial scales of models (cell size 30-50 m) and at the time scales over which numerical models are most useful (tides, events, months, years). Therefore, non-uniform roughness will better represent the natural situation in numerical models, although there may also be a need to incorporate time-varying roughness into models for short temporal intervals.
PART TWO-
THE STRATIGRAPHIC EXPRESSION OF
COMPLEX INNER SHELF SEDIMENTARY DEPOSITS

The following chapter is being prepared for submission to the journal *Geo-Marine Letters*
with authors: Trembanis, A. C. and Hume, T. M.
2.8 INTRODUCTION

Stratigraphic information from cores and rock sequences can provide valuable insight regarding paleoenvironmental conditions. Information on wave and current intensity, flow direction, water depth, and events responsible for the deposit can be inferred from careful interpretation of the stratigraphic record. Facies reconstruction is also possible by linking similar sedimentary units/horizons in adjacent cores. However, paleoenvironmental reconstruction is not without difficulty, particularly in heterogeneous sedimentary environments where the seabed is complex and comprised of mixed grain sizes (poorly sorted) and spatially variable (patchy) mixtures of sand and gravel that change with both space and time (Holland et al., 2003).

In the previous section of this study, several genetically different types of RSDs were identified at one geographic location. Short cores were taken through the RSDs and adjacent sand plains. Instrument deployments and numerical modeling of waves and currents characterized the hydrodynamics at scales ranging from the seabed boundary layer to the entire embayment. This information provided the opportunity to match the stratigraphic signature of RSDs from cores with their seabed signature and environmental conditions under which the facies were active. One of the conclusions from the present chapter that is relevant to paleo-environmental interpretation is that the RSD signature of fine/coarse sequences in cores does not reflect calm/storm sequences or embayment scale variations in oceanographic conditions, but rather reflects lateral adjustments in facies boundaries.
2.9 METHODS

Field measurements of the overall study (Trembanis et al., in press; Green et al.,
2004; Hume et al., 2003;) included coring, swath mapping by echo sounder, seismic
profiling, and high-resolution side-scan sonar, along with ground-truthing by seabed
sampling, SCUBA, and drop-camera video. In addition, seismic surveys of the offshore,
the deployment of instrumented tripods on the shoreface, and numerical modeling of
waves and currents were conducted.

Swath mapping of the seabed by heave compensated echo sounder and high-
resolution side-scan sonar along with the ground-truthing (Hume et al., 2003) allowed a
detailed facies map to be constructed (Figure 2.7). From this analysis, four
morphogenetically different RSD types were identified, that 1) were associated with rock
outcrop on the seabed (Figure 2.10, Facies 2) formed finger-like features in the nearshore
at 5–15 m depth (Figure 2.11, Facies 3) occurred as shore oblique features in 25 m depth
at the base of the shoreface (Figure 2.12, Facies 4) were associated with shore oblique
sand ridges in 35–45 m depth (Figure 2.13, Facies 6).

2.9.1 SEISMIC ACQUISITION AND PROCESSING

A boomer seismic system was utilized for sub-bottom profiling. Shore normal,
diagonal, and parallel lines were recorded throughout the field site and are shown in
planview in Figure 2.16. A schematic diagram of the boomer seismic set-up is shown in
Figure 2.17. The acquisition settings used in the field are summarized in Table 2.2.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
The seismic data were collected using a GeoAcoustics sound source (boomer) mounted on a catamaran with a Benthos 15/10S, high frequency, 10 element, 5 m-long hydrophone array. Both the catamaran and separate hydrophone array were towed approximately 25 m behind the survey vessel, on either side of the vessel's wake about 3 m apart (Fig 2.17). Analogue signals from the hydrophone array were filtered, digitized, and converted to standard SEG-Y format. Band pass frequency filtering was applied to the traces to remove noise outside the frequency range of the expected signal. Filtering was accomplished by converting the trace into the frequency domain using a Fourier transform. Parts of the frequency spectra then were filtered with a smooth cosine taper between the corner frequencies; an inverse transform was then applied to convert back into the time domain. The corner frequencies were 75, 150, 3500, and 4000 Hz.

A swell filter removed the heave associated with ocean swell and sea. This heave can be observed in the unprocessed records as undulations in the water bottom reflection and all subsequent reflections. The filtering is achieved by manually picking the sea floor reflection. A smoothed sea floor is calculated using a 40 trace gaussian moving average filter. The filtered sea floor was then subtracted from the user defined sea floor to recover the true seabed topography.

Following filtering, the seismic lines were loaded into Sonarweb Pro for analysis and digitization (Figures 2.22–2.26). Isopachs were calculated by taking the thickness between the seafloor and the reflector in question (Figures 2.27–2.29). Seismic profiles
were also incorporated as vertical images within the software package Fledermaus® in order to generate three-dimensional fence diagrams (Figure 2.26).

Short (~0.5 m long) diver-rammed cores of 8 cm diameter were taken from the seabed at 9 sites (Figures 2.19–2.21) to study the shallow sedimentary structure of the RSDs and contacts between the fine sand plain and coarse rippled sand facies. Cores were taken from locations near two types of RSD, namely the finger-like features (Type 2) and the shore oblique features (Type 3). The cores were split, described, photographed, and sub-sampled for grain size analysis. Gravel, sand, and mud concentrations were determined by wet sieving. Grain size was determined by dry sieving following washing and drying. The stratigraphic features of these cores are detailed below.

2.10 RESULTS

2.10.1 CORE LOGS

A set of three cores was taken at each of 3 sites, for a total of 9 cores, one set was taken in the RSDs that formed finger-like features in the nearshore at 5–15 m depth (Type 2) (Figure 2.19), and two sets within the large RSD that occurred as a shore oblique feature in 25 m depth at the base of the shoreface (Type 3) (Figure 2.20 and Figure 2.21). Each set of cores included a core from the coarse rippled bed, the adjacent fine sand plain, and the boundary between the facies. The core logs are shown in Figures 2.19–2.21. Two and three-dimensional reconstructions of the cross-section along one of the core transects is shown in Figure 2.18.
The key features of the stratigraphy in the cores include: alternating units of (i) grey, massive, well sorted, very fine sands and (ii) pinkish brown, massive, poorly sorted, gravelly coarse sand. The boundaries between the fine and coarser units generally are sharp. The fine sands are massive, or show weak horizontal banding due to the presence of sand sized shell fragments and possess thicknesses of only a few grains. When dry, the cores split along this banding. The coarse units are massive, show a weak tendency of fining upwards or are just abruptly coarser at the base. The gravel component is primarily shell material.

The fine units range in thickness from 5 cm at the boundary to 40 cm within the fine-sand plain. The coarse units range in thickness from 3 cm along the facies boundaries to 35 cm within the RSD.

2.10.2 SURFICIAL SEDIMENTS

The bedform and grain size characteristics of surficial sediments are described in part one of this chapter and summarized in Table 2.1. The fine-sand plain comprises a sandy seabed of well sorted to moderately well sorted very fine (0.07-0.12 mm) sand. The fine-sand plain is flat and featureless on the side-scan record, but diver observations and 900 kHz side-scan (Figure 3.2) reveal small symmetrical wave orbital ripples ($\eta = 3-5 \text{ cm}$, $\lambda = 15-20 \text{ cm}$), shallow pits, and bumps in places that are possibly the remnants of hummocky bedforms subsequently reworked by waves and bioturbation.
The coarse rippled bed in all types of RSD is broadly similar, comprising a poorly sorted, gravely coarse sand (mean size 0.6-2.0 mm) with large symmetrical wave orbital ripples (\( \eta = 15-35 \text{ cm}, \ \lambda = 70-130 \text{ cm} \)). The ripples are coarser in the troughs where shell fragments accumulate. The gravel component is primarily shell material. The ripples on both the fine sand plain and the coarser beds are oriented to the locally observed wave field.

The boundaries of the RSD with adjacent fine-sand plain generally are sharp, but can be more diffuse in places. Side-scan mapping in the ‘box’ on 4 occasions (Figures 2.8 and 2.9) shows that the nearshore shore-normal RSDs are ephemeral in nature, while the offshore shore-parallel RSDs are surprisingly stable, given the wave dominated environment.

2.10.3 SHALLOW SUBSURFACE SEDIMENTS

Seismic profiles conducted offshore of Tairua and Pauanui show a wedge of Holocene sediment overlies a pre-Holocene transgressive surface cut by numerous channels (Figures 2.22 and 2.23; and Figures 2.24 and 2.25). This surface is concave-up compared to the present day seabed that is convex-down. The Holocene sediment cover is several meters thick nearshore and thickest (~ 7 m) in about 15 m water depth and in the vicinity of Facies 4 (Nearshore shore-normal RSDs (Figure 2.27). In places, the Holocene sediment thins where the shoreface flattens and in the location of Facies 5
(Offshore, shore-parallel RSDs). At other locations the Holocene sediment cover is 3-4 m thick at this same break in slope (Figure 2.27).

The short core stratigraphy (Figures 2.18–2.21) provides some insight into the relationship between the coarse units and the adjacent fine sand. The cored sediment is unconsolidated and Holocene in age, as evidenced from the seismic data and age dating of similar deposits in the region (Bradshaw, 1991). The fine sand and coarse sand units in the cores are of similar grain size to the fine sand and RSDs facies on the seabed today (Figure 2.5). The fine-sand units are weakly laminated, whereas the coarse units are massive. Cores taken from a boundary in the RSD (Figure 2.20) in 22 m water depth off Tairua show: (1) the core in the rippled coarse sand some 20 m from the boundary penetrated 28 cm of coarse sand and 15 cm into fine sand below, (2) the core in the fine sand, some 10 m from the boundary, penetrated 32 cm of fine sand and 10 cm into coarse sand below and (3) the core taken at the boundary and in fine sand penetrated 5 cm of fine sand, then 13 cm of coarse sand, and then into 25 cm of fine sand below. The cores show that coarse sand is not confined to the RSDs but extends elsewhere as lenses underlying the fine sand. The coarse sand appears to form thin layers underlain by and interbedded with fine sand. The fine units in the cores are texturally similar though slightly more poorly sorted than the fine sand facies found on the seabed surface, perhaps owing to local wave reworking and mixing. The coarse samples from the cores exhibited grain size and sorting characteristics similar to the shell hash samples found elsewhere, though of a slightly smaller mean grain size, again perhaps due to local mixing with the adjacent fine sand (Figures 2.5 and 2.6).
The interpretation of the subsurface data is that the coarse sand units associated with RSDs (1) do not represent a pre-Holocene surface, (2) are not a continuous ‘pavement’ underlying the fine sands, but rather lenses of coarse sediment in the fine sand, (3) are perhaps lag deposits because they are poorly sorted, do not contain graded bedding, and have a thickness equal to the height of the ripples in the RSDs, and (4) interfinger with the adjacent fine sands, which implies that the boundaries are mobile at time scales longer than the span of the side-scan surveys (1 year). Tripod observations indicate that the ripples in the RSD are quite mobile throughout the year (Chapter 3; Trembanis et al., in press; Trembanis et al., 2002; Wright et al., 2002;).

2.11 DISCUSSION

2.11.1 RECOGNITION OF RSDs IN THE STRATIGRAPHIC RECORD

RSDs can be recognized in the stratigraphic record as associations of interbedded coarse and fine sedimentary units. The units comprise grey, massive, well-sorted, very fine sands, and pinkish-brown, massive, poorly-sorted, gravelly coarse sands. The coarse units are massive, displaying a weak tendency to fine upwards, or are just abruptly coarser at the base. The boundaries between the fine and coarser units are acoustically sharp, transitioning over a few meters laterally. The fine and coarse units range in thickness from 5–40 cm and 3–35 cm, respectively. Neither the coarse or fine units are globally extensive, i.e. the surficial pattern is not merely windows of coarse sand through spatially discontinuous fine sand deposits. Comparison with the surface deposits
suggests that the coarse units are approximately the thickness of the bedforms in the RSDs.

Plots of sorting versus grain size (Figures 2.5 and 2.6) for the surficial sediments and the core subsamples shows that the fine sands have a similar and narrow range of grain size and sorting. The coarse sand units range much more widely in size and sorting. Interestingly, the mean size for the coarse sediment on the contact lies somewhere between the fine and coarse sands, both in mean size and sorting, indicating mixing with the adjacent fine sand plain. Furthermore, the fine units in the cores are texturally similar though slightly more poorly sorted than the fine sand facies found on the seabed surface, perhaps owing to local wave reworking and/or bioturbation. This finding is consistent with the side-scan sonar data that show at spatial scales of meters and inter-annual time scales there is movement of the contact between the coarse and fine sand on the order of ~10m.

The coarse units are about the thickness of the bedforms and are coarser at the base and fine upwards. However, the stratigraphic sequence of upwards fining in the coarse beds is not necessarily graded beds resulting from deposition during storms. Instead the sequence may represent material from the coarser troughs of the ripples buried by the passage of coarse grained ripples over the bed within the RSDs, which is capped in turn by a layer of fine sand settling from suspension and originating from advection from the adjacent fine sand plain. The stratigraphy is the result of a cumulative pattern that takes a longer period to develop. First, a storm sets in
reactivating the large ripples concentrating the coarse shells in the troughs, and then the ripples migrate over the troughs. The large ripples become dormant as the energy drops, but there still exists an enhanced state of turbulence that potentially inhibits the settling of fine sand over the coarse bed. Next, background swell conditions take hold, which are energetic enough to mobilize the fine sands and make minor (i.e. sub 10s of meters) adjustments to the edges leading to interfingering in the case of the large RSDs. In the case of the shore perpendicular fingers, this sequence is capable of fully burying the features. Figure 2.30 is a conceptual diagram showing a possible sequence of lateral adjustments capable of producing the vertical sequences observed in the cores.

2.11.2 DEPOSITIONAL INTERPRETATION

The inner shelf environment, under which the RSDs and associated fine-sand plain form and exist, is wave dominated. Tripod measurements (Chapters 3 and 4) and numerical modeling show that tides on the open coast are diurnal and microtidal with spring ranges of about 1.5 m. Tidal currents are \(<10 \text{ cm s}^{-1}\). During the tripod deployments, the background long-period Pacific Ocean swell was interrupted by two 6-day periods of high waves. Sediment was in suspension at all three sites during the period of high waves. Sediment was in suspension continuously under the background swell at the 15 m fine-sand site, less so at the 22 m fine-sand site, and occasionally at the 22 m coarse-sand RSD site (Green et al., 2004; Chapter 4).

Importantly the large, coarse grained ripples in the RSDs are mobile during energetic events (Trembanis et al., in press; Trembanis et al., 2002; Wright et al., 2002;).
These ripples are wave orbital ripples that align themselves with the incoming waves. In contrast, the ripples on the fine bed re-align themselves with both small and large waves. The lack of cross stratification in the cores from the fine sand does not necessarily mean that there were no ripples, because ripples are observed on the surface of the fine sand plain. Ripples may not be apparent because the sediment is well sorted. In fact there is evidence that there may be hummocky stratification forming in the fine sand at the peak of large events (Green et al., 2004) that are not visible with the narrow cores.

Alternating coarse/fine inner shelf sediment deposits have often been thought of as passive and relict (Carter and Carter, 1986; Swift, 1976; Swift et al., 1971; Emery, 1968). In fact, radiocarbon dating of rippled coarse sands and gravels in 23m, 33–35m and 35m depth from the inner shelf just south of Tairua by Bradshaw et al. (1995) returned ages of 3,000–3,800 yrs BP. A key finding from the studies on the Tairua inner shelf is that the coarse grained sediment in the RSDs is modern and actively reworked during storms. Repeated side-scan sonar surveys, diver observations, and drop camera video show the rough bed to be covered by large wave orbital ripples that reform and sharpen during storm events. Suspended sediment data from ABSs and altimeter data confirm suspension and reworking of the coarse material during large events (Green et al., 2004). The total thickness of the bed appears to be reworked. The rippled coarse sediment in the RSDs is not relict sediment. Thus, it is perhaps better described as palimpsest or perhaps a mix of modern and palimpsest material.
2.11.3 PARADOXICAL ADJACENT OCCURRENCE OF FINE SAND AND COARSE UNITS

Rather paradoxically, the coarse and fine facies of RSDs coexist side-by-side on the seabed over several years. Furthermore, facies boundaries between unconsolidated sediments can be sharp despite the fact that the inner shelf environment is one of shoaling energetic waves with dynamic bedforms (diagnostic of sediment mobility and sand transport). Interpretation of the subsurface data (Hume et al., 2003) indicates that the coarse sand units associated with RSDs (1) do not represent a pre-Holocene surface, (2) are not a continuous 'pavement' underlying the fine sands, but rather lenses of coarse sediment in the fine sand, (3) perhaps are lag deposits because they are poorly sorted, do not contain graded bedding, and their thickness is about that of the height of the ripples in the RSDs, and (4) interfinger with the adjacent fine sands, which implies that the boundaries are mobile at time scales longer than the span of the side-scan surveys (1 year). Tripod measurements indicate that the ripples in the RSD are quite mobile throughout the year (Trembanis et al., in press; Trembanis et al., 2002; Wright et al., 2002). Once RSDs form and sand supplies are insufficient to bury the rippled coarse sediments, the coarse patches are maintained with the assistance of enhanced turbulence and inhibited deposition of fines over the rough bed (Green et al., 2004). Thus, while the coarse and fine contrasting sediment types occur side-by-side on the seabed under the same large-scale wave and current forcing conditions, they are in equilibrium with small-scale boundary layer conditions.
Lateral movements of the adjacent contrasting facies produces interfingering of coarse and fine units. As a consequence, interbedded coarse and fine sand units in shoreface stratigraphic sequences do not necessarily indicate classic fair-weather storm sequences or changes in base level (e.g. sea level change). They may just be the stratigraphic signatures of dynamic RSDs. Therefore, caution should be taken when correlating between cores because the RSDs are likely composed of non-continuous lenses with only limited lateral extent.

2.12 CONCLUSIONS

The cores examined in this study show the stratigraphic expression of a spatially complex seabed where coarse-grained, rippled sediments occur in shallow depressions within fine sand plains on the inner shelf in depths of 15 – 60 m. RSDs can be recognized in the stratigraphic record as associations of interbedded coarse and fine sedimentary units. RSDs in the stratigraphic record are indicative of an environment that is either wave dominated or a mix of waves and currents. Their use in determining the depth of deposition is limited because RSDs are found in depths ranging from 5 to 60 m. Because RSDs run at various angles to the shoreline, the orientation of the RSDs is no guide to the orientation of the paleoshoreline. However, the orientation of the ripples provides the direction of major waves in storms because ripples in the coarse sediments only move during storms. While the coarse and fine contrasting sediment types rather paradoxically occur side-by-side on the seabed under the same large-scale wave and current forcing conditions, they are in equilibrium with local hydrodynamic conditions at the scale of the boundary layer. Neither of these facies are relict, although they may be
considered to be palimpsest. Lateral movements of the adjacent contrasting facies produces interfingering of coarse and fine units. As a consequence, interbedded coarse and fine sand units in shoreface stratigraphic sequences do not necessarily indicate classic fair-weather storm sequences or changes in base level (e.g., sea level change). The resulting vertical sequences may just be the stratigraphic signatures of RSDs.
Figure 2.1 Photos Tairua and Pauanui Beaches, Coromandel Peninsula New Zealand
Figure 2.2 Ground Penetrating Radar profiles across the barrier complexes of (a) Tairua Beach and (b) Pauanui Beach. Courtesy Dr. S. Nichol
Figure 2.3 Location of sediment samples.
Figure 2.4 Adjacent sediment samples from Fine-Sand Plain (FSP) and Rippled Scour Depression (RSD) facies.
Figure 2.5 Cross-plot of mean grain size and sorting for shelf surface and diver core sediment samples
Figure 2.6 Histogram of Sediment Samples from Various Locations.
<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>Coarse Shell Hash/Gravel</th>
<th>Fine Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel (%)</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>93</td>
<td>99</td>
</tr>
<tr>
<td>Mud (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Carbonate (%)</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td>Mean grain size (phi)</td>
<td>0.42</td>
<td>3.11</td>
</tr>
<tr>
<td>Description</td>
<td>Coarse sand</td>
<td>Very fine sand</td>
</tr>
<tr>
<td>Mean grain size (mm)</td>
<td>0.90</td>
<td>0.12</td>
</tr>
<tr>
<td>Range of grain size (mm)</td>
<td>0.27 to 2.08</td>
<td>0.08 to 0.26</td>
</tr>
<tr>
<td>Standard deviation (mm)</td>
<td>0.54</td>
<td>0.05</td>
</tr>
<tr>
<td>Description</td>
<td>Poorly sorted</td>
<td>Well sorted</td>
</tr>
<tr>
<td>Overall textural description</td>
<td>Coarse sand</td>
<td>Very fine sand</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.50</td>
<td>-1.33</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>4.40</td>
<td>10.12</td>
</tr>
<tr>
<td>Bedforms</td>
<td>orbital ripples</td>
<td>small ripples</td>
</tr>
<tr>
<td>Bedform Height (cm)</td>
<td>26-36</td>
<td>3-5</td>
</tr>
<tr>
<td>Bedform Length (cm)</td>
<td>75-120</td>
<td>10-15</td>
</tr>
<tr>
<td>RSD</td>
<td>Fine Sand Plain</td>
<td></td>
</tr>
<tr>
<td>Sedimentary body type</td>
<td>Rippled scour depression</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 Summary of the Textural Analysis of Main Inner Shelf Sediment Types.
Figure 2.7 Map of bathymetry (2 m contour intervals) and sediment facies. The fine sand-plain (FSP) is yellow, the RSDs are red and the reefs are black.
Figure 2.8 Repeated Side-scan Sonar Mosaics of the Tairua/Pauanui Inner Shelf.
High backscatter = dark shades; Low backscatter = light shades
Figure 2.9 Outline of facies boundaries surrounding the large shore-parallel Rippled Scour Depression (background image represents September 2001 survey)
Figure 2.10 Facies 3 Outcrop Related, Rippled Scour Depressions (RSD)
Figure 2.11 Facies 4- Nearshore shore-normal Rippled Scour Dpressions (RSD)
Figure 2.12 Facies 5- Offshore shore-parallel Rippled Scour Depression (RSD)
Figure 2.13 Facies 6- Offshore shore-oblique Rippled Scour Depression (RSD)
Figure 2.14 Conceptual Diagram of Rippled Scour Depression Types Encountered in this Study
Figure 2.15 Peak flood tidal currents from MIKE21 (45 m cell spacing) Vector arrows scaled to current speed.
Figure 2.16 Tracklines for side-scan sonar, seismic, and bathymetric surveys
Figure 2.17 Diagram of Seismic Equipment Configuration. Courtesy M. Stevens
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot interval</td>
<td>1000 ms</td>
</tr>
<tr>
<td>Record length</td>
<td>120 ms</td>
</tr>
<tr>
<td>Sample rate</td>
<td>24 KHz</td>
</tr>
<tr>
<td>Filter (band pass)</td>
<td>150 Hz – 10 KHz</td>
</tr>
<tr>
<td>Source energy</td>
<td>300 J/shot</td>
</tr>
<tr>
<td>Vessel speed</td>
<td>4.5 – 6.5 kn</td>
</tr>
<tr>
<td>Shot spacing</td>
<td>2.3 – 3.5 m</td>
</tr>
</tbody>
</table>

Table 2.2 Sub-bottom Acquisition Settings
Figure 2.18 Cross-section of Short-core Stratigraphy from RSD (Facies 5) at 22 m water depth
Figure 2.19 Shallow core stratigraphy from site 1- Facies 4 nearshore shore-normal RSD
Figure 2.20 Shallow core stratigraphy from site 2 - Facies 5 offshore shore-parallel RSD
Figure 2.21 Shallow core stratigraphy from site 3- Facies 5 offshore shore-parallel RSD
Figure 2.22 Seismic line (Diagonal 2) off Tairua Beach (see Figure 2.16 for location) showing the Holocene sediment body and location of the RSD in 22 m water depth
Figure 2.23  Seismic line (Diagonal 2) off Tairua Beach (see Figure 2.16 for location) showing the Holocene sediment body and location of the RSD in 22 m water depth.
Figure 2.24 Seismic line (Seis 41) off Pauanui Beach (see Figure 2.16 for location) showing the Holocene sediment body and location of the RSD in 18 m water depth.
Figure 2.25 Seismic line (Seis 41) off Pauanui Beach (see Figure 2.16 for location) showing the Holocene sediment body and location of the RSD in 18 m water depth.
Figure 2.26 Fence diagram of sub-bottom profile lines off Tairua/Pauanui Embayment. Rock reef associated with Mt. Paku and the notch of the large RSD are both prominently visible.
Figure 2.27 Isopach of Holocene Sediment Thickness (meters)
Figure 2.28 Isopach of Upper Holocene Sediment (meters)
Figure 2.29 Isopach of Lower Holocene Sediment (meters)
Figure 2.30 Schematic Diagram Illustrating Sequence of Lateral Adjustments Resulting in Interfingering Stratigraphic Sequence. FSP = Fine-sand Plain facies. RSD = Rippled Scour Depression
CHAPTER 3

THE ROLE OF SEABED ROUGHNESS IN BOUNDARY LAYER DYNAMICS
OVERVIEW

In the previous chapter, the surficial and stratigraphic signature of heterogeneous sediment deposits was presented. This chapter builds on the contextual framework of the previous chapter, which examined the sedimentary composition and geologic signature of these features. In this chapter, studies of hydrodynamic behavior and boundary layer characteristics associated with variable roughness patterns are conducted.

In part one, a detailed analysis of the bedform dynamics and hydraulic roughness and turbulent fluctuations over rough and smooth beds from the tripod study in Tairua, New Zealand is conducted. Three tripods supported acoustic Doppler velocimeters, acoustic Doppler current profilers, acoustic backscatter sensors, and other sensors. Moreover, these tripods provided time series data on boundary layer processes, suspended sediment, and bedforms. Rough areas of coarse sand exhibited ripples with heights and lengths of ~25 cm and ~100 cm, while smooth areas supported smaller ripples with heights and lengths of ~5 cm and ~20 cm. Contacts between the two surfaces were sharp and maintained their position. Roughness contrasts were enhanced significantly during storms, which simultaneously accentuated migrating orbital ripples over the coarse bed and replaced ripples on the fine sediment bed with smoother hummocky features.

Spectra of the fluctuating vertical velocity components, $w'$, from both smooth and rough sites showed good fits to $-5/3$ slopes within the inertial subrange enabling independent estimates of bed stress to be made via the inertial dissipation method (IDM). We also utilized the vertical fluctuation data to obtain alternative estimates of the wave friction factor, $f_w$, following Smyth and Hay (2002; SH). These two methods yielded generally similar results. Under high wave conditions, $f_w$ estimated via IDM averaged 0.027 at the rough site and 0.0045 at the smooth site while the SH method gave respective values of 0.027 and 0.013. Under low energy conditions, $f_w$ from IDM averaged 0.0082 at the rough site and 0.012 at the smooth site, while the SH method yielded mean values of 0.0080 and 0.016. Thus, $f_w$ was much larger at the rough site than at the smooth site during storms but smaller at the rough site during fair-weather. During storms, structured vortices with frequencies at the first harmonic of the swell waves formed over the rough surface and penetrated above the wave current boundary layer.
causing retardation of mean currents. Such storm-induced vortices were only intermittently present over the smooth surface. The application of several bedform roughness models produced some qualitatively similar trends in $f_w$, although predicted $f_w$ was larger than observed values at the rough site. Additionally, low modeled values of $f_w$ over the smooth bed during high energy was assumed to be due to plane bed by theory rather than the observationally inferred hummocky bed. This study indicated that spatial and temporal variability in ripple roughness has significant effects on boundary layer thickness, mean current drag, and the wave friction factor in ways that are not adequately captured by present, widely used, models of seabed roughness.

In part two, the study shifts from a geologically stable setting to the rapidly transgressing barrier islands off the Eastern Shore of Virginia. Here, as in the case of Tairua, sharp contrasts in shoreface roughness are rampant. The study off of Cedar Island highlights the role of roughness and hydrodynamics in several unique ways relative to Tairua. Cedar Island is subject to typically far less energetic flow conditions as compared to Tairua. Additionally, whereas in the New Zealand study the roughness variation was largely physical (ripples or smooth/hummocks) roughness variability off of Cedar Island is composed of both physically and biologically (oyster shell beds, marsh peats) derived roughness elements.

Records from the past 150 years show that Cedar Island, has been receding landward at an average rate of over 5 meters per year by “rolling over” the marsh, estuarine and tidal channel deposits behind the island. This process has led to the progressive exhumation of marsh peat, oyster shell beds, and other coarse deposits on the foreshore and inner shelf as the thin veneer of sand has migrated toward the west through a combination of dune wash-over. Consequently, the inner shelf exhibits a complex pattern of spatially varying hydrodynamic roughness and associated variations in drag coefficients, wave boundary layer thickness and predicted bed stresses. Analysis of a 40-day record of near bed measurements indicates that exposed peat embedded with relict oyster shells exert a drag on mean currents in excess of three times that of adjacent smooth sand beds. Wave friction factors differed by an order of magnitude between shell and smooth sand beds. While this study lacks the full suite of detailed measurements collected at Tairua, suggests that complex and irregular spatial bed
patterns may significantly affect storm-driven flows on this and similar transgressive shoreface environments.
PART ONE
CASE STUDY FROM TAIRUA/PAUANUI EMBAYMENT NEW ZEALAND

The material in this chapter has been accepted for publication in Continental Shelf Research with authors: A.C. Trembanis, L.D. Wright, C.T. Friedrichs, M.O. Green, and T.M. Hume

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
3.1 INTRODUCTION
Numerous studies of inner-shelf settings around the world (Green et al., 2004; Murray and Thieler, 2004; Hume et al., 2003; Traykovski and Goff, 2003; Hume et al., 2000; Schwab et al., 2000; Drake, 1999; Wright et al., 1999; Riggs et al., 1998; Thieler et al., 1995; Cacchione and Drake, 1990; Green, 1986) demonstrate that morphologic complexity is more the norm than the exception. Recent work in the Middle Atlantic Bight (e.g. Friedrichs and Wright, 1998; Wright et al., 1994; Madsen et al., 1993; Wright, 1993), the Lower Chesapeake Bay (e.g. Wright et al., 1997), and the northern California shelf (e.g. Cacchione et al., 1999; Ogsten and Sternberg, 1999; Wright et al., 1999) show that temporal and spatial variations in bed roughness and sediment type can affect the bottom boundary layer thickness, bottom drag as sensed by the wind-driven mean currents, and the vertical suspended-sediment concentration profiles near the bed. However, roughness variations examined in those studies largely involve gradual across-shelf changes with depth rather than abrupt complex changes both along and across-shelf.

In reality, the seabed can be highly variable in space within any given subenvironment (e.g. inner shelf, mid-shelf, outer shelf). Hence, the boundary layer and sediment dynamics must also be spatially variable within those subenvironments. Understanding the hydrodynamics and sediment dynamics of such situations is a first step in gaining the ability to model the medium-term and long-term behavior of transgressive or temporally changing coastal reaches. Spatial variability in bed roughness also may cause corresponding variation in bottom-boundary layer thickness and turbulence thereby inducing or enhancing “patchiness” in bed sediment and roughness patterns. In this part
of Chapter 3, some manifestations and boundary layer consequences of complex roughness patterns on the continental shelf are explored, using a field study from the North Island of New Zealand.

A list of specific questions addressed in this portion of the study includes the following: How do bedforms and roughness on contrasting substrates vary spatially and temporally over the course of a storm and during intervening fair-weather periods? How well do existing models account for the observed differences? How does spatially varying roughness affect boundary layer turbulence and bed friction? How do temporal changes in roughness affect drag and turbulence over the course of a storm event? What are the appropriate wave friction or drag coefficients at both local and shoreface scales and at different times during a storm?

3.2 GENERAL AND THEORETICAL BACKGROUND

In addition to the general theoretical background presented in Chapter one, additional theoretical context is developed below.

3.2.1 DECOMPOSITION OF TURBULENCE FROM LINEAR WAVE THEORY

To distinguish among turbulence, vortices shed from bedforms, and wave-orbital motions, the following equation is used to “decompose” the measured vertical flows, \( w \):

\[
VAR_{\text{unexplained}} = VAR_{\text{measured}} - VAR_{\text{LWT}}
\]

where \( VAR_{\text{measured}} \) is the variance of the measured \( w(t) \), \( VAR_{\text{LWT}} \) is the variance of...
the vertical component of the wave-orbital motion, and $\text{VAR}_{wUn\,\text{explained}}$ is assumed to be the sum of the variance due to $w'$, the vertical component of turbulence and vortices. $\text{VAR}_{wLWT}$ was estimated using linear wave theory by multiplying the spectrum of measured $p(t)$, where $p$ is pressure, by the linear-theory transfer function for converting pressure to vertical component of wave-orbital velocity, and then integrating the result over the gravity-wave frequency band 0.5–0.005 Hz. Hence, $\text{VAR}_{wLwr}$ so estimated and the measured pressure signal are mutually consistent with linear wave theory. The rationale underlying this method is that fluctuations in measured pressure are related solely to wave-orbital motions and not to turbulence or velocity fluctuations associated with the passage of coherent vortices.

3.2.2 VORTEX RIPPLES AND HUMMOCKY BEDFORMS

An important consequence of well-developed, wave-induced ripples is the tendency for such ripples to cause the release of structured vortices that extend above the wave boundary layer, causing exchanges of both momentum and sediment.

Empirical models predict that once the bed becomes strongly mobilized, ripple geometries are diminished with increasing wave mobility number ($\psi'$) (equation 1.20) eventually the ripples are washed out and replaced by sheet flow. However, field observations show that irregular hummocky topography can develop under energetic storm flow conditions. For example, Green and Black (1999) observed a transition to a hummocky bed, not a plane bed, under energetic waves on a wave-dominated sandy shoreface at Mangawhai, New Zealand. The hummocky bed replaced the rippled bed.
when $\theta'$ exceeded 0.14, but observations ceased before the rippled bed reformed under diminishing waves. Traykovski and Goff (2003) observed a similar transition to "irregularly spaced pockmarks" on the fine sand plain surrounding a rippled scour depression off of Martha's Vineyard, Massachusetts. The hummocky topographies observed by Traykovski and Goff (2003) and Green et al. (2004) were characterized by irregular relief bedforms with heights of 10–15 cm and horizontal length scales ( spacings) of 2–5 m. Green et al. (2004) inferred that the same ripple-hummock transformation occurred at the onset of high waves at Tairua based on the same clustering of suspended-sediment reference-concentration estimates that Green and Black (1999) found to accompany the ripple-hummock transformation at Mangawhai. From the standpoint of friction and drag, the low relief and widely spaced hummocks may be considerably less rough to the fluid flow than a rippled bed. The ripple models described above predict the ripples and their replacement by sheet flow but do not account for the potentially important transformation to hummocky topography.

3.2.3 MOVEABLE BED ROUGHNESS

When the bed is in motion, the moveable bed roughness $k_m$ cannot be ignored. For $k_m$, Nielsen (1981) gives

$$k_m = (\theta' - \theta'_c) d_{50}$$

where $\theta'_c$ is the critical skin friction Shields parameter at which motion of particles is first initiated based on the $d_{50}$ grain size statistic. However, tests of roughness models using field data from shoreface environments conducted by Xu and Wright (1995) showed that a better (and typically lower) approximation is obtained from
where $\Omega$ is a proportionality constant $\sim 5$. Once ripples are washed out and sheet flow prevails or hummocky topography develops, $k_r$ can be ignored assuming that the roughness of hummocky topography is very small relative to $k_r$. Hence, $k_m$ becomes dominant and $k_b \rightarrow k_m$. Based on field observations of an inner shelf boundary layer under severe storm conditions, Madsen et al. (1993) concluded that the effective roughness of a flat movable bed under such conditions is approximated by

$$k_m \sim 15d_{50}$$

(3.4)

3.3 THE FIELD SITE

For this portion of the study, the key aspects of the field site were variations in hydrodynamics and bed roughness across changes in depth and substrate. Aspects of the field site pertinent to these issues are provided below.

The inner shelf profiles off Tairua and Pauanui Beaches are shown in Figure 1.8 in comparison with the well-studied shoreface off Duck, North Carolina. The profiles exhibit four main segments: (1) a concave upward segment extending from the shore to around the 8 m isobath; (2) a seaward steepening, convex upward segment between the 8 m and 15 m isobaths; (3) another concave upward segment extending from 15 m to 22 m depth; and (4) a linear segment extending from the 22 m isobath to the 50 m isobath. Within the concave upward region just seaward of the 22 m isobath, a very rough surface composed of shelly coarse sands is exposed and surmounted by large wave-generated ripples. The median grain size ($d_{50}$) of this surface is 0.78 mm but the poorly sorted
material ranges in size from 0.27 mm to 2.08 mm. Elsewhere, this rough surface is buried beneath well-sorted finer sand ($d_{50} = 0.22$ mm), resulting in a relatively smooth surface with smaller ripples. In general, the seabed surface is variable, giving rise to appreciable spatial variations in bed roughness.

On this the lee shore of New Zealand, the wave climate is composed primarily of mixed storm and swell waves. Storms, typically in the form of occluded cyclones, Tasman depressions and, occasionally, decaying tropical cyclones (Figure 3.4) generate large waves with maximum significant wave heights and periods of 7.0 m and 13 sec (Gorman et al., 2003). Tidal currents are generally weak, except at inlets and around the islands. In the near surface, tidal currents typically are overprinted by wind-generated currents. However, near bed mean currents are typically much weaker due to significant velocity shear with depth (Figure 3.7).

3.4 FIELD AND ANALYSIS METHODS

High-resolution data on morphology and bed characteristics were obtained at three separate times using side-scan sonar imagery supported by video footage using a drop-down camera, along with SCUBA observations and shallow coring of seabed sediments, as detailed in Chapter 2.

Two fully instrumented tripods similar to that shown in Figure 3.1 and one comparable tripod without acoustic Doppler velocimeters were deployed simultaneously on the Tairua shelf at different depths and on contrasting substrates. The tripods were
deployed for 6 weeks during the late summer and early autumn season of tropical cyclones (February 16 – March 23, 2001). Two of the tripods held: two acoustic Doppler velocimeters (ADV) for measuring three-dimensional turbulence; upward-facing acoustic Doppler current profilers (ADCP) for measuring currents between the sea surface and the region a short distance above the tripod; two or three acoustic backscatter sensors (ABS) for measuring suspended sand; vertical arrays of optical backscatterance sensors for additional measurement of suspended fines; a conductivity sensor; pressure sensors; a vertical array of electromagnetic current meters (EMCM) for measuring mean shear and wave-orbital velocities; and sediment fall traps (Table 3.1). The resulting datasets were used to assess differences in boundary-layer dynamics, including the time-averaged drag coefficient, 3D turbulence structure, and bedforms (3D geometry and shape). Mean velocity profiles, which included EMCM derived data, were not reliable enough to allow estimation of $z_0$ via equation (1.2) but the ADV data, sampled at 5 Hz, permitted application of the inertial dissipation method. The ADVs focused on 1 cm$^3$ averaging volumes located 16 cm beneath the sensors. Over the rough bed these foci were situated at elevations above the bed of 43 cm and 53 cm; above the smooth bed the selected elevations were 14 cm and 31 cm.

The analyses of the tripod data emphasized storm-generated swell “events” of several days duration. The data were utilized to reveal the nature of the local boundary layer and sediment dynamics at each deployment site, and the dynamics were interpreted in terms of the driving flows (waves and currents) and seabed (sediments and bedforms) at each site. Initially, a goal of the study was to distinguish between local and sub-
regional scale benthic dynamics using comparative analyses from ADVs vs. EMCM. However, some of the EMCMs failed and the resulting profiles were inadequate. In contrast, the ADV data proved very reliable. The ADVs focused on an averaging volume within two to three ripple heights above the bed and thus recorded information on \( f_r \), \( u^* \), and \( C_d \) values related to local roughness.

3.5 BED CONDITIONS AND FORCINGS DURING THE FIELD PERIOD

A map derived from a side-scan sonar mosaic of the inner shelf seabed in Tairua embayment (Figure 2.7) shows the spatial distribution of contrasting roughness types. The rough areas were composed of coarse sand \( (d_{50} = 0.78 \text{ mm}) \) and exhibited ripples with heights \( (\eta) \) and lengths \( (\lambda) \) of 25 cm and 100 cm, respectively, during the fair-weather conditions when surveys and diver observations were carried out. The smooth areas prevailed over the majority of the shoreface. During the fair-weather observations, this smooth fine sand surface supported smaller ripples with heights \( (\eta) \) of 5 cm and lengths \( (\lambda) \) of 20 cm. The rough surfaces were interpreted as morphologically similar to the “rippled scour depressions” (RSDs) described on other shelves (e.g. Traykovski and Goff, 2003; Thieler et al., 1995; Cacchione et al., 1984). In contrast to the migratory RSD features described by Traykovski and Goff (2003), contacts between the rough and smooth surfaces studied here were sharp and maintained their positions over a two-year period despite highly energetic conditions. Although direct evidence as to the genesis of the depressions is not conclusive, hindered settling of sediment suspended above the features is implicated in the maintenance of the rough surfaces (Green et al., 2004; Chapter 4). Hume et al. (2003) developed a morphogenetic classification of the features
found at the field site put forward in Chapter 2 part 1. At contact boundaries, the fine sand layer stood about 40 cm to 50 cm above the adjacent coarse layer. Figure 3.2 shows a side-scan sonar detail of the contact between the rough and smooth surfaces. Pronounced, long crested wave ripples with height \( \eta = 25 - 35 \) cm and length \( \lambda = 120 - 130 \) cm are evident in the right portion of the image and the smoother fine sand surface is in the left side of the image. Diver photographs and sonographs samples of the rough and smooth surfaces are shown in Figure 3.3.

Time series of atmospheric pressure and wind speeds as measured nearby during the period of tripod deployment are shown in Figures 3.5a and 3.5b, and the corresponding wave conditions as measured at the 22 m (rough) site are presented in Figures 3.5c, 3.5d, and 3.5e. The unremarkable atmospheric pressure and wind speed records belie the fact that the relatively intense Tropical Cyclone (i.e. hurricane) Paula passed 1600 km to the northeast of the field site during the experiment period. This storm, and another near the end of the deployment, generated high-energy, long period swell, that strongly agitated the seabed (Figures 3.5c and 3.5d). The 12-second swell associated with Paula reached heights of 2.6 m and produced bottom orbital speeds of 70 cm s\(^{-1}\) at a depth of 22 m (Figures 3.5c and 3.5e).

Mean tidal current vectors at about 3 m below the sea surface as observed by the upward-aimed acoustic Doppler current profilers over the rough (depth =22 m) and smooth (depth = 15 m) surfaces are shown in Figures 3.6a and 3.6b respectively. The currents exhibited elliptical rotations with long axes oriented approximately parallel to
isobaths. Typical speeds of these upper-water-column tidal flows were 30 – 50 cm s^{-1}. However, the currents decreased dramatically in speed with proximity to the bed. Figures 3.7a and 3.7b show time series of current speeds at three different elevations above the bed at the two sites. The uppermost series correspond to the vectors shown in Figure 3.6. The lowermost series were obtained from the EMCMs. Notably, the most pronounced reductions in near-bed mean currents do not coincide with times of weaker upper water column tidal currents but, rather, with the two high-energy swell events. Also, near-bed flow retardation was greatest over the rough bed. This retardation of the mean current profiles is interpreted as being caused by enhanced drag (momentum flux) related to vortices created by strong orbital flows over the large ripples.

3.6 OBSERVED BEHAVIOR OF BEDFORMS ON ROUGH AND SMOOTH SURFACES

Diver observations provided direct information on bed roughness elements during fair-weather. The altimetry records from the ADV and ABS sensors were used to construct time series of bedform evolution at both of the sites during two storms and the intervening fair-weather. The interpretation of point altimetry records was complicated by numerous factors including possible tripod settling, erosion/deposition, high concentrations of near-bed suspended sediment, and instrument noise levels. Although the altimeters remained focused on a fixed point, the migration of active ripples allowed ripple height to be estimated from temporal changes in bed elevation. However, when ripples were present but dormant, altimeters showed unchanged bed elevations. Under those fair-weather conditions, diver observations provided information on ripple
Figures 3.8a and 3.8b show altimetry time series obtained from ADV and ABS sensors at the rough and smooth sites. Notably, large amplitude variations in bed level were recorded at the rough site during high-energy conditions, while changes at the smooth site were considerably lower in amplitude. This behavior suggests that storm waves sustained active and pronounced ripple roughness at the rough site and that the ripples migrated as Traykovski and Goff (2003) observed off Martha's Vineyard. Therefore, an estimate of the ripple height can be obtained from the magnitude of the amplitude fluctuation (~20 cm). Under the same high-energy conditions over the fine site, slow, moderate amplitude (~10 cm) fluctuations were recorded. This result is inconsistent with plane bed formation theory (as predicted by roughness models) but consistent with observations of the development and passage of low amplitude widely spaced hummocky bedforms as has been observed in similar settings (Traykovski and Goff, 2003; Green and Black, 1999). The development of hummocky bedforms has also been inferred for this site (Green et al., 2004) from analysis of suspended sediment data (see Chapter 4 for a more detailed treatment of this topic).

The small-scale variability in the altimetry records from the rough site during background swell conditions represent the inherent noise level of the measurement. Hence, changes in ripple dimensions at the coarse site appeared to be limited mainly to the two storm events suggesting that, during background swell conditions, the bedforms at the rough site are dormant. The slow increase in bed level recorded by the ABS during
the background swell conditions between the two storms likely represents tripod settling, deposition, or some likely combination of the two. During background wave conditions over the fine site, high frequency small-scale variability (noise) and intermediate-scale fluctuations with amplitudes of 3–5 cm were recorded. These intermediate-scale fluctuations may represent the migration of the smaller ripples observed by divers and side-scan sonar (Figure 3.3). These fluctuations were not observed over the coarse bed, which was inactive during background waves. Diver observations during low energy conditions showed ripples to have heights, \( \eta \), and spacings, \( \lambda \), of 5 – 8 cm and 20 – 30 cm, respectively, at the smooth site. Correspondingly observed dimensions at the rough site were 15 – 25 cm and 75 – 120 cm for ripple height and length, respectively. These observations are consistent with the altimeter results shown in Figure 3.8.

3.7 DIRECT OBSERVATIONS OF TURBULENT FRICTION OVER ROUGH AND SMOOTH SURFACES

Assessing bottom boundary layer characteristics at the Tairua field site was complicated by the fact that mean currents were very weak near the bed, while wave orbital motions were strong, at least during the times of most interest (storms). Because of the weak currents, it was not feasible to apply the von Karman-Prandtl formula (Equation 1.2) to obtain estimates of bed stress or hydraulic roughness (\( z_{oc} \)). Instead, the inertial dissipation (IDM) method was applied utilizing ADV data, following the successful approach of Kim et al. (2000) along with the method of Smyth and Hay (2002) to obtain direct estimates of the relative spatial and temporal variation in wave friction.

3.8 RESULTS FROM THE INERTIAL DISSIPATION METHOD
In order to minimize contamination of turbulent spectra by waves in the application of the IDM analyses, the fluctuating vertical components, $w'$ were utilized. Figure 1.13 shows one example of $w'$ spectra from simultaneous bursts during the first high-energy event at the two sites. Despite the weak currents over the rough bed, the spectral slope of -5/3 was evident at both sites, and $w'$ was roughly an order of magnitude more energetic at the rough site than at the smooth site despite the rough site being deeper (22 m) than the shallow site (15 m). An example from stronger currents and weaker waves is shown in Figure 3.11c. Utilizing data for those bursts that exhibited a good fit to the -5/3 slope in a fashion similar to the examples shown in Figure 1.13, it was possible to estimate $C_d$ via equations (1.15) and (1.11). The resulting time series for the two surfaces are shown in Figure 3.9. Gaps in the time series correspond to times when the -5/3 slope was absent. Notably, the time series demonstrate that during times of fair weather background swell, $C_d$ values were on the same order over the rough and smooth beds and were often measurably larger over the "smooth" (fine sand) bed than over rough bed (Figure 3.9). This condition probably reflects the fact that, during times of relatively small orbital semi excursions ($a_w$), the widely spaced dormant ripples of the rough bed induced $w'$ fluctuations that were no more energetic than, and sometimes less energetic than, those generated by the closer spaced active ripples of the smooth bed. However, during high-energy events, $C_d$ increased by four fold over the activated ripples of the rough bed and decreased by more than five fold over the smooth bed, reflecting the replacement of ripples with more widely spaced and smoother hummocks.

Near-bed currents associated with many of the estimates shown in Figure 3.9 were weak and probably did not sustain strong signals of isotropic turbulence at elevations significantly above the wave-current boundary layer. Hence, the greatest
confidence exists for results from bursts where currents exceeded 10 cm s⁻¹ over both the rough and smooth surfaces. Estimates of $Cd$ for ten cases from Figure 3.9 where $u_c > 10$ cm s⁻¹ yielded $Cd$ values of 0.03 ± 0.01 at the rough site and 0.007 ± 0.001 at the smooth site (Table 3.2) when small 2-D vortex ripples were present and 0.003 ± 0.001 when hummocks were suspected to have formed. As will be addressed later, these values were lower than those predicted by the Grant and Madsen (1986) wave-current boundary layer model.

3.9 RESULTS FROM ESTIMATING $\tilde{f}_w$ VIA EQUATION 1.16

In order to obtain a second independent estimate of the time varying wave friction over the rough and smooth beds, the approach of Smyth and Hay (2002) was followed utilizing the ratio of vertical turbulence intensity, $w'_{rms}$, to orbital velocity, $U_{rms}$, to estimate a modified wave friction factor, $\tilde{f}_w$, from equation 1.16. Measurements of $w'_{rms}$ were made at elevations significantly above the wave boundary layer, $\delta_w$; ADV averaging volume elevations were 43 cm over the rough site and 13 cm over the smooth site. In the analysis of $w'_{rms}$, a high pass filter was used with a three-point taper and a low frequency cut off of 0.2 Hz to remove the direct contributions of wave orbital motion. The Smyth and Hay (2002) formulation assumes that $w'_{rms}$ is measured within the wave boundary layer so the application of their equation is not a true measure of $f_w$. However, application of equation (1.16) to these data should still provide a useful index of roughness-induced friction. The purpose of this exercise was to assess the likely temporal variability of wave friction over the contrasting beds.

Figure 3.10 shows the results from applying equation 1.16 to the data from the rough and smooth sites along with the ratio $\tilde{f}_w \text{ rough}/ \tilde{f}_w \text{ smooth}$. As discussed in section
4.4, the behavior of \( f_w \) qualitatively paralleled that of values predicted by familiar models, but for reasons other than those assumed by the models. Specifically, during high-energy events, \( f_w \) increased roughly five fold at the rough site and decreased at the smooth site. However, during fair-weather, \( f_w \) was on average larger at the smooth site than at the rough site. This reflects, in part, the fact that active vortex ripples were present in the fine sands of the smooth site during fair-weather and, in part, the fact that the ADV averaging volume was much closer to the bed over the smooth site. Because of the difference in sensor elevation, the absolute differences in \( f_w \) between sites may have less meaning. On the other hand, the contrasting temporal behavior of \( f_w \) between the two sites suggests a clear interpretation: active ripples were present and enhanced friction over the smooth site during fair-weather and were absent during high energy when a hydraulically smoother hummocky bed replaced them. However, the reduced roughness of the smooth bed during high-energy conditions was probably not a consequence of ripples being replaced by a plane bed as most existing models predict. Instead, the sharp reduction in \( f_w \) is most likely attributable to the development of a hummocky bed, which was hydraulically smooth because elevations changes were spatially more gradual than when orbital ripples are present. The opposite situation prevailed on the rough surface, which continued to exhibit active ripples throughout the storm.

3.10 RESULTS FROM W' SPECTRAL ANALYSIS AND THE IMPORTANCE OF STRUCTURED VORTICES

The classic theory of wave boundary layers or wave-current boundary layers considers wave (or wave-current) induced eddy viscosity to be confined to the thin wave boundary layer (elevations less than \( \delta_w \)) or wave-current boundary layer (elevations less than \( \delta_{cw} \)). Eddy viscosity (turbulence) at higher elevations is assumed to be attributable
to current shear alone. However, Nielsen (1992) presented compelling data and arguments in support of the idea that wave interactions with well developed vortex ripples, such as those observed at the rough site, produce structured (anisotropic) vortices, which can suspend sediments to elevations significantly above $\delta_w$. Based on ABS observations of suspended sand from the inner shelf off Duck, North Carolina, Lee et al. (2002) concluded that vortices shed off ripples under strong waves and weak currents caused the effective wave boundary layer to be five times thicker than that predicted by the Grant Madsen model. These vortices are generated on both the forward and backward strokes of the wave and thus should have a frequency equal to twice that (half the period) of the primary wave.

To explore the possibility that such vortices may have played a role in retarding near-bed mean currents over the rough surface during storms, the power spectra of $w'$ during the high energy events were examined. The selection of $w'$ (as opposed to $u'$ for example) was based on the fact that as wave orbits approach the bed, the vertical components vanish and orbital motion is manifest as back and forth horizontal oscillations. In contrast, vortices ejected from the bed should have more energetic vertical components near the bed, but these motions should attenuate rapidly with distance above the bed. Power spectra (Figure 3.11a) of $w'$ over the rough surface at $z = 43$ cm (the elevation on which the lower ADV focused) during the storm peak exhibited pronounced peaks at the frequencies $\omega$ and $2\omega$ (T and T/2). However, at $z = 53$ cm, the peak at $\omega$ was much less energetic and that at $2\omega$ had nearly vanished. Over the smooth surface, peaks at $2\omega$ were absent and those at $\omega$ were no more energetic than motions in the low frequency part of the inertial subrange (Figure 3.11a). During fair-weather and at the onset of the storm, no significant peaks in $w'$ at $\omega$ or $2\omega$ were evident at either site (Figures 3.11c & 3.11b); however during the waning phase, the rough site exhibited a
prominent peak at $\omega$ and a secondary peak at $2\omega$ (Figure 3.11d). Low energy peaks over the smooth site appeared at $\omega$ during the waning storm phase (Figure 3.11d), possibly reflecting the fact that ripples developed under the lower energy conditions replacing the non-rippled hummocky bed of the storm peak.

The prominent vortex-induced peaks observed over the rough site during the storm peak at $z = 43$ cm were appreciably above the wave-current boundary layer. This observation suggests that vortices shed by the accentuated ripples under high swell conditions were probably effective in transporting the benthic mean-current momentum deficit higher into the water column than would be expected from conventional wave-current boundary layer models. This vortex exchange is likely to be the reason for the pronounced retardation of near-bed mean currents over the rough site during storms (Figure 3.7). Although this chapter does not deal explicitly with sediment suspension \emph{per se}, these same vortices surely must lift sediment well above the wave-current boundary layer, as argued by Nielsen (1992), and may very well serve an important function in maintaining the rough surface by preventing deposition there. Suspended sediment dynamics associated with varying bed roughness at this site is the focus of the next chapter and a recent paper by Green et al. (2004).

3.11 APPLICATION OF LINEAR WAVE THEORY (LWT) TO REMOVE ORBITAL MOTIONS FROM $w'$

The $w'$ spectra above show evidence for pronounced structured vortices over the rough site under high waves but not under background swell. Furthermore, there is no indication of vortices over the fine site under either background swell or high waves. While the absence of vortices over the fine-sand plain during high waves is consistent with the formation of plain beds, it is not consistent with the expectation from previous
work (Green and Black, 1999) of vortices over hummocky bedforms. Another unexpected finding from the $w'$ spectral analysis is the seeming lack of structured vortices over the fine-sand plain during background swell conditions when small vortex ripples were observed to exist. It is assumed that the sensors above the small vortex ripples were situated at elevations too high to detect vortices over the fine-sand plain during background swell conditions. Furthermore, the reason strong vortices were not observed over the presumed hummocky bed is that the $w'$ spectra technique is designed to highlight only those vortices shed at harmonics of the incident wave period for well-ordered vortex ripples and not for the irregularly distributed hummocks. Therefore, in order to examine further the near bed turbulence dynamics over the rough and smooth beds, a hybrid technique utilizing observed $w'$ variance data and $w'$ variance derived from linear wave theory (LWT) was applied as described above.

The results from the LWT approach (Figure 3.12) help to explain discrepancies and support the interpretation of hummocky bed formation. Under high waves at the rough site, the unexplained variance (difference between $Var_{measured}$ and $Var_{LWT}$) is at a maximum value (Figure 3.12a) as expected for the large ripples of the RSD. A similar increase in "vortex" related turbulence is observed over the fine-sand plain during the storm (Figure 3.12b), further supporting the interpretation that hummocky bedforms and not a plane bed develop during high waves on the fine-sand plain. Under high waves, the unexplained or vortex variance is high over the smooth site; which would not be expected if the bed washes out to plane conditions. However, this behavior is consistent with intermittent (aperiodic) but energetic vortices released from hummocks. During background swell conditions over the rough site (Figure 3.12a) the unexplained energy does not collapse onto the LWT value as it does over the fine-sand site during the same conditions (Figure 3.12b). This observation suggests that even when they are relict, the large ripples at the rough site enhance turbulence above them. Similarly, the behavior of
the unexplained variance over the fine-sand plain suggests that vortex shedding is low or absent during low waves. Additionally, the collapse of the observed variance onto the LWT predictions serves as a good test of the methodology, showing that the variance is well described by linear wave theory in the absence of vortex shedding.

3.12 MODEL PREDICTIONS OF $k_b$, $u_{*w}$, $f_w$, and $C_d$

3.12.1 MODEL PREDICTIONS OF RIPPLE ROUGHNESS $k_b$

The observed sediments, orbital velocities, and wave periods were used as inputs in applying the ripple models of Nielsen (1981; equations 1.21, & 1.22), Wiberg and Harris (1994; equations 1.26-1.30), and Wikramanayake (1993; equations 1.23, 1.24 & 1.25). The purpose of this exercise was not to exhaustively test or refine these predictive models, but rather to determine whether a conventional engineering model were at least broadly consistent with the general trends of our observations of $f_w$. Comparisons of observations with model predictions showed that the Nielsen model under predicted ripple roughness at the rough site. At that site, the Wikramanayake model yielded the closest fit to observations. The Nielsen model gave the closest fit to ripple dimensions observed at the smooth site. The Wiberg and Harris model predicted ripple dimensions at the rough site nearly identical to that from the Nielsen model. Figure 3.13 shows instantaneous and low pass filtered ripple heights at the two sites as predicted from the models of Nielsen, Wiberg and Harris, and Wikramayake. The vertical bars in Figure 3.13 indicate the observed fair-weather dimensions. Another noted distinction between the model estimates and the observed ripple behavior is that all of the models predict a decrease in ripple dimensions over the rough bed at the peak of the storm. From the standpoint of the Wiberg and Harris (1994) classification, this behavior is easily
understood as a transitional period during which the ripples are sub-orbital and then begin to shift from scaling to the wave-orbital diameters (orbital ripples) to scaling based on the grain size (anorbital ripples) (Figure 1.14). However, indirect ripples estimates from the altimetry records (Figure 3.13) suggest the exact opposite occurs, namely that the largest ripple dimensions are developed during the peak of the storm. In their 1994 paper, Wiberg and Harris foresaw such difficulties, suggesting that their model “may not be ideal for estimating a time series of ripple properties owing to the sharp changes in the slope of the relationship for ripple wavelength at the orbital/suborbital and anorbital/suborbital transitions.”

Estimates of ripple-induced hydraulic roughness, $k_r$ (equation 1.17), obtained by applying the Nielsen model at both the rough and smooth sites are shown in Figure 3.14. The predicted ripple roughness contrast between the rough and smooth sites during times of heavy swell was dramatic: $k_r$ (defined by equation 1.17) was about 15 – 25 cm at the rough site and near zero at the smooth site because the model predicts the formation of a plane bed during high energy events (Figure 3.14). Accounting for movable bed roughness over the fine sand bed during high waves reduces the total difference in predicted effective roughness, $k_b$, to values about 1 cm. Models predict that storm roughness at the fine-grained smooth site was dominated by grain and movable bed roughnesses, $k_m$, which together produced a high-energy effective roughness height, $k_b$ in the neighborhood of 0.09 – 0.20 cm. In this analysis, the approach of Xu and Wright (1995) was followed and equation (3.3) was used to estimate $k_m$. Using equation (3.2) for the high-energy flat bed at the smooth site would return somewhat higher estimates of $k_b$ in the neighborhood of 0.3 cm for the storm peak. However, these empirical results suggest that, in reality, hummocky topography was likely to have dominated the
roughness and therefore, the assumptions underpinning the model predictions are wrong. The models return acceptable results only for the smooth bed under background swell conditions and for the rough bed under partially energetic conditions. Qualitatively, however, the models do capture the observed trend toward an enhanced difference in roughness between the two sites during the storms, with the rough site becoming rougher while the smooth site becomes smoother.

3.12.2 RESULTS OF WAVE-CURRENT AND WAVE BOUNDARY LAYER MODEL PREDICTIONS

To obtain first-order estimates of $u_w$ and $\delta_w$, the model of Grant and Madsen (1986) was applied. The Nielsen model predicted ripple ($k_r$) (equation 1.17) and movable bed ($k_m$) roughnesses (equation 3.3) were used together with observed orbital velocities and mean currents as inputs into the GM model. Time series of the model predicted values are shown in Figure 3.15. During the high-energy events, current effects were negligible in comparison to wave effects. At those times, the accentuated contrasts in ripple roughness between the rough and smooth sites caused correspondingly large contrasts in predicted bed friction (as manifest via $u_w$) and wave boundary layer thickness, $\delta_w$. Notably, because of the large $k_r$ and $f_w$ over the rough site during storms, high-energy wave friction velocity values were extreme: typical predicted $u_w$ values were in the vicinity of $8 - 10$ cm s$^{-1}$. These high $u_w$ values, combined with the long period of the swell, produced an uncommonly thick wave boundary layer over the rough surface with $\delta_w > 15$ cm. Corresponding high-energy $u_w$ and $\delta_w$ values over the smooth surface (at the shallower depth of 15 m) were in the vicinity of $5$ cm s$^{-1}$ and 6 cm respectively.
3.12.3 PREDICTED WAVE FRICTION FACTORS, $f_w$ BASED ON RIPPLE MODELS

Separate estimates of the wave friction factor, $f_w$, from equations 1.4, 1.5 & 1.6 are shown in Figure 3.16 along with a temporal comparison of the wave friction factor ratio based on Swart’s (1974) formula (equation 1.4) between the rough and smooth sites. Estimates of $f_w$ computed via equation (1.4) over the rough surface for predicted ripples during the high-energy events using $k_r$ from the Nielsen model yield $f_w$ estimates of 0.14 – 0.16. Predicted $f_w$ values at the smooth site during the same events, when movable bed roughness dominated, were about 0.009 – 0.013. Consistent with the direct observations of turbulent friction, Figure 3.16 shows a pronounced tendency for predicted $f_w$ to have increased significantly over the rough bed and simultaneously decreased significantly over the smooth site during storm events. From the bottom panel, one can see that during high-energy events, $f_w$ at the rough site exceeded that at the smooth site by an order of magnitude, regardless of which predictive model was used. This model result is consistent with the factor of 10 increase inferred from the IDM observations. However, as already noted, modeled roughness values for high-energy conditions over the fine sand bed may be wrong because the models predict plane movable beds under those conditions rather than the hummocky topography that is inferred to have prevailed. Additionally, as was mentioned earlier, the models underestimate ripple development during the peak of the storm at the rough site. Hence, even though the models give roughly the right answer, they may do so for the wrong reasons.

3.12.4 RESULTS FROM ESTIMATING $C_d$ FROM THE GM MODEL AND A SIMPLE ANALYTICAL APPROACH

By applying the roughness estimates from both Nielsen’s and Wikramanayake’s models (equations 1.21 – 1.25) to the two formulae (equations 1.4 and 1.5) for the wave friction factor (Swart, 1974 and Madsen, 1994), four separate estimates for $C_d$ can be
calculated from the Grant-Madsen model (Figure 3.17), producing an envelope of values depending on which combination of formulae are chosen. The close similarity in predicted ripple geometry between the Nielsen and Wiberg-Harris models allows the one to represent the other and thus eliminates the need to evaluate all three models in this analysis. The same four inputs were also introduced into the simple formulae (equations 1.7 – 1.14). The general qualitative agreement between the two approaches and the first order quantitative agreement suggests that the characterization of roughness is a first order source of uncertainty in several widely applied models. Furthermore, the overlap in estimates between the detailed model approach and the simple analytical approach emphasizes the utility of simple approaches and the need to focus more effort on the study of spatially complex, time variant roughness.

3.13 DISCUSSION

The inner shelf of the Tairua embayment has served as a laboratory for examining the bottom boundary layer complexity that often results from non-uniform depositional regimes and related geologic inheritance. Comparable situations exist throughout the world, particularly in inner shelf environments fronting transgressive, sediment deficient environments where bed surfaces are influenced by exhumation of relict deposits (Wright and Trembanis, 2003) and on shelves that exhibit RSDs of various origins (Traykovski and Goff, 2003; Thieler et al., 2001; Cacchione et al., 1984). In the present study, active transgression has not been a factor but distinct and dramatically contrasting bed surfaces have resulted because of irregular exposure of very rough coarse deposits from beneath surrounding deposits of fine, well-sorted sands. A remarkable, and perhaps counterintuitive, aspect of the bed micromorphology is the high degree of persistence of the locations of contrasting bed surfaces and of the contacts between them. This arrangement surely must reflect the operation of some self-maintaining process. Based
on the analyses presented here, it is inferred that a positive feedback loop involving formation of large ripples over the rough surface during high-wave events and the prevention of deposition on this surface by the energetic vortices shed from the ripples may be involved. Thieler et al. (2001) and Murray and Thieler (2004) have suggested such a “self cleansing” mechanism. However, analyses of the behavior of suspended sediment above the rough and smooth sites off Tairua by Green et al. (2004) (see Chapter 4 for a detailed treatment) suggests that the tendency for inhibited settling and “self-cleansing” during storms is more complexly balanced against a tendency for burial during fair-weather, such that the basic mechanism suggested by Murray and Thieler (2004) may not adequately explain the varied morphological patterns observed at this site.

Roughness on the fine-sand plain is predicted from model results to be temporally variable under normal background swell. With a few key important exceptions, the observational data support the predictions and are generally consistent with the results of the models of Grant and Madsen, Nielsen, Wiberg and Harris, and Wikramanayake (GM/N/WH/W). The exceptions are the cases of high-energy roughness on both the rough bed (coarse-sand) and the smooth bed (fine-sand). In the former, the most pronounced ripples developed under the most intense conditions while the models suggested a trend of reduced bedform dimensions. In the latter, the bed actually became hummocky while the models predicted plane beds. Under non-storm background swell, the models suggest very little change in roughness at the coarse site and the observations also support this prediction, suggesting that the bed is rippled but dormant under these conditions. Altimetry records indicate that roughness on the coarse site increased during high waves and never reached washout plane bed flow conditions. The GM/N/WH/W models predict a similar result with the noted exception of predicted diminished bedforms during peak conditions. So far the data suggest that the GM/N/WH/W models adequately predict the bedforms dynamics over the rough site during background swell and moderate
wave conditions but not during high-energy conditions, and the models do well over the fine-sand bed only during background swell and not under high-energy conditions.

The GM/N/WH/W models predict a decrease in roughness (and therefore drag) under high waves on the fine-sand bed, associated with washout of pre-existing ripples and the formation of a plane bed with sheet flow. The Smyth-Hay (2002) $f_w$ estimates are consistent with this prediction and yield a decrease in $f_w$ under high waves. The GM/N/WH/W models correctly predicted that washout does not occur on the coarse bed. In fact, under the high waves it is observed that the ripples on the coarse bed were activated and reformed and that they migrated as was similarly observed by Traykovski and Goff (2003) off Martha's Vineyard, Massachusetts. The estimates of $f_w$ (equation 1.16) support this prediction, as does the observed increase in drag on the coarse bed under high waves. However, closer examination of the altimetry data and comparison to the suspension dynamics by Green and Black (1999) and Green et al. (2004; Chapter 4) suggest a different interpretation for the roughness of the fine-sand plain: hummocky topography probably replaced the ripples during storms.

Green et al. (2004; Chapter 4) found that the Tairua reference concentrations fell into two clusters when plotted against $\theta'$ (equation 1.19). Green and Black (1999) report this same clustering from another shoreface (Mangawhai, New Zealand), which they explained in terms of the development of hummocks under high waves. The Tairua data fell into the same two clusters as the Mangawhai data, leading Green et al. (2004) to conclude that hummocks probably formed on the fine-sand plain at Tairua under high waves. The results demonstrated that the inferred hummocky bed would have had a significantly lower friction factor than a rippled bed. Analysis of the drag over observed
hummocky beds from the Mangawhai dataset using both the law of the wall (equation 1.2) and the IDM technique (equation 1.15) also indicate that the hummocky-bed drag coefficient was indeed generally lower than the rippled-bed drag. This result generally provides indirect support to the conclusion that hummocks were formed on the fine-sand plain under high waves at Tairua. The general implication of this is that the GM/N/WH/W ripple models are not sufficient to explain sediment transport and bed micromorphodynamics on either the coarse bed or the fine bed during storms.

3.14 CONCLUSIONS

Like many inner shelves (Wright and Trembanis, 2003; Wright, 1995), the Tairua inner shelf probably is molded largely by storms and high-energy swell with negligible changes during fair-weather. The combined roles of fair-weather and storm processes over rough and smooth beds are examined through observations and evaluation of a recent complexity model in Chapter 4. The roughness contrasts between the smooth and rough surfaces are enhanced by high bed stresses because of the existence of a threshold in the Shields parameter, \( \theta' \) (equation 1.19) beyond which ripples in the fine sand cease to grow and are instead replaced by a hydraulically smoother hummocky bed. Thus, during storms, the rough surface of coarse sand becomes rougher as orbital ripples grow at the same time that the smooth surface becomes smoother as ripples there are destroyed and hummocks are formed. The contrasts in the hydrodynamic structures of the boundary layers overlying these surfaces are equally dramatic. Figure 3.18 illustrates, conceptually, that the major boundary layer responses to high-energy forces over the two types of surface. Over the smooth surface, a hummocky bed probably replaces ripples even though established models predict a plane, movable bed. During the field study, this bed type only intermittently induced vortices that reached the sensors. Near-bed mean currents over the smooth surface experienced only the “conventional” retardation
predicted by equations (1.2) and (1.3). Over the rough surface, the predicted wave boundary layer thickness was over 15 cm because of the large roughness length of 15–25 cm. In addition, structured vortices shed by the ripples extended upward to elevations of over 40 cm above the bed, presumably contributing to an excess vertical momentum flux as well as to sediment suspension. Mean currents near the bed were measurably retarded by the thick boundary layer and energetic vortices.

From this study, the following conclusions can be drawn. Spatial gradients in roughness between bed types were strong and persistent. Furthermore, roughness contrasts were enhanced during storms. The altimetry records were not consistent with the theoretical models that suggest the formation of planar beds under high waves but are consistent with the formation of hummocky bedforms as have been observed in similar settings. In addition, the altimetry records were not consistent with the theoretical models that suggest the reduction of ripple dimensions at the rough site during high waves, but rather with the development of the largest ripple dimensions. Observed drag coefficients \( (C_d) \) and wave friction factors \( (f_w) \) were four to five times greater over the rough bed than at the fine site during storms but were smaller over the rough bed than the fine site during low waves. Energetic vortices shed by the pronounced ripples over the rough surface enhanced vertical transfer of momentum and may play a crucial role in maintaining the morphological integrity of that surface. Under growing waves, ripples on the rough bed grew in equilibrium with the flow dynamics, in general accordance with the Grant-Madsen/Nielsen/Wiberg-Harris/Wikramanayake ripple models. Under background waves, observed ripples on the coarse bed were relict features formed from previous storm events. Under background swell, the bed roughness behaved in
accordance with the models of Grant-Madsen/Nielsen/Wiberg-Harris/Wikramanayake. The resulting variations in drag during background swell are attributed to wave-induced variations in bedforms. Under high waves, the models of Grant-Madsen/Nielsen/Wiberg-Harris/Wikramanayake failed to adequately predict the bedform behavior over either the rough bed (large orbital ripples) or the smooth bed (hummocks). Under high waves, the drag was measurably reduced on the fine-sand plain relative to the RSD. This was more likely caused by development of a hummocky bed than by a plane bed. While the models of Grant-Madsen/Nielsen/Wiberg-Harris/Wikramanayake correctly predicted drag reduction over the fine-sand plain during storm events, they did so based on a false assumption of plain bed sheet flow conditions. Improved models of ripple geometry accounting for hysteresis effects and hummock bedform development are needed.
PART TWO

COMPLEX SHOREFACE MORPHOLOGY OF A RAPIDLY TRANSGRESSING BARRIER ISLAND: CASE STUDY FROM CEDAR ISLAND VIRGINIA

The content of the following chapter was published in the proceedings of the Coastal Sediments 2003 Conference with authors: L.D. Wright and A. Trembanis
3.15 INTRODUCTION

Inner shelf surfaces and bottom boundary layers fronting transgressive coasts have received relatively little attention and are poorly understood. Nevertheless, such regimes are characterized by bottom boundary layer complexity that often results from non-uniform depositional regimes and related geologic inheritance (e.g. Schwab et al., 2000; Barnhardt et al., 1998). Such situations exist throughout the world in inner shelf environments fronting transgressive, sediment deficient environments where bed surfaces are influenced by exhumation of relict deposits. The shoreface and inner shelf immediately offshore of the Eastern Shore of Virginia affords an ideal laboratory for examining the micromorphodynamics of such transgressive surfaces. In this chapter, the case of Cedar Island, Virginia is used to examine the inherited morphology and bed roughness patterns on a storm-driven inner shelf fronting a transgressive and actively eroding coast. The likely connections between observed variability in bed roughness and consequent drag and boundary layer properties are also explored.

3.16 SITE DESCRIPTION

In contrast to the long, straight, and relatively stationary barrier coast along the North Carolina Outer Banks, the barrier islands of Virginia form an irregular, sand depauperate, and generally receding archipelago interrupted by numerous migrating tidal inlets. Representative of the end member transgressive regime, Cedar Island is located roughly in the middle of the Eastern Shore barrier island chain (Figures 3.19 and 3.20a). VIMS analyses of this island show that over the past 150 years, the island has been receding landward at an average rate of over 5 meters per year by “rolling over” the
marsh, estuarine, and tidal channel deposits behind the island. Figure 3.20b shows the historical trends in shoreline position. Pronounced tidal inlets bound the 11 km long barrier island on its northern and southern termini; appreciable accumulation of marginal sand shoals has recently prevailed adjacent to Wachapreague Inlet at the island’s southern end. The inner shelf profile of Cedar Island is considerably flatter than that of the well-studied shoreface off Duck, North Carolina to the south (Figure 1.8).

As the barrier has receded landward, marsh peat and coarser sediments on the foreshore and inner shelf have been progressively exhumed as the thin veneer of sand has migrated toward the west through a combination of dune overwash (Figure 3.21) and offshore sand loss. Figure 3.22a represents an example of a rough peat surface presently exposed on the intertidal foreshore of Cedar Island. Such deposits are intermittently exposed over the entire inner shelf fronting the island (Figures 3.24 and 3.25) and cause appreciable local increases in bottom drag coefficients and, hence, in the friction “felt by” waves and currents. In many locations, exhumed marsh surfaces exhibit very rough beds of oysters and other shellfish in growth position similar to that shown in Figure 3.22b.

3.17 HYDRODYNAMIC REGIME

The Eastern Shore domain is dominated by northeasterly winds associated with extratropical storms in autumn and winter. These winds generate moderate to high waves and southerly-setting currents accompanied by downwelling benthic flows over the inner shelf (e.g. Wright, 1995). Tides are semidiurnal with a mean spring-tide range of 1.2 meters. Time series of burst-averaged wave orbital velocity peak spectral wave period,
and mean current speed and direction were measured at a depth of 10 meters over the
period from 29 September to 10 November 1999 using a bottom tripod supporting an
electromagnetic current meter and pressure sensor located 1 m above the bed. The
sampling rate was 1 s and the burst duration was 34 minutes. The results (Figure 3.26)
show that, as expected, the benthic flow regime off Cedar Island in autumn is similar to
that described by Kim et al. (1997) and Wright (1995) for Duck, North Carolina. Strong
southwesterly bottom-currents accompanied by strong wave agitation and downwelling
flows are forced by moderate extratropical northeasters. The tripod record (Figure 3.27)
showed that the largest of three such events was overprinted by a mean water level rise of
40 cm (at a depth of 10 m). Mean bottom currents had southerly (along-shelf) speeds of
about 25 cm s⁻¹ and offshore (downwelling) components of about 5 cm s⁻¹. Strong
infragravity signals were present during storms. Southerly and offshore sediment fluxes
prevail during such events.

Seasonally during storms, the break point boundary between the nearshore and the
inner shelf sweeps back and forth over the shoreface. Over low gradient (dissipative)
profiles such as that fronting Cedar Island, the ratio of breaker height, \( H_b \), to local breaker
depth, \( h_b \), is in the neighborhood of \( H_b/h_b \sim 0.5 \) (e.g. Wright, 1995). Thus, during
moderate to severe storms, the nearshore flow component may extend to somewhere
between the 5 m and 10 m isobaths which lie respectively between 1 and 4 km seaward
of the shore; a typical nearshore width during storms is of 2 km. Within any given
storm, the “groupy” nature of storm waves in the Middle Atlantic Bight (e.g. Wright et
al., 1994) should cause large amplitude oscillations of surf zone width within cycles of
minutes. In the case of transgressive, storm-dominated barrier islands, such as Cedar Island, storm-surge-elevated water levels translate the surf zone across the sandy coastal fringe during storms.

3.18 MICROMORPHOLOGICAL VARIABILITY

High-resolution side-scan sonography (300 kHz) of the field site (Figure 3.23) shows bottom micromorphology with a high degree of spatial heterogeneity. This complexity is attributable to the fact that the inner shelf is characterized by a thin mantle of sand overlying a substrate of relict peat. In certain areas where sand is absent, peat "windows" appear producing the "black holes" shown in Figure 3.24. These features are exhumed manifestations of shoreface peat deposits such as that shown in Figure 3.22a and shell deposits similar to those in Figure 3.22b dominate their roughness. Elsewhere, variations in grain size are responsible for sharp gradients in ripple roughness, which ranges from oscillatory wave ripples (Figure 3.25b), sand wave features (Figure 3.24) to large lineations. Pronounced ebb-tide shoals bound the shoreface at its northern and southern ends. As explained in the following section, the actual hydraulic roughness length, $k_b$, of shell beds in Figure 3.22b probably exceeds that of the sandy bed by roughly an order of magnitude.

3.19 VARIABILITY OF BED STRESS AND HYDRAULIC ROUGHNESS

Studies in the Middle Atlantic Bight (Madsen et al., 1993 and Wright, 1993) have shown that temporal and spatial variations in bed roughness and sediment type can affect the bottom boundary layer thickness, bottom drag as sensed by the wind-driven mean
currents, and the vertical suspended-sediment concentration profiles near the bed. Bed stress is crucial not only to sediment suspension and transport but also to modulating the near-bottom currents over the inner shelf. As presented in Chapter one, the effective roughness, $k_b$, consists of three time-varying components (Nielsen, 1992): grain roughness, $k_d$; ripple roughness, $k_r$; and movable bed roughness, $k_m$. In other words, $k_b = k_d + k_r + k_m$. For cases where shell beds such as that shown in Figure 3.22b dominate the roughness, Wright et al. (1990) conducted laboratory flume experiments, which showed that mature oyster shells produce a roughness length, $k_b$, of approximately 3 cm.

On the inner shelf, waves and mean currents interact and estimation of bed stress and roughness are more complicated. To examine the effects of wave–current interaction, the model of Grant and Madsen (1986; 1979) was used, to obtain estimates of $u_{c_m}, u_c$ and wave-current boundary layer thickness, $\delta_{c_m}$. This study was limited to a single EMCM and thus independent estimates of boundary layer parameters such as was conducted for the New Zealand case study (Chapter 3, part one) were not possible. While the previous section suggested shortcomings in the way that the Grant-Madsen model deals with ripple behavior it is still a very mature, robust, and insightful model for exploring the role of measured roughness on bottom boundary layer dynamics.

In order to estimate the likely effects of the contrasting bed surfaces on bottom boundary layer properties such as $u_{c_m}, C_d, f_m$, and $\delta_{c_m}$, the equations summarized in Chapter 1, were applied to near-bed currents and wave orbital velocities for three observed micromorphological conditions off Cedar Island, namely, shell bed roughness.
(\(k_b = 3\) cm), sand rippled bed (\(k_r = 2\) cm), and fine sand beds (\(k_d = 0.025\) cm). The resulting time series, corresponding to the near-bed fluid flow time series (Figure 3.26) are shown in Figure 3.27. For the fine sand beds, the grain roughness was assumed to dominate under low-energy conditions (\(k_b \sim k_d \sim 0.025\) cm). Table 3.3 summarizes the estimated values of \(k_b, C_d\) and \(f_w\) for shell beds, unrippled sands or muds, and rippled beds averaged over the period of the records in Figure 3.26.

3.20 RESULTS

Results of applying the Grant-Madsen model using observed roughness estimates and tripod measurements of flow conditions are plotted in Figure 3.27 for the end member cases of oyster shell bed (blue line) and fine-sand (red line). Wave boundary layer thickness (Figure 3.27c) varied from 3 – 9.5 cm in the shell bed case and from 0.5 – 4.5 cm in the case of a fine-sand plain, with dramatic increases occurring during the two storm events for both cases. Wave-current friction velocity (Figure 3.27a) ranged between 1.3 – 7.8 cm s\(^{-1}\) and 0.5 – 3.7 cm s\(^{-1}\) for the shell bed and fine-sand plain respectively. Wave-current friction velocity exhibited similar increases during storm events for both cases. Wave friction factor \((f_w)\) (Figures 3.27b and 3.29) gets reduced over both beds during storm events because of the large increase in orbital semi-excursion \((a_w)\) relative to roughness length \((k_b)\) in equation 1.5. The time-series of mean current drag \((C_d)\) shows increased values during large events for both cases (Figures 3.27d and 3.28).
A conceptual diagram illustrating key variations in bottom boundary characteristics over bed morphologies such as those encountered in the present study is shown in Figure 3.30.

3.21 DISCUSSION AND CONCLUSIONS

Bottom boundary layer complexity often results from non-uniform depositional regimes and related geologic inheritance. Situations comparable to that just described exist throughout the world, particularly in inner shelf environments fronting transgressive, sediment deficient systems where bed surfaces are influenced by exhumation of relict deposits. This situation is particularly likely where transgressive sand barriers are migrating across peat-producing marshes and relict tidal inlet and channel deposits. Although more detailed field experiments are needed to assess the actual effects of this complex topography on turbulence and eddy viscosity especially during energetic events, this pilot study provides anecdotal support for the notion that spatially variable bed roughness can significantly affect storm-driven flows by causing large spatial variations in the bottom drag coefficient of both wind driven currents and storm surges. One might also expect patterns in the sediment-flux divergence (i.e. erosion and deposition) to result from the effects of roughness on boundary layer and sediment dynamics. Spatial variability in bed roughness may also cause corresponding variations in bottom-boundary layer thickness and turbulence thereby inducing, or enhancing “patchiness” in bed sediment and roughness patterns. Models that address questions of across-shelf and along shelf sediment fluxes in such environments must, in the future, take account of that complexity. It may be that for short-term models the
spatially varying roughness might be considered essentially fixed in position as is demonstrated on the shoreface off of Tairua, New Zealand (Chapter 2 and Chapter 3, part 1) thus allowing modelers to focus efforts on contending with the time varying components of roughness variation.
Figure 3.1 Schematic Diagram of Instrumented Tripod Deployed on the Inner Shelf

EMCM = Electro-Magnetic Current Meter
OBS = Optical Backscatter Sensor
ADV = Acoustic Doppler Velocimeter
ADCP = Acoustic Doppler Current Profiler
ABS = Acoustic Backscatterance Sensor
CTD = Conductivity Temperature Depth
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sampling Frequency (Hz) (Δf)</th>
<th>Burst Duration (BD) (min)</th>
<th>Interval Between Burst Start (IBB) (min)</th>
<th>No. of Bursts</th>
<th>Process measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADV</td>
<td>5</td>
<td>5</td>
<td>60</td>
<td>836</td>
<td>Waves, currents, turbulence, elevation</td>
</tr>
<tr>
<td>ADCP</td>
<td>0.5</td>
<td>5</td>
<td>10</td>
<td>5044</td>
<td>Water column currents</td>
</tr>
<tr>
<td>ABS</td>
<td>5</td>
<td>5</td>
<td>60</td>
<td>836</td>
<td>Suspended sediment concentration elevation</td>
</tr>
<tr>
<td>EMCM</td>
<td>1</td>
<td>15</td>
<td>60</td>
<td>836</td>
<td>Waves, currents</td>
</tr>
<tr>
<td>OBS</td>
<td>1</td>
<td>15</td>
<td>60</td>
<td>836</td>
<td>Suspended sediment concentration</td>
</tr>
<tr>
<td>CTD</td>
<td>1</td>
<td>1</td>
<td>120</td>
<td>418</td>
<td>Salinity and temperature</td>
</tr>
</tbody>
</table>

Table 3.1 Tripod Instrument Sampling Settings Tairua/Pauanui Study
Figure 3.2 Side-scan sonar image showing coarse-sand rippled scour depression (RSD) with prominent ripples surrounding, relatively, featureless fine-sand plain at 22 m water depth. Brighter colors denote higher acoustic backscatter.
Figure 3.3 Close-up Side-scan sonar and photographic images of small vortex ripples associated with fine-sand plain (a) and large wave orbital ripples within rippled scour depression (RSD) in 22 m water depth.
Figure 3.4 (a) 12 hour tracking position of Cyclone Paula color indicates wind speed (green=15 m/s, yellow=20 m/s, orange=25 m/s, red=40) (b) Satellite image of Cyclone Paula at 3/2/02 00:00 UTC Wind speed 40 m/s
Figure 3.5 Time Series of Observed Atmospheric and Oceanographic Conditions During Field Experiment Tairua, New Zealand 2/16/01 - 3/23/01
Figure 3.6 Rose diagrams of current vectors in the upper water column (~3 m below surface) during the tripod deployment period. (a) Rough bed site (h = 22 m); (b) smooth bed site (h = 15 m)
Figure 3.7 Smoothed time series of hourly current speeds at ~3 m below the sea surface, ~5 m above the bed, and 1 m above the bed. (a) rough site (h = 22 m); (b) smooth site (h = 15 m)
Figure 3.8 Altimetry time series obtained from ADV and ABS records over the rough and smooth bed. Changes in elevation over short time intervals (~1 day) are assumed to be the result of ripple migration and thus express ripple height.
Figure 3.9 Time series of $C_D$ estimated from $w'$ spectra by the inertial dissipation method (IDM) for bursts over the rough and smooth sites that yielded reasonable fits to the expected $-5/3$ slope.
Figure 3.10 Time of $f_w$ for rough and smooth surfaces via equation 1.16
Figure 3.11 Power spectra of $w'$ at elevations of 43 cm and 53 cm above the rough surface and at elevations of 14 cm and 31 cm above the smooth surface (a) during storm peak (b) early stage of storm development (c) fair-weather background swell (d) during waning phase of the storm. Note the prominent peaks corresponding to the primary swell frequency ($\omega$) and its first harmonic ($2\omega$) at the lower elevation over the rough surface during the storm.
Figure 3.12 Time series of $w'$ variance based on total measure variance, and variance predicted from linear wave theory for (a) rough surface; and (b) smooth surface. Note how the variance over the smooth surface collapse onto the prediction from linear wave theory during the low waves period between the storms (days 70-75).
Figure 3.13 Ripple heights as predicted from the models of Nielsen (1981), Wikramanayake (1993), and Wiberg and Harris (1994) at the (a) rough and (b) smooth sites. Vertical bars indicate heights observed by divers under fair-weather conditions.
Figure 3.14 Time series of predicted total roughness ($k_b$) rough and smooth site
Figure 3.15 Time series of predicted (a) $u_{cw}$, (b) $u_{sw}$, (c) $\delta_w$, and (d) $C_{d100}$ for the rough and smooth site based on Grant-Madsen formulae.
Figure 3.16 Time series of $f_w$ estimated for rough and smooth surfaces via equations 1.4 (a), 1.5 (b), and 1.6 (c) is Swart's $f_w$ ratio for rough/smooth.
Figure 3.17 Envelope of estimates for $C_{d100}$ based on application of various $k_s$ and $f_w$ estimates as inputs to the GM model (red lines and circles, where circles indicate mean value) compared to same inputs applied to the simple analytical approach (black lines and (circles).
Figure 3.18 Conceptual diagram of the major distinguishing bottom boundary layer features of the rough and smooth surfaces during storm conditions.
<table>
<thead>
<tr>
<th>Site</th>
<th>$C_d$ (IDM)</th>
<th>$K_b$ (Nielsen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough Uc&gt;0.10 m/s</td>
<td>0.030 ± 0.01</td>
<td>11 cm</td>
</tr>
<tr>
<td>Smooth Uc&gt;0.10 m/s</td>
<td>0.007 ± 0.001</td>
<td>2.2 cm</td>
</tr>
</tbody>
</table>

Table 3.2 Estimates of $C_d$ (via Inertial Dissipation Method) and $k_b$ (observed ripple dimensions and Nielsen's formula) for rough site and smooth site for cases with mean currents greater than 10 cm s$^{-1}$. 

N=10
Figure 3.19 Shaded relief map indicating location of Cedar Island, Virginia along the Eastern Shore barrier island chain. Note highly irregular shelf surface topography.
Metompkin Inlet

Overwash fan and breach point

Wachapreague Inlet

1986

Retreat Rates
Average (A-C) = 4.2-4.9 m/yr
Maximum = 15 m/yr

Figure 3.20 (a) View of Cedar Island Virginia looking North from Wachapreauge Inlet. (b) Historical Shoreline Retreat Rates
Figure 3.21 Aerial photo of Cedar Island, Virginia showing extensive overwash aprons extending into lagoon. Courtesy S. Hardaway
Figure 3.22 (a) Patches of lagoonal peat embedded with oyster shells, recently exposed on the intertidal beach-front due to rapid transgression of the barrier island. (b) Close-up view of oyster shells in life position within the swash zone of Cedar Island, Virginia. Photos courtesy W. Cohen
Figure 3.23 Trackline of Side-scan Sonar Survey 1999 Cedar Island, Virginia

Trackline: 51 km
Frequency: 600kHz
Depths: 4-10m
Exposed peat and oyster shell

Wave ripples

Sharp roughness gradient

Sand waves

Figure 3.24 Sonographs from the shoreface off Cedar Island, Virginia (dark color represents low backscatter return)
Figure 3.25 Sonographs from Cedar Island, VA (a) Exposed peat/shell beds surrounding patches of sand ripples (300 kHz at a depth of 12 m). (b) Close-up view of large wave orbital ripples (Ripple spacing approximately 30 cm). (High backscatter is bright, low backscatter is dark).
Figure 3.26 Burst Averaged Time Series of Observed Hydrodynamic Conditions from Cedar Island Tripod Study 9/99-11/99. (a) Hydrostatic water depth; (b) Spectrally Averaged Wave Period; (c) Magnitude of wave orbital velocity (blue) and mean current (red) 1 m above the bed; (d) Cross-shore component of mean current (positive is offshore); (e) Along-shore component of mean current (positive is to the North).
<table>
<thead>
<tr>
<th>Bed Type</th>
<th>$K_b$ (cm)</th>
<th>$C_d$</th>
<th>$f_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>3.0</td>
<td>0.009</td>
<td>0.11</td>
</tr>
<tr>
<td>Smooth sand</td>
<td>0.025</td>
<td>0.003</td>
<td>0.011</td>
</tr>
<tr>
<td>Rippled</td>
<td>2.2</td>
<td>0.007</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 3.3 Summary of Roughness Properties for Three Bed Types Cedar Island, Virginia
Figure 3.27 Bottom boundary layer characteristics estimated via the model of Grant and Madsen (1986) for the inner shelf off Cedar Island at a depth of 11 m using observed benthic currents and wave conditions (Figure 3.36) and observed bed micromorphologies (Figure 3.35). (a) Wave-current friction velocity, $u_{*cw}$; (b) wave friction factor, $f_w$; (c) wave boundary layer thickness, $d_{bw}$; and (d) drag coefficient, $C_{d,tot}$, experienced by mean currents. Estimates for shell beds are indicated in blue and those for smooth sand beds are indicated in red.
Figure 3.28 Drag Coefficient estimated from model of Grant and Madsen, (1986) using observed benthic currents and wave conditions and observed bed micromorphologies for three cases: oyster shell (red); sand ripples (blue) and smooth bed (green).
Figure 3.29 Wave friction factor ($f_w$) estimated from Swart, (1974) using observed benthic currents and wave conditions and observed bed micromorphologies for three cases: oyster shell (red); sand ripples (blue) and smooth bed (green).
Figure 3.30 Conceptual diagram of the major distinguishing bottom boundary layer features of surfaces encountered off Cedar Island, Virginia.
CHAPTER 4

SUSPENDED SEDIMENT TRANSPORT- IMPLICATIONS FOR THE DEVELOPMENT AND MAINTENANCE OF RIPPLED SCOUR DEPRESSIONS

Large portions of the content of this chapter were published in the journal *Continental Shelf Research* 2004, vol. 24, pages 317–335 with authors: Malcolm O. Green, Christopher E. Vincent, and Arthur C. Trembanis.
OVERVIEW

In the previous chapter, the inter-relationships between variable seabed roughness (physical and/or biological) and fluid flow characteristics such as drag and turbulence were examined. Pronounced and persistent effects were seen to be the result of sharply contrasting bed compositions. The ability of several widely used ripple models to capture the observed bedform dynamics especially during storm conditions was called into question. In this chapter, the focus is on measured and modeled sediment transport dynamics within the bottom boundary layer immediately above these contrastingly rough and smooth beds. As was the case with bedform geometry models, the classic models for suspended sediment dynamics fall short of capturing some critical behavior over contrasting beds, particularly during storms. Observations of suspension dynamics, sediment flux, and fluid flow are introduced into an exploratory parameterized model for sediment sorting developed initially by Murray and Thieler (2004) and adapted here to consider local conditions. Field observations are utilized to assess the role of storm and fair-weather conditions in forming and maintaining some of the distinct sedimentary features observed at the site and commonly referred to as rippled scour depressions (RSDs) or sorted bedforms.

Measurements of waves, currents, and sediment suspension from a 35-day deployment of three instrumented tripods on the wave-dominated shoreface off Tairua Beach, New Zealand, are presented. Two tripods were deployed at 22 m depth, one within a coarse-sand rippled scour depression (RSD), and the other nearby on the surrounding, relatively featureless fine-sand plain. A third tripod was deployed at 15 m depth, also on fine sand.

Background, long-period swell was interrupted by two 6-day periods of high waves. At the 15 m, fine-sand site, only fine sand appeared in suspension. However, at the 22 m, fine-sand site, coarse sand appeared in suspension together with fine sand when the waves were highest. This observation suggests that coarse sand resuspended from the RSD can be dispersed on the adjacent fine-sand plain, at least along the same isobath. At the RSD, there was no coarse sand in suspension under background swell, but there was a fine-sand “washload,” presumably advected from the surrounding fine-sand plain, even
though the coarse bed sediment in the RSD itself was not in motion. Under high waves, both fine and coarse sands were in suspension. The fine sand appeared again as a washload, while the coarse sand was confined relatively close to the bed in accordance with a sediment diffusivity that decreased linearly with elevation above the bed.

Measurements of fine-sand reference concentration over both fine-sand beds (15 m and 22 m depth) plot against wave-induced skin friction in one cluster under the background swell and in another cluster under the high waves, which suggests a change in the bedforms, possibly to a hummocky bed, related to wave conditions and thus alters the suspension dynamics. The coarse-sand reference concentrations over the RSD fall into the “hummocky cluster,” which supports this interpretation.

The fine-sand washload is indicative of an unfavorable settling environment over the RSD, which could constitute a positive feedback that causes RSDs to self-organize from initial perturbations. Under high waves, the suspended-sediment load from the surrounding plain will be correspondingly high, but turbulence will also be more energetic on the RSD, thus more effectively inhibiting deposition. Under low waves, deposition may be less inhibited, but the suspended-sediment load arriving from the surrounding fine-sand plain will also be lower. Thus, the deposition rate on the RSD will be small, even though conditions are more favorable for settling. Modeling could be expanded to consider the balance between inhibition of settling and the tendency for burial by the sediment load that impinges from the area surrounding an RSD and the way wave climate and water depth might mediate the basic self-organization process. Escape of coarse sand from RSDs under high waves may seed the growth of new RSDs.

Field observations of sediment and hydrodynamics are incorporated into a recently developed exploratory model of RSD formation (Murray and Thieler, 2004). Model scenarios of high (storm) and low (fair-weather) energy conditions are run and the resulting morphologies are compared to the locally observed sediment patterns. The model is seen to robustly form sorted patterns of coarse and fine sand bedforms under both low energy and high energy conditions. The nature of exploratory modeling is not typically well suited for quantitative observational comparison. As presently parameterized, the self-organization model partially replicates only one of the four morphogenetically different RSD features classified by Hume et al. (2003). The model
does a reasonably good job at potentially explaining the formation of commonly observed sorted sand ridge bedforms found ubiquitously throughout the region. The model predicts the formation of RSD features everywhere and under all conditions, in contrast the observed patchy distribution of features. Furthermore, the model results in two well sorted sediment species, one coarse and one fine; whereas in the field, the coarse sediment is poorly sorted, while the fine sediment is well sorted. Also, the observed bedforms are oriented generally parallel to and not orthogonal to the weak mean currents as suggested by the model. Still, the observations of suspended sediment dynamics supports the central tenets of the Murray and Thieler model which may offer a reasonable explanation for the formation of the “offshore shore-oblique RSDs” encountered at Tairua. Further research and ammended modeling efforts will be required to address the formative processes associated with the numerous other classes of RSDs observed at Tairua and elsewhere.
4.1 INTRODUCTION

Field measurements tend to support a one-dimensional point of view that links "local" boundary-layer and sediment dynamics with the local seabed configuration (bedforms, sediment type) and local driving forces (waves, currents) (e.g. Storlazzi and Jaffé, 2002; Williams et al., 1999; Green et al., 1995; Madsen et al., 1993; Vincent et al., 1991; Wright et al., 1991; Huntley and Hanes, 1987; Wright et al., 1986; Cacchione and Drake, 1982). However, it is the sediment-flux divergence that drives evolution of geomorphology, not the local dynamics per se. On the shoreface, which is the zone of shoaling waves between the breakpoint and the edge of the inner shelf (Niedoroda et al., 1984), there is a marked spatial gradient in driving forces related primarily to change in water depth and the effect that depth has on penetration of wave-orbital motions down to the bed. There may also be less predictable and more localized variability related to non-uniform bed sediments, including RSDs (Thieler et al., 1995; Hunter et al., 1988; Cacchione et al., 1984). The shoreface, with its mix of large-scale gradients in forcing and more localized variability in seabed characteristics, is a particularly good setting for studying how large-scale sediment-flux divergence emerges from spatially variable local dynamics. The first step is to determine how the local dynamics vary with substrate and depth on the shoreface. This understanding then can be codified in models to investigate spatial patterns of sediment transport and associated sediment-flux divergence. At least two fundamentally different modeling approaches are available (which could be argued occupy the opposite ends of a modeling continuum): solution of the partial differential equations that describe momentum and mass (sediment) conservation and construction of "abstract" models based on scale-dependent, usually simplified equations (or "rules"). The aim of this chapter is to determine how time-averaged suspended-sediment
concentration varies over the shoreface. Specifically, measurements from three locations on the shoreface that encompass different combinations of water depth and seabed configuration are compared. A recent addendum to this study has been a collaborative effort aimed at exploring a recently developed self-organizing model for RSD formation using driving forces and seabed configuration values derived from field observations.

It is recognized that by focusing on the properties of the time-averaged suspension, information that might relate to any suspended-sediment flux that arises by “flux coupling” (Jaffe et al., 1985) is being discarded. Although flux coupling at gravity- and infragravity-wave frequencies does occur under shoaling waves (e.g. Hanes and Huntley, 1986), field measurements have confirmed that advection of the mean suspension field by the mean current is typically the dominant transport term for fine-sand seaward of the surfzone (e.g. Green et al., 1995). Medium to coarse sand is moved mainly by waves outside the surf-zone (Traykovski et al., 1995). Thus, flux coupling might perturb or modulate the transport field in significant ways (e.g. Storlazzi and Jaffe, 2002), and might therefore play a part in shaping shallow shoreface morphology, particularly for coarse sediment.

The data are from a 35-day deployment of three instrumented tripods on the shoreface off Tairua Beach (Figure 1.7). Tripods Kelly and Alice were both deployed at 22 m depth off Tairua Beach, but Kelly was located within a coarse-sand rippled scour depression with prominent ripples, whereas Alice was located on the relatively featureless fine-sand plain that surrounded the RSD. The third tripod, Bud, was also located on the
fine-sand plain, but at 15 m depth. Table 4.1 provides a summary of the depth and seabed characteristics at each tripod location.

In Chapter two, it was found that the coarse-sand flooring the RSDs on the Tairun shoreface is underlain by fine sand; also coarse-sand lenses are interbedded with fine sand especially along the boundaries of RSDs (Hume et al., 2003). Hunter et al. (1988) described a similar situation from southern Monterey Bay (California) and suggested that RSDs are best explained as lag deposits in areas of localized scour.

Recently, Murray et al. (2003) and Murray and Thieler (2004) have advanced an alternative explanation for the origin and growth of RSDs based on a morphodynamic instability driven by sediment–flow feedbacks. Interactions between flow and sediment transport that are driven by grain-size sorting and resultant variations in bed roughness lead to segregation of coarse and fine sediment, albeit, initially, at a scale much smaller than the scale of natural RSDs. However, subsequent interactions between flow and growing finite-amplitude features as well as merging of features that are growing at different rates may then produce patterns with scales and shapes that are similar to natural features. This school of thinking, known as “self-organization” (in the sense that initial perturbations grow or “organize: to become the features themselves), differs fundamentally from the school that postulates a passive sediment bed that is imprinted by a spatial pattern of hydrodynamic forcing. To emphasize the distinction, Murray and Thieler suggested the term “sorted bedforms” be used to name the features that are otherwise known as “rippled scour depressions.” The flow–sediment interaction
hypothesized by Murray and Thieler (2004) to be at the heart of the self-organization is a winnowing process. In essence, increased energy and scales of turbulence over coarse-sediment domains inhibit deposition of fine suspended sediment locally. The fine sediment prevented from settling on the coarse domain is advected downstream until it encounters an area of fine bed sediment, where turbulence is relatively less energetic and deposition is favored. Thus, fines are preferentially deposited in areas where fines are already on the seabed. This positive feedback will cause any initial perturbation in the distribution of coarse and fine grains on the seabed to grow. This chapter utilizes analysis of the Tairua dataset to shed some light on this process.

4.2 METHODS

4.2.1 DATA

Each tripod had a pressure sensor for measuring waves; current meters for measuring turbulence, mean currents, and wave-orbital currents (Figure 4.1); and a multi-frequency acoustic backscatter sensor (ABS) for measuring suspended-sediment concentration (SSC) close to the bed (Figure 4.2). Table 4.2 shows sampling details. Wave statistics were estimated from pressure and current data as follows.

Significant wave-orbital speed at the bed, $U_w$, was calculated using linear wave theory as:

$$U_w = \left( \int_{1/30}^{1/2} f_{\text{ss}} \Gamma(f) df \right)^{1/2} \frac{2}{\cosh[k(z + h)]}$$

(4.1)
where $\Gamma_n(f)$ is the power spectrum of $u(z,t)$, which is the current-speed time series at elevation $z$ above the bed; $f$ is frequency; the limits of integration correspond to the gravity-wave range of frequencies; and $k$ is the linear-theory wavenumber corresponding to mean water depth $h$ (calculated from pressure data after correcting for a nominal atmospheric pressure and assuming a nominal seawater density) and mean spectral period $T_{mo}$ (also calculated from the pressure data, using the definition of Longuet-Higgins, 1975). Significant wave height, $H_s$, was estimated as:

$$H_s = (U_wT_{mo} / \pi) \sinh(kh)$$  \hspace{1cm} (4.2)

The ABS ensonifies a 120 cm long cone of water and registers the backscattered acoustic pressure from 1 cm thick bins along the entire length of the cone. Suspended-sediment concentration in each 1 cm bin is inferred from ABS echo data by solving an equation that relates SSC, echo intensity, a size-dependent term that describes the amount of energy back-scattered from the sediment (form function), range from transducer and a system-specific calibration constant (e.g., Thorne and Hanes, 2002; Thorne et al., 1991). With one operating frequency, the grain size distribution of suspended sediment needs to be specified in order to evaluate each term in the equation and to solve for SSC. Furthermore, the grain size distribution is assumed to be constant through time and across the sounding range. For multi-frequency ABS units, which were used in this study, backscatter data from two or more frequencies can be combined to calculate concentration and suspended-particle size (Crawford and Hay, 1993). However, the inversion can be "noisy" and only permits a single size at each range and time. In this study, we assumed that: both the coarse sand found in the rippled scour depressions...
(mean grain size 0.75 mm) and the fine sand that comprises the surrounding plain (mean grain size 0.22 mm) will supply the suspended-sediment field over the shoreface. With this assumption, we developed a simultaneous two-frequency data inversion scheme to partition the SSC into these two size components.

Burst-averaged, SSC profiles, $\overline{C}_{\text{fine}}(r)$ and $\overline{C}_{\text{coarse}}(r)$, were obtained by applying the two-frequency data inversion to the echo data, where $r$ is range of bin from transducer face, “fine” denotes the 0.22 mm particle size and “coarse” denotes the 0.75 mm particle size. Each ABS was positioned such that the seabed surface would intersect the ensonifying cone at some nominal range. The actual range from the transducer to the bed surface, $r_{\text{bed}}$, is readily discernable as a distinct break in slope in $\overline{C}(r)$ when plotted in log$_{10}(\overline{C})$ – $r$ space (Green and Black, 1999) (Figure 4.3). $R_{\text{bed}}$ for each burst was estimated by locating the break of slope in $\overline{C}_{\text{fine}}(r)$, and $r_{\text{bed}}$ thus determined was used in the transformation $z = r_{\text{bed}} - r$ to convert $\overline{C}_{\text{fine}}(r)$ and $\overline{C}_{\text{coarse}}(r)$ to $\overline{C}_{\text{fine}}(z)$ and $\overline{C}_{\text{coarse}}(z)$, respectively.

The dual-frequency data inversion, as applied in this study, yields only burst-averaged concentration profiles (fine and coarse particles), which precludes any analysis of intra-burst suspension processes (e.g. intermittency due to interaction of wave-orbital motions with bedforms). To enable at least a qualitative description of such processes, the single-frequency inversion of acoustic backscatter data employed by Green (1998) and Green and Black (1999), which requires specification of a single particle size and which yields estimates of “instantaneous” concentration (i.e. at the sampling frequency),
was also used. For this calculation, a mean grain size of 0.22 mm (fine sand) was assumed, hence the inversion of each burst of echo data results in an estimate of $C_{\text{fine}}(r, t)$, where $t$ is time and the interval between points and points per burst can be seen in Table 2. It is noted that $(1/BD)\int_0^{BD} C_{\text{fine}}(r, t)\,dt$ (where $BD$ is the burst duration and $C_{\text{fine}}(r, t)$ is from the single-frequency inversion) is not identical to the burst-averaged concentration $\bar{C}_{\text{fine}}(r)$ from the dual-frequency inversion, although they will be very similar when no coarse sand is in suspension.

4.2.2 SORTED BEDFORM MODEL

A new exploratory model for RSD formation based on enhanced turbulence over rough rippled beds and associated hindered settling of fine sand has been made available to this study through recent collaboration of the developer, Dr. Brad Murray of Duke University. The “sorted bedform” model parameterizes much of the specific physical processes into a set of equations that encapsulate the interactions between wave motions, varying substrates, and advective currents. The model assumes that wave motions interact with the larger bedforms associated with RSDs deposits such that turbulence is enhanced relative to fine-sand plain deposits. Enhanced turbulence is thus considered to increase entrainment and inhibits settling of fine sand over RSD domains, which are then subject to advective forces happen to be present. Fine sand will then remain in suspension and be carried away by mean currents until it encounters a patch of fine sand with reduced turbulence where deposition can take place. In this way positive feedbacks emerges as fines are preferentially removed from coarse domains that become coarser and gain further turbulent enhancement. A conceptual diagram illustrating the
enhanced-entrainment-hindered-settling component of the sorted bedform model is shown in Figure 4.15.

Exploratory models are not usually designed to implement a time series of input conditions (Murray, personal communication). Instead, the model is designed to run hypothetical scenarios specified by the modeler based usually on some observed or perhaps intuitive settings. The goal of this modeling exercise is to assess the ability of the sorted bedform model to form features under observed conditions from the Tairua tripod study. The resulting bedforms, if any, will then be assessed alongside the morphology of locally observed features.

Two case studies were chosen for model simulation, one based on observed storm conditions of wave and current flow and a second run for fair-weather conditions. Table 4.5 summarizes the sediment and hydrodynamic inputs used in the model simulations. The model was compiled and executed on a Unix workstation and run until output results reached a statistical equilibrium.

4.3 RESULTS

Figure 4.1 shows wave statistics estimated from the Alice data. Background, long-period Pacific Ocean swell ($H_s = 50 - 100$ cm) was interrupted by two 6-day periods of high waves ($H_s > 200$ cm). During those times, $U_w$ exceeded 60 cm s$^{-1}$. $U_c$, the mean current speed measured at 64 cm above the bed, was small relative to $U_w$. During the period of high waves, sediment was in suspension at all three sites (described below).
Under the background swell, sediment was in suspension continuously at the 15 m, fine-sand site (*Bud*), less so at the 22 m, fine-sand site (*Alice*), and only occasionally at the 22 m, coarse-sand RSD (*Kelly*).

### 4.3.1 OVERVIEW OF SUSPENSION PATTERNS

Suspension was generally intermittent at two scales: the wave-group and the individual-wave (Figure 4.2). Forced long waves associated with wave groups can cause a flux coupling (Jaffe et al., 1985) at the infragravity scale, which results in net offshore sediment transport (e.g. Green and MacDonald, 2001; Villard et al., 1999; Shi and Larsen, 1984). Intermittency at the individual-wave scale is usually attributable to the orderly ejection of sediment-laden vortices from the bed, which is caused by interaction between wave-orbital motions and seabed ripples (e.g. Hanes and Huntley, 1986; Sleath, 1982; Bagnold, 1946). The data in Figure 4.2, which are typical of energetic conditions, show that intermittency at the individual-wave scale is accentuated at both deep sites relative to the shallow site. Furthermore, vortex entrainment is more “pronounced” (i.e. sediment in suspension for a greater proportion of the time; more sediment in suspension; suspension to higher levels in the flow) over the fine-sand plain compared to over the RSD at the same depth. These differences suggest that net sediment flux arising from flux coupling at the individual-wave scale will vary strongly with both depth and substrate.

A kind of “washload” suspension was frequently observed over the rippled scour depression. Washload was characterized by virtually zero intermittency at both wave-
group and individual-wave scales. Furthermore, SSC in the washload was virtually uniform to at least 1 m above the bed. The significance of this observation will be explored.

4.3.2 SUSPENSION TYPE AND COMPOSITION

The data from each ABS burst were sorted into four categories: “no suspension,” “intermittent suspension” (sediment in suspension for \(< \sim 15\%\) of the time during a burst), “full suspension” (sediment in suspension for \(\sim 15\%\) of the time of a burst), and “washload.” The classification was performed by inspecting data plots of the type shown in Figure 4.2. Bursts in the category “no suspension” were easily identified. The difference between intermittent suspension and full suspension was discerned from a rough estimate of the percentage of time sediment clouds were present during the burst. Washload was recognised on a subjective basis as described above (approximately zero intermittency; SSC approximately uniform to at least 1 m above the bed). The results of the classification are shown in Figure 4.4, where \(U_{\text{crit}}\) is the critical wave-orbital speed at the bed for initiation of suspension estimated from Komar and Miller (1975). \(U_{\text{crit}}\) for the fine-sand plain was based on grainsize \(d = 0.22\) mm and \(d = 0.75\) mm was used for the coarse sand in the RSD. Following Green (1999), Komar and Miller’s (1975) equation for \(U_{\text{crit}}\) was evaluated using significant wave height \((H_s)\) and mean spectral period \((T_{\text{mo}})\).

Also shown in Figure 4.4 is the grain size that was in suspension, either coarse (0.75 mm) and/or fine (0.22 mm). The presence of coarse and fine sand was inferred from \(\bar{C}_{\text{coarse}}(z)\) and \(\bar{C}_{\text{fine}}(z)\), respectively; when the burst-averaged concentration was at
the background noise level of the ABS (~ 0.1 mg L\(^{-1}\)) at all elevations above the bed, the corresponding component was deemed not to be present in suspension.

At both fine-sand sites (Alice, 22 m depth, and Bud, 15 m depth), \(U_{\text{cri}}\) based on \(d = 0.22\) mm effectively divides no suspension from full suspension. During full suspension at the fine-sand 15 m site there was never any coarse sand in suspension. However, at the fine-sand 22 m site, which is between RSD patches also at 22 m depth, coarse sand appeared in suspension with the fine sand when the waves were highest. This condition suggests that coarse sand resuspended from the RSD by high waves can be dispersed on the adjacent fine-sand plain at least along the same isobath and possibly farther. An alternative explanation for the source of the suspended coarse sand that appears over the fine-sand plain at 22 m depth under high waves is that it is local, which is not likely for two reasons. First, the surficial sediments of the fine-sand plain are very well sorted (< 1% by weight of the sediment is within the coarse sand range) (Hume et al., 2003; see Chapter 2, part 1) and, hence could not act as a significant source of coarse sand. Second, the lenses of coarse sand that are known to be variously buried beneath the fine-sand plain are, at a minimum, 30 – 40 cm below the sediment surface (Hume et al., 2003; see Chapter 2, part 2), which is at least an order of magnitude greater than the scour or “erosion depth” (estimated as the thickness of settled sediment corresponding to the total suspended-sediment load). Hence, local exhumation of buried coarse material is unlikely.
Intermittent suspension at both fine-sand sites tends to straddle $U_{\text{crit}}$ with more intermittent-suspension bursts occurring below $U_{\text{crit}}$ than above. A possible explanation is that wave groupiness tends to bias $U_w$ estimates low, but the ABS still captures the intermittent suspension. At both fine-sand sites, only fine sand was present in intermittent suspension.

At the RSD site (Kelly, 22 m depth), $U_{\text{crit}}$ based on $d = 0.75$ mm effectively divides full suspension from no suspension. Both coarse sand and fine sand were always present during full suspension. In contrast, the washload, which tended to occur at times when $U_w$ was greater than $U_{\text{crit}}$ based on $d = 0.22$ mm but less than $U_{\text{crit}}$ based on $d = 0.75$ mm (Figure 4.4), was always composed entirely of fine sand. This suggests that the fine sand in the washload was resuspended from the adjacent fine-sand plain and advected across the RSD at times when the coarse bed sediment in the RSD itself was not in motion. Intermittent suspension tends to straddle $U_{\text{crit}}$ based on $d = 0.75$ mm (Figure 4.4). It is not clear what grain size composed the intermittent suspension. On the one hand, the burst-averaged concentration estimates $\bar{C}_{\text{coarse}}(z)$ during intermittent suspension were all at the ABS background noise level, which implies no coarse sand was present. On the other hand, inspection of raw ABS data revealed short bursts of high concentration originating at the bed, which implies resuspension of the local (i.e. coarse) bed material. Another line of thinking also suggests the presence of coarse sand during intermittent suspension as follows. There appears to be hysteresis in coarse-sand suspension at RSD: note in Figure 4.4 that full suspension (which is always composed of coarse and fine sand) appears to begin at a higher $U_w$ than it appears to cease.
However, that hysteresis (i.e. coarse sand appearing in suspension at a higher orbital speed than it disappears from suspension) is seen to largely disappear if the intermittent suspension is composed of coarse as well as fine sand.

4.3.3 BURST-AVERAGED SUSPENSION

Table 4.3 shows a summary of results regarding the burst-averaged fine-sand and coarse-sand concentration profiles, which can be referred to throughout the following discussion. \( C_0 \) is the time averaged suspended-sediment reference concentration, which is specified at the level \( z = 0 \) cm. \( C_0 \) was obtained by fitting a straight line to \( \log_{10}(C) \) vs. \( z \) over the domain \( 1 \text{ cm} < z < 5 \text{ cm} \) and extrapolating the fitted line to \( z = 0 \) cm.

4.3.4 FINE-SAND SUSPENSION OVER THE FINE-SAND BED

At both of the fine-sand sites (Alice, 22 m depth, and Bud, 15 m depth), the fine-sand suspension data (full and intermittent suspensions) tend to fall into two clusters when plotted in \( C_0 \)-versus-\( \theta' \) space. One cluster is described by the model \( C_0 = 0.10 \rho_s \theta'^3 \) and the other by \( C_0 = 0.005 \rho_s \theta'^3 \) (see top left panel in Figures 4.6 and 4.7). Here, \( \theta' \) is the dimensionless wave-induced skin friction or Shields parameter (equation 1.19).

Green and Black (1999) found a similar clustering of reference-concentration estimates from another New Zealand wave-dominated shoreface (Mangawhai, on the northeast coast of the North Island). By examining video observations of the seabed and suspension process that were acquired at the same time the ABS data were acquired, they were able to relate the clusters to the existence of two distinct bedform types, these being
a rippled bed and a hummocky bed (Table 4.4 provides a summary). Green and Black
(1999) found that the hummocky bed replaced the rippled bed when $\theta'$ exceeded
approximately 0.14. They did not observe how the rippled bed reformed under decaying
waves.

The Tairua fine-sand reference concentrations over the two fine-sand beds (15 m
and 22 m depth) fall into the same two clusters in $C_0$-versus-$\theta'$ space as the Mangawhai
data, which suggests that the rippled and hummocky beds observed at Mangawhai also
occurred at Tairua. However, $\theta' = 0.14$ does not adequately demarcate the two bedform
types/data clusters for the Tairua dataset (top left panel in Figures 4.6 and 4.7). Instead,
the rippled bed appears to occur under the background swell and is replaced by the
hummocky bed when $U_w$ exceeds 35 – 45 cm s$^{-1}$ (bottom panel in Figures 4.6 and 4.7).
This range of values is significantly higher than $U_{crit}$, but note that the rippled bed
apparently does not become re-established until $U_w$ falls back towards $U_{crit}$ (bottom panel
in Figures 4.6 and 4.7).

Green and Black found that it was possible to collapse the Mangawhai reference-
concentration data onto a single model by accounting for flow contraction in the wave
boundary layer. This collapse was achieved by using $\theta''$ in place of $\theta'$ to describe the
near-bed flow:

$$\theta'' = \frac{(0.5 \rho'_w U'_w^2)}{\left\{ \frac{\left( \rho'_w - \rho_w \right) g d}{\left( 1 - \pi \eta / \lambda \right)^2} \right\}^2}$$ (4.3)
where \( \eta \) is the ripple height and \( \lambda \) is the ripple length, which resulted in all of the reference-concentration data collapsing onto the single model:

\[
C_0 = 0.005 \rho_s \Theta^3
\]  

(4.4)

Note that Green and Black used \( \eta = 0 \) and \( \lambda = \infty \) for the hummocky bed, which has the effect of negating or "disabling" the flow-contraction correction. They defended this choice by arguing that because sediment was entrained principally from hummock slopes as a sheet flow, rather than from ripple crests under locally accelerated flow, the flow-contraction correction was not needed for the hummocks.

The Tairua fine-sand reference-concentration data over the fine-sand beds (15 m and 22 m depth) also collapse onto equation (4.4) (top right panel in Figures 4.6 and 4.7). For the background-swell data, the figures given in Table 4.1 for \( \eta \) and \( \lambda \) were used in equation (4.3) to estimate \( \theta'' \). Note, these are ripple dimensions determined from sidescan sonar surveys of the Tairua shoreface conducted during fairweather \((U_w < U_{crit})\). For the hummocks that are presumed to form under high waves, \( \eta \) was assumed to be zero and \( \lambda \) was assumed to be infinite, following Green and Black (1999).

Note even if one were to replace \( \eta \) and \( \lambda \) with field based estimates of appropriate dimensions (nominally \(-10 \) cm height based on altimetry and 10 m spacing), the stress enhancement factor maintains a factor to leading order of approximately unity.
In addition to governing the relationship between bed shear stress and erosion of the seabed, the seabed shape, rippled or hummocky, also appears to control the mixing of suspended fine sand close to the bed as follows. Starting from the assumption that there is an exact balance at every level in the flow between time-averaged settling flux $\bar{C}w_s$ (where $w_s$ is sediment settling speed) and turbulent diffusion $K(\partial \bar{C} / \partial z)$ (where $K$ is sediment diffusivity), sediment diffusivity can be estimated from the concentration data as:

$$K = \frac{\bar{C}w_s}{(\partial \bar{C} / \partial z)}$$  \hspace{1cm} (4.5)

Shown in Figure 4.9 are two values of $r^2$, one value being for the fit of $K$ between 1 and 20 cm above the bed to one model and the other value being for the fit of $K$ over the same range to another model. The two models are: constant $K$, and $K$ increasing linearly with elevation above the bed, where $K$ was evaluated from equation (4.5) with $w_s = 2.2$ cm s$^{-1}$ (Stokes settling speed for grain size 0.22 mm). At the deeper of the two fine-sand sites (22 m depth, Alice), it is particularly clear that $r^2$ for the constant-$K$ model exceeds $r^2$ for the linearly-increasing-$K$ model during background swell, when the bed was presumed to be rippled, but the converse is the case (the linearly-increasing-$K$ model fits the data better) for the period of high waves, when the bed was presumed to be hummocky. At the shallower site (15 m depth, Bud), the linearly-increasing-$K$ model is also clearly the better model for the presumed hummocky bed. However, the two values of $r^2$ tend to alternate during background swell, such that the constant-$K$ model is the better fit when the waves are slightly smaller, and the linearly-increasing-$K$ model is the
better fit when the waves are slightly larger. This observation suggests that there are not in fact two different shapes of the sediment-diffusivity profile, as follows.

The commonly accepted model for linearly increasing $K$ is:

$$K = \beta ku_\ast z \quad (4.6)$$

where $u_\ast$ is a characteristic friction velocity, $\kappa$ is von Karman’s constant and $\beta$ is an empirical constant such that $\beta = K/K_m$, where $K_m$ is momentum diffusivity and

$$\beta = 1 + 2[(w_s/u_\ast)^2] \quad (4.7)$$

is proposed by van Rijn (1993) as being applicable to steady flow. Using equation (4.7) for $\beta$ with $w_s = 2.2$ cm s$^{-1}$ (fine sand), $\beta ku_\ast$ is seen to decrease for decreasing $u_\ast$ over the range of friction velocities encountered during the background swell, even though $\beta$ increases (Figure 4.10). (Here, the characteristic friction velocity is taken as $u_\ast = 0.5 f_s U_*^2$, which is the wave-induced friction velocity, with $f_s$ given by equation (1.4) and $k_d$ in that equation set to the ripple roughness $k_r = 28 \eta^2/\lambda$ (Grant and Madsen, 1982) (Table 4.1) to reflect wave-induced mixing in the near-bed region.) Hence, the slope of the linearly-increasing sediment-diffusivity profile reduces with decreasing $u_\ast$, such that the profile could become indistinguishable from a constant value. This behavior may explain the observed alternation of $r^2$ at the 15 m site under background swell, with the apparent appearance of constant sediment diffusivity under low waves.

Values of $\beta$ for the fine-sand suspensions over the fine-sand beds (22 m depth, Alice, and 15 m depth, Bud) are shown in Figure 4.11 together with equation (4.7). There is one value of $\beta$ per burst, where $\beta = X/\kappa u_\ast$ and $u_\ast = 0.5 f_s U_*^2$, as above. Here, $X$ is the
slopes of the straight line fitted to $K$ versus $z$ over the domain $1 \text{ cm} < z < 20 \text{ cm}$, where $K$ was estimated as described previously. The values of $\beta$ for the fine-sand suspensions over the fine-sand beds (15 m depth and 22 m depth) scatter widely around equation (4.7).

4.3.5 COARSE-SAND SUSPENSION OVER FINE-SAND BED

The reference concentration for the suspended coarse sand that appeared at the 22 m fine-sand site at times of highest waves tended to plot just below the model $C_0 = 0.005 \rho_s \theta''^3$, which was applicable to the suspended fine sand at those same times (top right panel in Figure 4.6). Note that for the case of coarse sand suspended over the fine-sand bed, it is not clear what grain size should be used to evaluate dimensionless wave-induced skin friction (either $\theta'$ or $\theta''$). For the coarse-sand datapoints shown in the top right panel of Figure 4.6 that plot just below the model $C_0 = 0.005 \rho_s \theta''^3$, $\theta''$ was evaluated with $d = 0.75 \text{ mm}$ (i.e. coarse sand). Also shown in the top right panel are the coarse-sand datapoints with $\theta''$ evaluated with $d = 0.22 \text{ mm}$ (i.e. fine sand); these datapoints plot well below the model $C_0 = 0.005 \rho_s \theta''^3$.

A possible explanation for the smaller-than-predicted coarse-sand reference concentrations is that the source of the suspended coarse sand, assuming it was the RSD, was distant and therefore the suspended coarse sand was not "in equilibrium" with the local bed material. In mechanistic terms, this disequilibrium means that there could be no continuous exchange of bed and suspended particles that normally maintains an
equilibrium suspension, with the result that the suspension gradually dwindles as it moves farther from its source material.

$K$ for the coarse sand (inferred from the coarse-sand concentration profiles using equation (4.7) with $w_s = 6.4$ cm s$^{-1}$, which is the Stokes settling speed for $d = 0.75$ mm) increased linearly with increasing $z$, which was also the case for the fine sand in suspension at the same time. Values of $\beta$ for the coarse sand are shown in Figure 4.11 together with predicted values by equation (4.7). The observed values are somewhat larger than the predicted values.

4.3.6 SUSPENSION OVER THE RSD

During full suspension under high waves at the RSD (Kelly, 22 m depth), both coarse and fine sand were always in suspension. The high-wave coarse-sand reference-concentration data plotted on the model $C_0 = 0.005 \rho_s \theta'^3$ (Figure 4.8) (where $\theta'$ was evaluated with $d = 0.75$ mm, i.e. coarse sand), hence the data can only collapse onto the model $C_0 = 0.005 \rho_s \theta'^3$ by assuming $\eta$ is zero and $\lambda$ is infinite in order to effect the transformation of $\theta'$ into $\theta''$ (Figure 4.8). The obvious inference is that sediments within the RSD evolved into a hummocky bed under high waves, in the same way that the ripples on the surrounding fine-sand plain were inferred to evolve into hummocks under high waves. Another possibility, however, is that sediment was entrained principally as sheet flow from the relatively larger ripples of the RSD, which, referring back to Green and Black's (1999) argument presented earlier, negates the need for the flow-acceleration correction. Without direct observations of the RSD bedforms under high waves, it is not
possible to know which, if either, is correct. Altimetry records (Figure 3.8), however, suggest that prominent ripples existed during high waves conditions. It is also possible that some mixed transitional bed (prominent ripples becoming hummocks) existed, as has been observed in other RSD settings (Traykovski, personal communication). It should be noted, though, that from a process point of view, sheet-flow entrainment from hummocks and sheet-flow entrainment from prominent ripples are, of course, the same.

The high-wave, fine-sand reference-concentration data plot well below the model $C_0 = 0.005\rho_s \theta''^3$ when $\theta''$ is evaluated with $d = 0.22$ mm (i.e. fine sand) (Figure 4.8). Thus, the explanation that was developed for the smaller than predicted coarse-sand reference concentration over the fine-sand bed can be applied here, too: the smaller than predicted fine-sand reference concentration over the coarse-sand bed is due to the suspended fine sand not being in equilibrium with the local (i.e. coarse) bed material of the RSD. However, if $\theta''$ is evaluated with $d = 0.75$ mm, (i.e. coarse sand), then the fine-sand reference-concentration data plots, together with the coarse-sand data, on the model $C_0 = 0.005\rho_s \theta''^3$ (Figure 4.8). This agreement suggests an equilibrium suspension, which in turn suggests that fine sand might be exhumed from within the RSD when high waves mobilise the RSD coarse sand (and when hummocks appear?), thus enabling sustenance of an equilibrium fine-sand suspension over the RSD at those times. While local exhumation of coarse material at the 22 m water depth fine-sand site is unlikely, the possibility of local exhumation of fine material at the RSD site is quite possible owing to the poorly sorted composition of the sediment such that fine sand comprises ~20% of the bed material (Figure 2.6). On the other hand, the possibility of a
non-local advected source is consistent with the observed direction of advective currents during high wave conditions (Figure 3.7), which would allow fine-sand from the adjacent fine-sand plain to be transported over the RSD site. It is not clear, from this dataset, which possibility (nonlocally-sourced, nonequilibrium suspension or equilibrium suspension fed by exhumation of local fine source material), is correct.

Under high waves at the RSD, fine sand was mixed uniformly throughout the near-bed region, and therefore it was not possible to estimate a corresponding value for the sediment diffusivity (because $\frac{\partial C_{\text{fine}}}{\partial z} = 0$). Presumably, when waves were large, the diffusivity of the fine sand (low settling velocity) over the rough bed of the RSD was high, which is consistent with a uniform concentration profile. On the other hand, $K$ for the coarse sand suspended over the RSD during high waves increased linearly with elevation above the bed and the value of $\beta$ inferred from the data (assuming $w_s = 6.4$ cm s$^{-1}$) compared favourably with van Rijn's (1993) model (Figure 4.11).

The reference concentration of the washload, which was always composed entirely of fine sand and which appeared over the RSD when $U_w$ was greater than $U_{\text{crit}}$ based on $d = 0.22$ mm but less than $U_{\text{crit}}$ based on $d = 0.75$ mm (Figure 4.5), plots with large scatter in Figure 4.8. Previously, it was suggested that the source area for the washload was the fine-sand plain that is adjacent to the RSD. Reasoning from the equilibrium argument presented previously, if that is the case then the washload over the RSD would not have been in contact with its source area, which might explain the scatter in Figure 4.8.
4.4 SORTED BEDFORM MODEL TEST CASES

Select output results of surface composition from the sorted bedform model runs are shown for the case of storm waves (Figure 4.16) and fair-weather conditions (Figure 4.17). Model output was saved for every 120 hours of time simulated.

Model results indicate that large, well-defined sorted sediment patches can develop both under storm and fair-weather conditions. The major difference between the two involved the amount of time required for bedform conditions to develop. In the case of storm waves, large, sharply-defined well sorted patches of coarse and fine material develop within a couple of weeks. The overall characteristic of the final model domain could be described as a sea of coarse material interspersed with sinuous patches of fine sand. The resulting patches of fine sand have length and width dimensions of approximately 400 m and 100 m respectively. Sorted bedform development under fair-weather conditions is over an order of magnitude slower than for the case of storm waves. The resulting compositional arrangement of the model domain is less clearly organized than the storm wave case with more gradual transitions between coarse and fine patches. Coarse patches still dominate the landscape but with thinner and longer intervening patches of fine sand with lengths of ~600 m and widths of ~60 m.

4.5 DISCUSSION

4.5.1 INHIBITED DEPOSITION OF FINE SANDS ON COARSE BEDS
The fine sand observed in suspension over the Tairua RSD under both background swell and high waves was always uniformly mixed (see Table 4.3 for a summary of observations) throughout at least the bottom meter of the water column, which suggests a high level of turbulent mixing. Although this turbulence will not prevent deposition of fine sand, it is indicative of an unfavorable settling environment, which supports Murray and Thieler's (2004) choice of mechanism (i.e. inhibited deposition of fine sand over coarse domains) at the heart of the positive feedback that causes sorted bedforms (i.e. rippled scour depressions) to self-organize. Other insights can be developed from further analysis of the Tairua dataset, as follows.

Under the long-period background swell that preceded the first high-wave event, fine sand was in almost continuous suspension on the fine-sand plain that surrounded the RSD at 22 m depth. For $U_w \approx U_{\text{crit, fine}}$ (where $U_{\text{crit, fine}}$ is critical wave-orbital speed at the bed for initiation of suspension of fine sand), suspended-sediment concentration over the Tairua RSD was zero, even though fine sand was in suspension over the surrounding fine-sand plain. Taking for granted the existence of an advecting current, the simplest explanation for this observation is that the fine sand sourced from the surrounding plain settled to the bed (of the RSD) before reaching the measurement location (in the interior of the RSD). Hence, fine sands can settle on the RSD, which is consistent with the observation that sediments of the Tairua RSD are poorly sorted mixtures of fine and coarse sand (Chapter 2 and Hume et al., 2003). A summary of suspension type during low and medium background swell conditions is presented in Figure 4.12. Under these conditions, the slow burial and/or migration of RSDs is favorable.
It follows that as $U_w$ becomes larger (resuspending a greater quantity of sand on the fine-sand plain) and/or the advecting current becomes stronger, suspended fine sand will penetrate further into the interior of the RSD. The data support this conjecture: for $U_w > U_{crit, fine}$ fine sand appeared at the measurement location in the interior of the RSD in a washload. Although the uniform fine-sand suspension profile that is characteristic of the washload is indicative of inhibited settling, deposition of fine sand on the RSD may still occur. This condition of fine-sand advection throughout the RSD domain during medium waves is evident in the data shown in Figure 4.12.

Under large storm wave conditions full suspension of coarse and fine-sand is observed at both the RSD and fine-sand plain sites (Figure 4.13), which suggests the potential for previously deposited fines to be exhumed from the RSD and for coarse RSD material to be transported into the adjacent fine-sand plain for possible initiation of new RSD patches. The sequence of suspension type during transitions from storm to fair-weather are illustrated from the data in Figure 4.13.

The Tairua RSD thus cannot be viewed as a static patch of coarse material that resolutely resists the intrusion of fine sand from the surrounding fine-sand plain. Under high waves, the suspended-sediment load impinging from the surrounding plain will be correspondingly high, but turbulence will also be correspondingly more energetic on the RSD, more effectively inhibiting deposition (Figure 4.13). Under low waves, deposition may be less inhibited on the RSD, but the suspended-sediment load arriving from the
surrounding fine-sand plain will also be lower (Figure 4.12). Thus, the deposition rate on the RSD will be small, even though conditions are more favorable for settling.

On a wave-dominated shelf, the wave-orbital speed at the bed is the principal control on sediment resuspension and also the “level” (energy) of turbulence. In this case, at any particular water depth, as waves get higher, more bed sediment is entrained, and the potential for RSD burial increases (simply because there is more sediment in suspension that has to eventually settle somewhere). However, at the same time, turbulence levels generally increase (Chapter 2 part 1). It is not clear whether turbulence levels would increase faster over the rougher bed of an RSD, but, either way, the ability of the RSD to cleanse itself of fine sand would also increase. This observation suggests the possibility of a balance between RSD burial and persistence, mediated by wave climate. For instance, under a wave climate characterized by long periods of competent (i.e. able to resuspend bed sediment) but low waves, whenever fine sand is in suspension, turbulence over any incipient RSD might be weak, and hence the incipient RSD may not be very effective at inhibiting deposition of that suspended fine sand on itself. In this case, the incipient RSD, which is small, might be obliterated by the slow burial processes under the low waves before it has a chance to grow. This sequence may explain the ephemeral nature of the small incipient RSDs (Facies 4, near-shore shore normal RSDs) noted in Chapter 2 (Hume et al., 2003). On the other hand, on a shelf where waves are either incompetent or very high, whenever fine sand is in suspension and burial potential is high, turbulence over any incipient RSD would also be strong. In this case, incipient RSDs might grow and coalesce to form large, stable features. Indeed, there are examples
at Tairua where moderately sized RSDs are seen to join together and ultimately connect to the large RSD studied here (Figure 2.12). Hence, some wave climates might promote the formation of RSDs, and others might suppress them. If that is so, then water depth would play a similar role, since orbital motions are attenuated by water depth, which controls the way the surface wave climate is transformed into a "seabed wave climate." Therefore, a more accurate conclusion is that some combinations of wave climate and water depth might promote the formation of RSDs, and other combinations might suppress their growth. A conceptual diagram illustrating conditions favorable for RSD burial and favorable for RSD maintenance is shown in Figure 4.14). Additional factors that are likely to be important are underlying geology, sediment supply and availability as was noted in Chapter 2 (Hume et al., 2003).

The self-organization model of Murray and Thieler (2004) is founded on an assumption of inhibited deposition of fine sediments, not an absolute absence of deposition. This distinction is important, since it implies that RSDs are not guaranteed to persist, which is necessary since buried RSDs have been observed on a number of shelves (Thieler et al., 2001 and Hunter et al., 1988) including this one (Chapter 2 and Hume et al., 2003). Consideration of the balance between inhibition of settling and the tendency for burial by the sediment load that impinges from the area surrounding an RSD leads to a focus on wave climate and water depth as possible "mediators" of the basic self-organization process. The existence of such balances, which might tip first one way and then another under a typically variable wave climate, further reinforces the view that RSDs are not static, relict, features, which is consistent with the sedimentological
evidence of occasional migration and interfingering of strata around the edges of RSDs (e.g. Hume et al., 2003; Thieler et al., 2001; Chapter 2). Further modeling, taking into account factors such as the role of wave climate and depth, might shed some light on how these subtle balances are played out and whether there are indeed combinations of wave climates and water depths that either promote or suppress the formation of rippled scour depressions on wave-dominated shelves.

Another possibility is that flux coupling plays a role, which has been suggested recently by Traykovski and Goff (2003). Fine sand would be inhibited from accumulating on the RSD if flux coupling were suitably larger over the RSD compared to over the fine-sand plain at the same time. This situation seems unlikely during periods of background swell at Tairua, since the fine sand appeared in suspension over the RSD at those times as a washload, which was characterized by virtually zero intermittency at both the individual-wave and wave-group scales. Hence, the flux-coupling can be expected to be small or zero. Suspension under high waves at the Tairua RSD was intermittent, which might translate into a larger flux coupling compared to under background swell. A detailed analysis of the flux coupling term might therefore shed some further light on how RSDs are maintained.

Finally, it seems that coarse sand entrained from the RSD does escape onto the surrounding fine-sand plain, as evidence by nonequilibrium coarse-sand suspension that developed over the fine-sand bed adjacent to the RSD during periods of high waves. Dispersal of coarse sand in this way may be the establish “seeds” that might grow into
RSDs, given the right water depth, sediment supply and a favorable sequence of waves over a period of time.

4.5.2 SELF-ORGANIZATION OF BEDFORMS

Central to the sorted bedform model of Murray and Thieler (2004) is the idea that RSDs are largely compositional and not topographical bed features. Original model formulation assumed conditions of alongshore dominated mean current flow as an explanation of the generally shore perpendicular features that were studied. Model simulations using inputs based on observed conditions from the inner shelf at Tairua, New Zealand indicate that well defined sorted bedforms develop.

The greatest strength of the sorted bedform model is its simplicity. The stripped down approach to modeling involves the fewest physical components necessary and only at the scale of interest forces the modeler integrate processes up to the spatial and temporal scales involved and not rely simply integrating a fully inclusive physical model up in space and time. This modeling approach thus sidesteps problems associated with trying to scale up first-principles physical models over several orders of spatial and temporal scale. Another aspect of the model that this experiment has demonstrated is the robustness of the self-organizing behavior. Sorted bedform patterns were seen to develop under all test conditions.

One of the shortcomings with the sorted bedform model is one of the very facets that the model was intended to help explain, namely the compositional nature of RSDs.
In this regard, the model results are found wanting in the following way. First, the model forms RSDs everywhere within the model domain under both storm and prolonged fair-weather conditions. The resulting compositional patterns consist of large coarse domains punctuated by patches of fine sand. In contrast, field observations indicate largely fine-sand domains interspersed with limited but persistent coarse patches. Second, model simulations result ultimately in two well-sorted facies. While the patterns are similar to the contrasting grain size populations observed in the field, they do not capture the marked and characteristic variations in sorting between coarse and fine domains. Stated quite simply, in the field fine-sand plains are well sorted but RSD sediments are poorly sorted, whereas the model produces well sorted fines adjacent to well sorted coarse deposits.

Given the very generalized physical parameterization that goes into the model it is encouraging that features develop under conditions like those encountered at Tairua. In fact, the resulting “sorted bedforms” have dimensions and compositional characteristics quite similar to Facies 6 (Offshore Shore-Normal RSDs) encountered in the field site. Yet, in its present development the model assumptions and numerical configuration are not sufficient to help explain many of the morphological and compositional characteristics of the numerous other types of RSDs found here and in other shelf systems. Specifically, the model could benefit from an approach that considers the importance of bedform dynamics and hysteresis along with the observed variations in sediment suspension based on the way in which storm waves set in and then wane at the end of wind events.
4.6 CONCLUSIONS

The Tairua dataset provides insights into the comparative resuspension of fine and coarse sands by waves on this shoreface. Sediment suspension shows changes through time as waves conditions change (changes in bedforms, changes in entrainment, changes in mixing), differences with substrate (e.g. vortex entrainment of fine-sand on open plains versus fine-sand “washload” over RSDs), and differences with depth (cross-shelf variation in intermittency at the wave scale). In addition, there appear to be subtle behavioral effects such as a hysteresis in the way bedforms evolve, nonequilibrium sediment loads, and possibly exhumation of fine sands from within the RSD.

Intermittency at the wave scale showed differences between depths (more intermittent at greater depth) and between seabed types at the same depth (vortex entrainment of fine sand more pronounced over the fine-sand plain compared to over the RSD at 22 m depth). These observations suggest that there will be marked differences in flux coupling with depth and substrate. Although flux coupling may give rise to a minor term in the transport budget, such differences might be significant in the sediment-flux divergence and, hence, evolution of the shoreface morphology. Flux coupling may also play a role in maintenance of the RSDs. Therefore, flux coupling merits further study.

Table 4.3 provides a summary of features of the time-averaged suspended-sediment load, grouped by substrate and wave conditions. There is no obvious interaction between the fine and coarse suspensions. Hence, fine and coarse particles
could be treated independently in a shoreface sediment-transport model. In fact, most observations could be readily incorporated into a model, with a few notable exceptions. First, the RSD needs to explicitly be incorporated into any such model, since it is a source of coarse material, as evidenced by the nonequilibrium coarse-sand suspension that appeared over the surrounding fine-sand plain under high waves. The RSD also has an effect on mixing of the fine-sand load that is sourced from the surrounding plain (fine sand is uniformly mixed over the RSD during times of background swell and high waves), which might affect settling of fine sand on the RSD and patterns of fine-sand transport. Secondly, bedforms need to evolve with the wave conditions to capture possible ripple-hummock transformations, which might include a hysteresis in the construction of a rippled bed under decaying waves. This parameterization is required because the seabed configuration is a first-order control on the relationship between wave-induced skin friction and reference concentration, and may also control the sediment diffusivity, although that is less clear. Finally, exhumation of fine sand from within the RSD might need to be accounted for in any model.

Suspended fine sand encounters an unfavorable, though not impossible, settling environment over the RSD which Murray and Thieler (2004) hypothesized was at the heart of a positive feedback that causes RSDs to self-organize from initial perturbations. The Tairua data suggest the possibility of a balance between RSD burial and the tendency to self-organize, mediated by wave climate and constrained by water depth. Furthermore, escape of coarse sand from RSDs under high waves may seed the growth of new RSDs.
<table>
<thead>
<tr>
<th></th>
<th>Tripod <em>Kelly</em></th>
<th>Tripod <em>Alice</em></th>
<th>Tripod <em>Bud</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth (m)</strong></td>
<td>22</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td><strong>Substrate</strong></td>
<td>RSD</td>
<td>fine-sand plain</td>
<td>fine-sand plain</td>
</tr>
<tr>
<td><strong>Mean grainsize (mm)</strong></td>
<td>0.75</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Fairweather bedform height / length (cm)</strong></td>
<td>35 / 125</td>
<td>5 / 20</td>
<td>3 / 16</td>
</tr>
</tbody>
</table>

Table 4.1 Depth and seabed characteristics at each tripod location, Tairua New Zealand.
<table>
<thead>
<tr>
<th></th>
<th>Tripod Kelly</th>
<th>Tripod Alice</th>
<th>Tripod Bud</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure</strong></td>
<td>Δf, BD, IBB / z</td>
<td>Δf, BD, IBB / z</td>
<td>Δf, BD, IBB / z</td>
</tr>
<tr>
<td>EMCM</td>
<td>1,900, 60 / 200</td>
<td>4,512, 60 / 120</td>
<td>1,900, 60 / 200</td>
</tr>
<tr>
<td>ADV</td>
<td>1,900, 60 / 115</td>
<td>4,512, 60 / 64</td>
<td>1,900, 60 / 76</td>
</tr>
<tr>
<td>ABS</td>
<td>5,300, 60 / 53, 64</td>
<td>– / –</td>
<td>5,300, 60 / 24, 41</td>
</tr>
</tbody>
</table>

|                    | Δf, BD, IBB / z | Δf, BD, IBB / z | Δf, BD, IBB / z |
|--------------------| F1, F2, F3     | F1, F2, F3     | F1, F2, F3     |
| ABS                | 2.5, 300, 60 / 67 | 5,600, 60 / 109 | 2.5, 300, 60 / 67 |
|                    | 0.92, 3.55, –  | 1.08, 1.97, 4.38 | 1.09, 1.98, 4.97 |

Table 4.2 Instrument Sampling details, Δf is sampling frequency in Hz. BD is burst duration in seconds. IBB is the interval between bursts in minutes. z is the elevation of the sensor above the bed in cm. "EMCM" denotes two-axis, 3.8 cm diameter, Marsh-McBirney electromagnetic current meter (measuring two horizontal components of flow). "ADV" denotes three-axis Sontek acoustic Doppler velocimeter (measuring two horizontal components and the vertical component of flow). "ABS" denotes multi-frequency acoustic backscatter sensor, where F1, F2, and F3 are operating frequencies in MHz.
<table>
<thead>
<tr>
<th></th>
<th>Fine-sand plain / 22-m depth</th>
<th>Fine-sand plain / 15-m depth</th>
<th>Coarse-sand RSD / 22-m depth</th>
<th>Coarse-sand RSD / 15-m depth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kelly</strong></td>
<td>Large ripples.</td>
<td>Large ripples.</td>
<td>Hummocky bed?</td>
<td>Large ripples.</td>
</tr>
<tr>
<td></td>
<td>Nonequilibrium $C_0$,</td>
<td>Nonequilibrium $C_0$,</td>
<td>No coarse sand in</td>
<td></td>
</tr>
<tr>
<td></td>
<td>implies nonlocal</td>
<td>implies nonlocal</td>
<td>suspension.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>source (washload).</td>
<td>source.</td>
<td>$C_0 = 0.005 \rho \theta^3$,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uniform profile.</td>
<td>Uniform profile.</td>
<td>where flow-contraction</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>term uses $\eta = 0$ and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\lambda = \infty$, and:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1) $d=0.22$ mm...</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>non-equilibrium $C_0$,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>implies nonlocal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>source.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) $d=0.75$ mm...</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C_0 = 0.005 \rho \theta^3$,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>implies local</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>exhumation of fines.</td>
<td></td>
</tr>
</tbody>
</table>

|                   | $C_0 = 0.005 \rho \theta^3$,| $C_0 = 0.005 \rho \theta^3$,| No coarse sand in           |                                 |
|                   | where flow-contraction      | where flow-contraction      | suspension.                 |                                |
|                   | term uses $\eta$, $\lambda =$| term uses $\eta = 0$ and    | $C_0 = 0.005 \rho \theta^3$,|                                |
|                   | ripple dimensions.          | $\lambda = \infty$.         | where flow-contraction      |                                |
|                   | Constant $K_v$.             | Linear $K_v$,               | term uses $\eta = 0$ and    |                                |
|                   |                             | van Rijn $\beta$.           | $\lambda = \infty$.        |                                |
| Rippled/hummocky  |                             | Linear $K_v$,               | Linear $K_v$,               |                                |
| hysteresis?       |                             | van Rijn $\beta$.           | van Rijn $\beta$.          |                                |

|                   | $C_0 = 0.005 \rho \theta^3$,| $C_0 = 0.005 \rho \theta^3$,| No coarse sand in           |                                 |
|                   | where flow-contraction      | where flow-contraction      | suspension.                 |                                |
|                   | term uses $\eta$, $\lambda =$| term uses $\eta = 0$ and    | $C_0 = 0.005 \rho \theta^3$,|                                |
|                   | ripple dimensions.          | $\lambda = \infty$.         | where flow-contraction      |                                |
|                   | Constant/linear $K_v$,      | Linear $K_v$,               | term uses $\eta = 0$ and    |                                |
|                   | van Rijn $\beta$.           | van Rijn $\beta$.           | $\lambda = \infty$.        |                                |
| Rippled/hummocky  |                             | Linear $K_v$,               | Linear $K_v$,               |                                |
| hysteresis?       |                             | van Rijn $\beta$.           | van Rijn $\beta$.          |                                |

Table 4.3 Summary of Suspended Sediment Behavior for Fine and Coarse Substrates under Background Swell and High Waves
<table>
<thead>
<tr>
<th>Bedform characteristics</th>
<th>Rippled bed</th>
<th>Hummocky bed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symmetrical, with rounded crests and troughs surmounting otherwise level seabed</td>
<td>Large-scale irregular deformation of the seabed</td>
</tr>
<tr>
<td>Bedform dimensions</td>
<td>Height ($\eta$) 1–3 cm</td>
<td>“Height” 10–20 cm</td>
</tr>
<tr>
<td></td>
<td>Length ($\lambda$) 10–20 cm</td>
<td>“Length” 1–2 m</td>
</tr>
<tr>
<td>Suspension process</td>
<td>Suspension “carpet”</td>
<td>Sheet flow–bursting sequence</td>
</tr>
<tr>
<td>Reference concentration</td>
<td>$C_0 = 0.10 \rho_s \theta'^3$</td>
<td>$C_0 = 0.005 \rho_s \theta'^3$</td>
</tr>
<tr>
<td>model, $C_0 = f(\theta')$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference concentration</td>
<td>$C_0 = 0.005 \rho_s \theta''^3$</td>
<td>$C_0 = 0.005 \rho_s \theta''^3$</td>
</tr>
<tr>
<td>model, $C_0 = f(\theta'')$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4 Bedforms observed by Green and Black (1999) on the wave-dominated shoreface at Mangawhai, New Zealand, and the associated suspension process and models that described the relationship between reference concentration and wave-induced skin friction. The data were from two depths (7 m and 12 m), both with seabed sediment composed of well-sorted fine sand ($d = 0.23$ mm).
Figure 4.1 Waves and currents during the experiment measured at the Alice tripod site and symbols showing whether sediment was in suspension at each site.
Figure 4.2 Three bursts of suspension data (C_{fine}(z,t) from the single-frequency data inversion); different locations at the same time. The color scale is the same for each plot: cool colors (dark) represent zero SSC and hot colors (light) represents high SSC. The seabed is at the bottom of each panel. (a) Fine-sand 15 m water depth (tripod- Bud); (b) Fine Sand 22 m water depth (tripod- Alice); (c) Coarse sand (RSD) 22 m water depth (tripod- Kelly).
Figure 4.3 Individual burst average concentration profile from RSD tripod ABS instrument, illustrating definition of bed elevation. Note sharp jump in concentration at the bed.
Figure 4.4 Bursts classified by suspension type (none, intermittent, full, washload) and grain size (coarse, fine) in suspension plotted versus the ratio of wave orbital velocity to critical orbital velocity.
Figure 4.5 Bursts classified by suspension type (none, intermittent, full, washload) and grain size (coarse, fine) in suspension plotted versus the ratio of wave orbital velocity to critical orbital velocity.
Figure 4.6 Fine sand reference concentration plotted against skin-friction Shields parameter at the fine-sand bed at 22 m depth (Alice tripod).
Figure 4.7 Fine-sand reference concentration plotted against skin-friction Shields parameter at the fine-sand bed at 15 m depth (Bud tripod).
(C) Sand Suspension over Coarse RSD Bed at 22-m Depth (Kelly)

- Full suspension / coarse [θ'' evaluated with D=0.75 mm]
- Full suspension / fine [θ'' evaluated with D=0.75 mm]
- Washload / fine [θ'' evaluated with D=0.75 mm]
- Full suspension / fine [θ'' evaluated with D=0.22 mm]

\[ C_0 = 0.005 \rho_s \theta^{''3} \]

Figure 4.8 Fine-sand reference concentration plotted against skin-friction Shields parameter at the fine-sand bed at 22 m depth (Kelly tripod).
Figure 4.9 $r^2$ for the fit of measured K profile (fine sand) to the constant-K model and to the linearly increasing-K model. (A) 22 m depth (Alice) and (B) 15 m depth (Bud).
Figure 4.10 Cross-plot of $\beta$ (equation 4.7, with $w_s = 2.2$ cm/s, which is the Stokes settling speed for quartz grain of diameter 0.22 mm) and $\beta u_*$ (the slope of the linearly-increasing sediment-diffusivity profile) plotted against $u_*$. 
van Rijn (1993) with $w_s = 6.4 \text{ cm/s}$ (coarse sand)

Coarse-sand suspension over fine-sand bed (22-m depth, Alice)

Coarse-sand suspension over RSD (22-m depth, Kelly)

Fine-sand suspension over fine-sand bed
+ 22-m depth (Alice)
+ 15-m depth (Bud)

Figure 4.11 Observed and model predicted $\beta$. Observed values are shown only for bursts for which $r^2$ for the fit of the straight line to $K$ versus $z$ over the domain $1 \text{ cm} < z < 20 \text{ cm}$ exceeds 0.99.
BACKGROUND SWELL  $U_w > U_{crit, fine}$ but $< U_{crit, coarse}$

A. Medium waves - clear RSD.

B. Low waves - bury RSD at updrift ends, but at low rates. Could cause RSD to migrate downdrift, but slowly.

Figure 4.12 Comparison of suspension dynamics over the fine-sand plain and the RSD under medium wave (a) and low wave (b) conditions. Note fine-sand is in suspension over both beds during medium waves but is only observed over the fine-sand plain during low wave conditions.
**Sequence of Storm - fairweather - storm**

1. Large storm maintains clear RSD.
2. Fate of RSD depends on storm aftermath:
   a. Prolonged aftermath with "medium waves" helps RSD stay clear.
   b. Prolonged aftermath with "low waves" will bury RSD.
   c. No aftermath will bury RSD.

---

**Figure 4.13** Comparison of suspension dynamics over the fine-sand plain and the RSD during an observed sequence of storm, fair-weather and storm conditions. (a) high waves (b) waning storm (c) fair-weather (d) second storm. Note coarse and fine-sand are in suspension over both beds during high waves but coarse suspension is in not in equilibrium with flow conditions over fine-sand plain.
Figure 4.14 Conceptual diagrams illustrating suspension dynamics (a) under low energy background swell when low flux of fine sand is expected to bury edges of the RSD; (b) under moderate waves when a flux of vertically well mixed fine sand penetrates over the entire RSD but enhanced turbulence limits deposition; and (c) under high storm waves when deposition of fine sand is inhibited over the RSD and coarse RSD material is actively transported and deposited to the adjoining fine-sand plain.
Figure 4.15 Schematic diagram illustrating variations in suspended sediment concentrations over differing substrates as parameterized by the sorted bedform model of Murray and Thieler (2004).
<table>
<thead>
<tr>
<th>Hydrodynamic Case</th>
<th>Depth (m)</th>
<th>$H_s$ (m)</th>
<th>$T$ (s)</th>
<th>$U_w$ (m/s)</th>
<th>$u_c$ (m/s)</th>
<th>Reversing Current (y/n)</th>
<th>Coarse Fraction</th>
<th>Forcing Duration (hr)</th>
<th>$d_{50}$ (mm)</th>
<th>$w_s$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy (Storm)</td>
<td>22</td>
<td>2.5</td>
<td>12</td>
<td>0.5</td>
<td>0.05</td>
<td>No</td>
<td>0.15</td>
<td>24</td>
<td>0.22 (fine)</td>
<td>1.8 (fine)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75 (coarse)</td>
<td>8.7 (coarse)</td>
</tr>
<tr>
<td>Low Energy (Fair-weather)</td>
<td>22</td>
<td>1</td>
<td>10</td>
<td>0.18</td>
<td>0.05</td>
<td>Yes</td>
<td>0.15</td>
<td>24</td>
<td>0.22 (fine)</td>
<td>1.8 (fine)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75 (coarse)</td>
<td>8.7 (coarse)</td>
</tr>
</tbody>
</table>

Table 4.5 Input settings for self-organizing bedform model run.
Figure 4.16 Results from sorted bedform model using storm conditions (Table 4.5). Light shades indicate higher percentage coarse material, dark shades indicate greater percentage of fine material.
Figure 4.17 Results from sorted bedform model using fair-weather conditions (Table 4.5). Light shades indicate greater percent coarse material, dark shades indicate greater percent fine material.
CHAPTER 5

DEVELOPMENT AND ANALYSIS OF AN EMPIRICAL MODEL FOR SEABED SCOUR PROCESSES
OVERVIEW

The preceding chapters have focused on observations and models of mutually interdependent changes in the shape of the seabed and the overlying fluid, a topic generally known as morphodynamics. Now, the study shifts slightly to examine cases in which the changes are the result of some object resting on or in the bed, a process defined earlier as scour. The previous and present studies are mutually related because objects that disturb the flow are quite common both naturally, such as the case of exposed rock outcrops, and anthropogenically, due to objects placed either intentionally (mines) or unintentionally (shipwrecks) on the seabed. Whatever their origin, however, once present such objects become part of the morphodynamic feedback system helping to form and maintain persistent patterns of roughness.

In this chapter, the focus of research is scour processes related to seabed objects. In part one, a simple empirical model for scour related burial of seabed mines is developed and assessed against a field study of mine burial conducted off of the west coast of Florida. The model is developed with knowledge of boundary layer dynamics of complex inner shelves examined in the previous chapters. Specifically, the role of combined wave-current hydrodynamics, sediment size variation, and bed roughness variation are brought to bear on the development of the model. The empirical scour model is part of an ongoing effort to develop simple yet reliable forecasts of mine burial suitable for addressing operational needs of the Navy.

A simple, parameterized scour related burial model based on the Soulsby-Whitehouse equations for scour, forced by readily available wind and wave forecasts, was developed as part of this study and demonstrated to provide a useful degree of forecast accuracy for both local hydrodynamic variables and mine burial. Several web-based graphical user interfaces (GUIs) were developed to facilitate sensitivity testing of the model as well as allowing case studies based on additional field data to be run. Previous observations were used to develop empirical transformations between nearest model grid cell and local hydrodynamic conditions. Once established, the transform functions were used to translate model forecasts to local conditions. During the field experiment, this work represented the first successful attempt by investigators in the
Office of Naval Research (ONR) Mine Burial Prediction (MBP) program to provide real-time forecasts of hydrodynamics and mine burial. Subsequent analysis of the field data indicated that the model did a remarkable job predicting hydrodynamics and a reasonable job predicting the burial behavior of mines situated on the fine-sand plain facies, but a less satisfactory job predicting burial of mines situated over a persistent RSD.

Variations in the forecast wave conditions were seen to introduce the largest source of uncertainty to the burial forecasts. The parameterized model predicts periods of rapid scour to accompany near bed orbital velocities \( (U_b) \) exceeding 1.25 times the critical velocity for initiation of motion. Rapid burial follows once \( U_b \) drops below 0.75 times the critical velocity \( (U_{cr}) \). The model is seen to do a better job of predicting the behavior of mines associated with the fine sand-plain than with those placed within coarse rippled, gravel patches, owing to the absence of ripple dynamics in the model.

In part two, the scour model is modified to include a simple parameterization for vertical variations in grain size and adapted for the non-military purposes of addressing the fate of artifacts associated with the wreckage of the shipwreck *Queen Anne's Revenge*. Measurements of varying wave energy events were fed into the modified scour model. Comparison between model estimates and the observed state of the artifacts suggest that long-term maximum settling depth is controlled by the magnitude of near-bed flow, local scour, overall seabed movement, and the characteristics of the underlying sediments. Including the effects of shallow stratigraphic variations in erosion resistance brings the model predictions into close agreement with observed long-term local scour conditions. The results from this study suggest that numerical forecasts of wave conditions might be useful in predicting the short-term settling depth and the exposure of important historical artifacts due to high energy events.

Together these component studies highlight the interconnections between scour processes, roughness variation, and the role of underlying geology in developing and maintaining heterogeneous sedimentary systems on the inner shelf.
PART ONE-
SCOUR MODEL DEVELOPMENT AND CASE STUDY FROM
INDIAN ROCKS BEACH, FLORIDA

This chapter is being prepared for submission to a journal with authors: Trembanis, A.C., Friedrichs, C.T., Richardson, Traykovski, P., M., Howd, P.A., and Elmore, P.
5.1 INTRODUCTION

Understanding the processes that lead to scour and burial of seabed objects and providing meaningful estimates of the degree of settling and/or exposure of such objects is of critical concern in mine counter measure efforts (Figure 5.1) (Friedrichs, 2002; Whitehouse, 1998; and Soulsby, 1997). A major goal of ONR’s MBP program is to provide the operational Navy a model for forecasting mine burial that works with a known and useful degree of accuracy in regions of strategic interest, defined initially as sandy inner shelves dominated by waves. In order to be useful under real world conditions, such a model must be reasonably accurate and reliable but also simple and fast enough to be executed in a practical, straightforward manner. Thus, it must parameterize the complicated and computationally intensive details of localized mine scour. In response to the above needs, the aim of this study is to demonstrate the practical utility of forecasting scour related mine burial using a simple parameterized model forced by readily available wave, wind, and tidal forecasts. To this end, a combined field and modeling study of scour related mine burial was conducted in the winter of 2003 off of Indian Rocks Beach (IRB), along the Gulf coast of Florida (Figure 5.3).

5.2 MOTIVATION/BACKGROUND

Over the last 50 years the predominant source of strikes against Naval vessels has come from mines (Dr. Peter Fleischer, personal communication). Figure (5.1) depicts the damage to a South Korean vessel during mine sweeping operations. During the 1991 Persian Gulf War, the USS Princeton was damaged by a seabed mine. Recent activities
in the Persian Gulf and a previously rather poor record of prediction have prompted funding of the Mine Burial Prediction Program (MBP) by the Navy (Richardson et al., 2001).

Friedrichs (2002) conducted a review of several scour related mine burial models and determined that the Whitehouse-Soulsby equations (see Chapter 1 for a theoretical treatment of scour) were robust and they were most physics-based models available. In this study, the Whitehouse-Soulsby equations are used to estimate real-time forecasts of mine burial based on inputs from a global wind and wave model.

5.3 WAVEMODEL

NOAA’s Wavewatch III (WW3) wave model is a 3rd generation global wave model (Tolman, 2002). WW3 provides five-day forecasts of winds and waves in the northwest Atlantic with 0.25 degree resolution in latitude and longitude (Figure 5.2). WW3’s time step is a three-hour interval. Model output includes mean wave parameters such as wave height, direction of propagation, and period along with estimates of u and v components of winds 10 m above the surface. Model forecasts are updated twice daily, with the first 12 hours of each model run representing hindcast conditions. Binary files of each model run and monthly hindcast summaries are available for free public download from the NOAA wave model website in the WMO GRIB format (NCEP, 1998). Binary files are downloaded and archived at the VIMS MBP webpage: http://www.vims.edu/~cfried/MBP/.

5.4 STUDY SITE
The field site for this experiment was located approximately 10 km offshore of Indian Rocks Beach, along the West-Central coast of Florida in water depths of 11–15 m (Figures 1.6 and 5.3). The region is characterized by a series of NW trending Holocene sand ridges with intervening coarse sand floored RSDs (Locker et al., 2002) (Figure 5.3). The sand ridges are approximately 1 km wide and 4–8 km in length with sediment thickness of up to 3 m. A boomer seismic profile line across one of the sand ridges is shown in Figure 5.4. Inner shelf sediments are composed of quartz rich, fine-sand \( (d_{50} = 0.18 \text{ mm}) \) plains overlying coarse gravelly shell hash units \( (d_{50} = 0.80 \text{ mm}) \) (Figure 5.7). Adjacent to and underlying the large sand ridges are smaller RSD patterns often with complex dendritic planview shapes (Figure 5.5). Persistent RSD patches were specifically targeted for mine placement ( Locker et al., 2002). A 1.3 x 0.9 km region atop one of the sand-ridges was chosen for the location of the mine deployments (Figures 5.5–5.7). A suite of oceanographic instruments were utilized for the field study including instrumented mines, quadpods, and Autonomous Underwater Vehicles (AUVs) (Richardson et al., 2003). Additionally, numerous cores and sediment grab samples were collected and analyzed prior to and following the experiment ( Locker et al., 2003).

The Winter 2003 IRB field experiment involved the deployment of 16 different mine and mine like shapes over three different sites (Figures 5.3 and 5.5). Site 1, a fine-sand plain (FSP), was the primary deployment location where 4 Acoustic Instrumented Mines (AIMS) and 2 German, FWG instrumented mines (Figure 5.8) were placed. Site 2, a ripple scour depression (RSD) was a secondary location where 2 FWG instrumented mines were deployed. Other, non-cylindrical mines were also placed at each site but are
not considered in this study. Table 5.1 provides the exact deployment (on the seafloor) time, recovery time, mine diameter, depth, sediment type, and grain size for each mine.

The Acoustic Instrumented Mines (AIMs) were developed by the Naval Research Laboratory (NRL) and Omni Technologies, Inc. (Figure 5.8). The AIMs use 112 acoustic burial sensors that are mounted flush with the mine surface. Roll, pitch, and headings are measured with accelerometers and electronic compasses. Accelerometers (3-axis) are used to detect mine motion that occurs when the mine falls into scour pits or the seafloor liquefies. Pressure sensors measure bottom pressure fluctuations associated with tidal changes and surface gravity waves.

Ingo Stender of Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik (FWG) in Kiel, Germany developed self-recording mines that use optical methods to record the mine burial state (Figure 5.8 insert). Burial is measured by three rings of paired optical sensors externally mounted at even intervals around the mines. Transmitting optical sensors are LED’s and receiving sensors are phototransistors. Burial is detected by blockage of these sensors.

Previous measurements of nearbed hydrodynamics indicate that the inner shelf at this field site is dominated by storm waves. Significant wave height ($H_s$) ranges between 0 and 3 m with the largest waves occurring during winter cold fronts and tropical storms (Howd and Brodersen, 2003). Mean currents are primarily of tidal origin though fairly weak with peak velocities below 20 cm s$^{-1}$ (Howd and Brodersen, 2003). Analysis of wave climate records indicates that the typical average wave period during storms is between 7 and 10 seconds (Friedrichs and Trembanis, 2003).
5.5 METHODS

The approach in forecasting wave climate at the IRB field site is to transform forecasts from the nearest grid cell location provided by the NOAA Wavewatch III global wave model (Figure 5.2) to local conditions. An empirical transformation between the model and local conditions was developed based on historical time-series of measured wave conditions at the IRB field site (Figure 5.9). A local estimate of significant wave height is related to the closest WW3 grid cell forecast value by the equation

\[
H_{s(irb)} = 0.9545H_{s(ww3)} + 0.0450
\]

where the units of wave height are in meters.

During this experiment, the model was run using forcing from waves alone. However, ongoing experiments off of Martha’s Vineyard Massachusetts are using the combined effects of waves, wind driven currents, and tides in the model simulations.

Model inputs were updated every 12 hours with new forecasts. The first 12 hours of any model run represented the hindcast record. At each time step, the initial portion (12 hours) was retained and the subsequent forecast was appended. In this manner a growing hindcast/forecast record of model inputs and outputs was created. The results of each individual forecast leading up to that point 5 days in the future when the forecast was replaced by a hindcast estimate represents a range of possible predicted outcomes. This situation is similar to comparing the weather recorded on any given day to the weather forecast reported each morning by the local news anchor. An example of the
variations common between subsequent forecasts leading up to the hindcast estimate is shown in Figure 5.14.

Because of occasional unrealistic values in predicted wave period generated by the WW3 model, this experiment utilized a constant wave period of 7 seconds, based on examination of historical wave records (Friedrichs and Trembanis, 2003). Next, an empirically determined constant wave friction factor of 0.08 was used to predict skin friction. Comparisons by Elmore et al. (2003) suggested negligible difference between fixed and time varying values for wave friction factor when applying the Whitehouse-Soulsby equations. Given the uncertainties in the formulation and performance of various wave friction formulae (Chapter 3), the simple fixed approach followed here provides consistently reasonable results. It should be noted that the fixed wave friction factor was based on model tuning to the initial Martha's Vineyard experiment and has remained unchanged in subsequent model experiments.

Once WW3 wave estimates were converted to local near bed values using the empirical transformation and linear-wave theory, they were introduced into the Whitehouse-Soulsby equations along with observed values of bathymetry (Figure 5.5) and grain size (Figure 5.7), resulting in a mapview model estimate of burial (Figure 5.15). Model input settings and output results were displayed through a series of web-based graphical interfaces. The operational design of this study was to make the model simple and intuitive allowing non-specialist users to meaningfully interact with and obtain results from the model in a real-time fashion. This goal was accomplished through the
use of a Labview® front-panel graphical user interface (GUI) which interactively passes control inputs to Matlab® code for numerical computation. Development has included both one-dimensional single point and two-dimensional map planview versions of the model.

The most active portion of this study took place during the field experiment, when real-time forecasts were constantly being produced and published on the web. In particular, at the 2003 ONR Mine Burial Prediction Meeting in St. Petersburg, Florida, Friedrichs and Trembanis (2003) presented forecasts of mine burial while instrumented mines were in the water offshore. This effort represented the first attempt to provide real-time forecasts of mine burial for the entire Mine Burial Prediction Program. To demonstrate the potential for rapid response to changing operational needs, similar forecasts of mine burial for the northwest Persian Gulf were developed during the early stages of Operation Iraqi Freedom (Trembanis et al., 2003).

5.6 RESULTS

The parameterized burial model was successfully calibrated using NOAA wave model output and observations from current meters and instrumented mines deployed at the Martha’s Vineyard field site (Figure 5.13).

Five-day forecasts of the WW3 model have been archived at the VIMS MBP website twice daily since September 2002. Using an empirical linear transformation from the nearest model grid point, hindcasts by this model adequately reproduced wave
heights observed at the Indian Rocks MBP field site (Figure 5.9). Close examination of Figure 5.9 reveals a consistent trend of slight under prediction of wave heights by the model during large wave (storm) events. During low background swell conditions, model wave heights exhibit a tendency to predict slightly higher than observed waves. Errors in estimating low wave conditions are not critical as low waves are incapable of inducing scour. Model estimates during high wave conditions, defined as significant wave heights greater than 1.5 m, were generally within 20 percent of the observed value. The lower than observed predictions of wave height during storms suggests that subsequent model derived estimates of scour are slightly conservative values.

Observed hydrodynamic conditions during the experiment as measured by one of the instrumented quadpods are graphically summarized in Figure 5.10. Data were obtained from an upward looking ADCP sensor and were reported in 2 hour burst intervals. Low energy background conditions were interrupted by 4 brief storm intervals during which Hs exceeded 1.5 m. Wave period during the storm events was between 6–9 seconds. Mine burial reported by diver observations are summarized in Table 5.2 and in the photos shown for both the coarse and fine domain in Figure 5.12. Observed mine burial behavior is strongly associated with energetic wave events. As in the case of previous studies at Martha’s Vineyard Coastal Observatory (MVCO) (Richardson and Traykovski, 2002), scour and re-exposure was seen to occur during the peak portions of storms with rapid burial during the waning stages.

Diver observations during mine recovery at the end of the experiment (Table 5.2)
revealed the following scour characteristics of mines at the two sites.

**Fine-Sand Plain:** Extensive scour noted around the ends off all mines with build up of sand against the middle portions of the mines. Large shallow scour pits surrounded the mines, which were resting in the pits between 40 - 60 cm down relative to ambient bed level. At several mines, noticeable accumulations of shell fragments and gravel were noted adjacent to and within the scour pits.

**Rippled Scour Depression (RSD):** Large wave orbital ripples comprised the dominant bed morphology at this site. Observed mine burial was markedly different over the RSD than over the FSP site. Most noticeable was an absence of pronounced scour pits surrounding the mines. Surface area burial of mines was low ~ 30% and burial related to scour depth varied between 20 - 30%. Cyclic episodes of burial and exposure were observed from the acoustic sensors (J. Bradley, personal communication) discussed later, is presumed to be the result of ripple migration through the domain.

Running hindcasts and five-day forecasts of scour related mine burial, based on the MVCO calibration (Figure 5.13), were produced for the Indian Rocks Beach site (Figure 5.11). Differences between successive forecast wave conditions lead to significant differences between forecast mine burial (Figure 5.14).

Distinct scour related, burial behavior phases are evident in the model forecasts. In the first phase when hydrodynamics conditions are mild and near bed velocities ($U_b$) are much less than 0.75 times the critical value for the initiation of motion ($U_{cr}$), both scour and burial are zero (Figure 5.14). In stage two, near bed velocities approach and
then exceed $0.75 \, U_{cr}$ at which point clear-water scour takes places gradually. The parameterized model predicts rapid active scour once $U_b$ exceeds $1.25 \, U_{cr}$. Rapid burial follows once $U_b$ drops below $0.75 \, U_{cr}$. Individual forecasts of wave height, bottom wave orbital velocity, surface winds, and mine burial for the duration of the field experiment are available for download via the VIMS MBP web site at www.vims.edu/~cfried/MBP.

A 2-D, interactive, GUI interface for the $\sim 1 \, \text{km}^2$ Indian Rocks field site was developed, allowing users to rerun any portion of the numerical experiment for a selected geographic point within the field area (Figure 5.15). The 2-D, interactive model includes observed spatially varying bathymetry and grain size along with temporally varying wave height. Users can specify mine diameter and then globally vary both wave height and grain size to further examine model sensitivity or run specific case studies. Since operational Navy needs often depend on several metrics describing distinct aspects of mine behavior, both percent exposed surface area and the depth of the mine relative to the far-field seabed level are reported. Time series animations of the 2-D model predictions for the completed MBP field experiments at Indian Rocks (Jan-Mar 2003) and at MVCO (Jan 2002) can be viewed at:

www.vims.edu/physical/projects/CHSD/projects/MBP/ONR03_report

5.7 DISCUSSION AND CONCLUSIONS

Wavewatch 3 wave model estimates do a reasonably good job estimating local wave conditions after an empirical linear transform function is applied. The model tends to slightly under predict wave conditions during storms and slightly over predict wave
conditions during fair-weather. Variations in model estimates from one forecast to the next are larger than the differences between modeled and observed wave conditions, suggesting that the largest uncertainty in estimates of wave inputs lies in the forecast model, not in the local transformations.

A simple parameterized scour model easily integrates observed bathymetry and grain size distribution together with model hindcast/now-cast/forecasts to produce reasonable, real-time estimates of scour related burial. The web-based, graphical user interface allows non-specialists to quickly and easily adjust parameters to test certain combinations of settings or assess model sensitivity. Variations in wave climate predictions from one model forecast to another introduce large errors into subsequently derived estimates of scour related burial. The model is sensitive to a lesser degree to both local water depth and grain size variation.

In situ observations of mine burial indicate that scour behavior is highly variable over short spatial distances based on variations in depth, substrate, and mine type. This spatial heterogeneity often exhibits itself over length scales far below the resolution of existing large domain operational models, suggesting that high resolution models with well constrained field reconnaissance data will be essential for meaningful, future fleet operations. Mine orientation does not appear to be a major factor affecting scour behavior because of rapid re-orientation during the first wave event. Consistent with model predictions and observations at other MBP sites (Richardson and Traykovski, 2003) significant differences exist between burial estimates depending on which metric
(either scour depth or surface area) is reported. These differences suggest that mine burial prediction efforts should continue to use multiple metrics and not simply rely on any single determinant of mine condition.

Model estimates of percent burial are reasonably satisfactory for forecasting observed conditions with mines resting on the fine-sand plain facies. The VIMS model does a less satisfactory job forecasting burial conditions of mines within the coarse gravelly shell hash of the RSD facies. Difficulties in forecasting mine burial within RSD domains are a result of the dynamic bedform behavior attendant with such deposits, which is not accounted for in the model parameterization. Cyclic variations in burial recorded by acoustic sensors, particularly during wave events, suggest that bedform migration may play the dominant role in the exposure of mines within RSDs. Furthermore, bedform migration is likely responsible for the absence of scour pits typically observed in association with mine scour. Future efforts to forecast mine burial behavior will require improved understanding and models of bedform behavior associated with RSD deposits. Further laboratory and field analysis is also required to determine the appropriate empirical values for use with non-traditional mine shapes in the Whitehouse-Soulsby equations.

Mine burial experiments were conducted on fine and coarse sandy sediments, in 15 m water depths, 10 km off Indian Rocks Beach, West-Central Florida. Experiment sites were chosen based on extensive acoustic (side scan sonar, chirp seismic profile, and multibeam sonar) surveys and sediment samples. Eight cylindrical mines were deployed
January through March 2003. The extensive sediment data combined with predictions from an advanced NOAA wave model during these experiments was used to predict burial by wave-induced scour (VIMS scour model). Extensive hydrodynamic data collected with bottom-mounted quadpods is compared to physical oceanographic model predictions. Time-dependent scour measured using the optical and acoustic mines, characterized by sector scan sonar, video, and diver photographs/observations compares favorably to model predictions for mines within the fine-sand plain (FSP) facies but less favorably for mines located within RSD facies, suggesting an important role is played by bedform dynamics unaccounted for in the model. Errors associated with individual forecast wave conditions are seen to introduce the largest uncertainty in burial predictions because of model sensitivity to wave height. Additional errors in burial predictions within coarse rippled RSD deposits are due to the lack of bedform dynamics in the model. Future research into mine burial within heterogeneous, wave dominated, sandy shelf settings should include attempts to parameterize dynamic bedform behavior.
PART TWO-
CASE STUDY FROM THE QUEEN ANNE’S REVENGE SHIPWRECK

The content of this chapter was published in the proceedings of the Coastal Sediments 2003 Conference with authors: Arthur C. Trembanis and Jesse E. McNinch
5.8 INTRODUCTION

The discovery of an early 18th century shipwreck near Beaufort Inlet, North Carolina, believed to be the pirate Blackbeard's flagship *Queen Anne's Revenge (QAR)*, affords an incredible opportunity to examine the long-term fate of artifacts in an energetic, shallow-water setting. The ship, which ran aground in waters less than 4 m deep while attempting to navigate Beaufort Inlet, now rests in 7 m of water on the shoals of the ebb tidal delta. Archaeological evidence indicates the wreck has remained in the same location since the initial grounding, which suggests that the numerous and varying-sized artifacts scattered around the debris field have settled through approximately 3.5 m of substrate (Figure 5.16). McNinch et al. (2001) hypothesized that this extensive settling through unconsolidated, sandy sediment resulted from episodic periods of scour and burial, and that the wreck's recent exposure occurred because the sedimentologic nature of the underlying geology limited continued scour. In this study, an analytical model designed for predicting scour around objects on the seafloor is used to test the episodic scour-settling hypothesis and to evaluate the model's utility as a basis for a refined model that predicts scour and maximum settling depths over long periods and with varying geologic strata. Specifically, a model that has successfully predicted the scour and settling of mines is applied to previously measured boundary conditions at the *QAR* wreck site and results are evaluated from seafloor and sub-bottom surveys as well as from the location and characteristics of artifacts. A simple model that predicts scour and maximum settling depths over short time periods will be an extremely valuable tool for the management and recovery of shipwrecks or other artifacts of cultural significance.
Queen Anne’s Revenge, formerly the French slave ship Concorde, was a three-masted ship of approximately 250-tons (Moore, 1997) with a keel depth that likely extended 3.7 m below the surface of the water. Written documentation by David Harriot, who sailed with Blackbeard, noted that the QAR “ran aground” on the shoals of the ebb tidal delta while attempting to enter Beaufort Inlet in 1718 (Moore, 1997) (Figure 5.16). Beaufort Inlet, a barrier-island, tidal inlet, has remained open and navigable since at least 1585 (Fisher, 1962). Consistent channel depths of 5 m has fostered maritime traffic since the late 17th century, but the dynamic nature of the ebb channel position (Wells and McNinch, 2001) as well as conditions across the shallow portions of the ebb tidal delta can be quite treacherous for deep-drafted vessels. Observations of currents and waves, seafloor bathymetry, and analysis of historic charts suggest that the wreck is periodically exposed to considerable energy (McNinch et al., 2001). The main inlet channel appears to have migrated across the site numerous times since 1718, and its strong currents have eroded the surrounding seafloor to depths of at least 5–6 m (Wells and McNinch, 2001). Near-bottom currents and waves were measured over a nearly continuous interval of two years and, fortuitously, captured the effects of a hurricane, a nor’easter, a sou’wester, and intervening periods of fair weather. Estimates of sediment transport reveal that sediment is stable under fair-weather and moderate storm conditions, but that a significant volume of sediment is mobilized when wave heights exceed 1.5 m.

QAR artifacts have been mapped on the southwestern flank of the ebb tidal delta and are scattered over a 30 x 50 m area (Figure 5.17). Interestingly, from the perspective
of this work, all of the artifacts appear to rest on the same depth horizon (within 50 cm),
although the largest pieces are typically more exposed above the seafloor surface. The
wreck site, measuring approximately 5x10 m (Figure 5.18) includes a large rubble
mound, the lower portion of the hull, and a host of artifacts such as cannons, ballast
stones, and anchors all of which have become concreted into one indistinct mass (Figure
5.20). Smaller mounds encasing cannons, anchors, cannon balls, etc., that were likely
separated from the vessel at the time of sinking litter the perimeter of the main rubble
mound and lie at varying states of exposure on the seafloor or within 50 cm of the surface
(Figure 5.21). Given that the area around the wreck site has undergone considerable
erosion related to a combination of waves, currents, and a migrating ebb channel, it was
fascinating and intriguing that artifacts of different size and mass were all found resting
on the same horizon after almost 300 years on the bottom. Remarkably, evidence ranging
from the relatively unspoiled condition of the bottom timbers, location of all the artifacts
at roughly the same depth horizon, and young encrusting coral (less than 15 years old; N.
Lindquist, personal communication) all suggest that a process, which preserves the
artifacts through burial and maintains an equal rate of settling, regardless of size, has
been operating. McNinch et al. (2001) hypothesized that basic principles of seafloor
scour may explain these observations but could only speculate as to whether scour
occurred evenly between different sized artifacts and under varying hydrodynamic
conditions. Numerical simulations with a recently developed VIMS scour model based
on the Whitehouse-Soulsby equations (Friedrichs, 2002; Whitehouse, 1998) combined
with direct observations from the QAR site allow us to evaluate this hypothesis.
The Whitehouse-Soulsby equations utilize a simple relationship for rates of burial (equations 1.31–1.34). Observations suggest a cylindrical mine on a sandy inner shelf buries by repeatedly falling into its own scour pit (Briggs et al., 2002; Friedrichs, 2002; and Whitehouse, 1998). We hypothesize that the same mechanism occurs in the case of artifacts lying on the seafloor. The depth of burial of a shipwreck relative to the undisturbed surrounding bed is given approximately by the maximum depth of scour, $S_{max}$ (equation 1.34), experienced to that point by the wreck.

5.9 METHODS AND RESULTS

5.9.1 FIELD OBSERVATIONS

Numerous swath bathymetry and side scan sonar surveys were collected by McNinch at the QAR site from 1999 to 2002 utilizing an interferometric (Submetrix 234 kHz) swath sonar system integrated with a motion sensor and a real-time kinematic global positioning system (Figure 5.17). These surveys yielded data consistent with diver observations of continued exposure of the main rubble mound, extending approximately 1–2 m above the seafloor surface, along with scour excavations around the mound (Figure 5.20). McNinch et al. (2001) documented the excavation of a large, tear-drop shaped scour depression in the lee of the mound following hurricane Bonnie. More recent surveys show, however, that the mound continues to remain exposed above the seafloor and has not settled a measurable distance into the depression. Figure 5.18 shows a planview view of side scan sonar backscatter overlying swath bathymetry. The concretions of the artifacts yield a strong backscatter signal, visible in the background immediately behind the mound (Figure 5.17). Diver observations and geophysical
surveys show that the area is covered ephemerally with fine-sand and silt, which settle from the water column and drape the rubble mound and periodically covers the adjoining RSDs, as has been documented in association with other shipwrecks (Quinn et al., 1997; Caston, 1979) (Figure 5.19). The RSDs found in association with the QAR wreck-site are morphologically quite similar to the small elongate nearshore shore-normal RSDs (Facies 4) observed off Tairua Beach, New Zealand (Hume et al., 2003; Chapter 2).

Large-scale sandy bedforms have also been seen to migrate through the area and temporally cover some of the artifacts and previous scour excavations.

Many attempts were made by McNinch to collect vibracores from around the wreck site and directly beneath the main rubble mound. A large, Alpine vibracoring system obtained nine cores but none of them penetrated more than 1.5 m, terminating on a stiff, well-sorted, silty sand. Smaller diver-held vibracores, used to core beneath the mound, also met refusal roughly 1 m below the surface. Preliminary analyses of the cores and diver observations during archaeological trenching revealed three distinct substrates (Figure 5.21). The surface sediment varies in thickness from 0 to 1 m and is a poorly sorted, fine to medium sand with fine shell hash. Beneath the surface sand is a very poorly sorted sand and coarse shell layer that contains most of the artifacts (Wilde-Ramsing, personal communication). The layer beneath the shelly substrate is a very well-sorted, grey, silty sand that is stiff and slightly cohesive. Archaeologists report that this substrate is culturally sterile, meaning that no artifacts are found within this layer. It is suspected that not only is this lower substrate difficult to core, its cohesive properties make it resistant to erosion and thereby serves as a boundary to further scour. The side-
scan sonar surveys show exposure of the coarse shell layer in bathymetric lows around the site. The coarse material, presumably the shell fraction, appears to be reworked by waves into large wave ripples and is quite visible in the side scan record (Figure 5.18). It is suspected that the shell layer underlies much of the area and represents a relict channel lag when the ebb channel was located at the site, or alternatively, may form lenses of coarse material interfingered with fine-sand layers as was observed at Tairua, New Zealand (Hume et al., 2003; Chapter 2).

An electromagnetic current meter (EMCM) with integrated pressure sensor, InterOcean S-4A, was deployed approximately 15 m southwest of the main rubble mound to provide information on waves and currents near the wreck. The meter was rigidly mounted to a stand that held the sensors 1 m above the bottom. Measurements of pressure and flow were collected at 2 Hz for 12 minutes every hour and continued for 298 days from May 1998 to April 1999.

5.9.2 MODEL SIMULATIONS

The Whitehouse-Soulsby scour equations were chosen because of their reliance on well-established engineering relations for scour around seabed objects (Friedrichs and Trembanis, 2003; Chapter 5 part 1 and Chapter 1). The Whitehouse-Soulsby relationships form the basis of the mine burial model developed by Friedrichs (2001) and implemented by Trembanis and Friedrichs (2003). This study, therefore, represents an application of Whitehouse-Soulsby to the case of submarine archaeological artifacts. For purposes of this experiment, three artifacts with distinctly different sizes were
modeled, namely a cannon ball, a cannon, and the main rubble mound of the QAR wreck site (Figure 5.20). Four distinct wave condition episodes, a tropical hurricane, an extratropical winter storm (Nor'easter), a series of sustained southwesterly winds (Sou'wester), and a fair weather period, were culled from two years of observed near bed velocities and fed into the model to predict the resulting scour and burial (Figure 5.23). Each model run was treated separately assuming each artifact was initially at rest on the surface of the seabed. The resulting scour depths were then compared to the observed condition of the wreck artifacts and used to assess the role of underlying geology on artifact resting depth. The key environmental parameters to the model when applied to the shipwreck were near bed orbital velocity, grain size, diameter of the object, and time. Orbital velocity was set by each time series dataset. A $d_{50}$ grain size of 0.19 mm (fine sand) was chosen based on previous sediment samples from the fine sand plain surrounding the QAR mound (McNinch et al., 2001). The representative diameter for each artifact ($D = 0.15, 0.25, \text{ and } 2 \text{ m respectively}$) was based on archaeological analysis of the wreck site (Wilde-Ramsing, personal communication) (Figure 5.20).

The input of orbital velocity into the Whitehouse-Soulsby model can come either in the form of direct near bed measurements ($U_{ob}$) or from predictions of near bed orbital velocity ($U_b$). In order to generate estimates of the later, first significant wave height ($H_s$) and peak wave period ($T_p$) were determined from spectral analysis of the time series of pressure data recorded by the S4 current meter, following the approach of McNinch et al. (2001). Next, near bed orbital velocities were estimated by applying linear wave
theory to the wave height \((H_s)\) and period \((T_p)\) values using the solution for horizontal velocity of a linear progressive wave (equation 4.1).

In this study, \(U_b\) was chosen over \(U_{ob}\) for several reasons. First, as will be shown in the results, linear wave theory estimates \((U_b)\) were in close agreement to the observed values \((U_{ob})\) (Figure 5.22). The \(U_b\) values, in fact, represent slightly conservative estimates of near bed flow conditions. Second, by utilizing time series of wave height and period, the possibility exists for using global wave forecast models such as the Wave Watch 3 (WW3) model to predict real-time scour conditions for the QAR wreck and other similar sites in the absence of bed mounted instruments. A similar approach has been successful in forecasts of environmental conditions and burial of seabed mines (Trembanis et al., 2004; Friedrichs and Trembanis, 2003; Richardson et al., 2003; Briggs et al., 2002; Chapter 5 part 1). One of the anticipated products of this study is the development of an operational model of artifact related scour burial that could be utilized by marine archaeologists in finding wreck sites and estimating their exposure to decay. An example of an operational model for artifact scour is shown for the case of the QAR wreck study in Figure 5.24.

5.9.3 WAVE CONDITIONS

The time series of wave height \((H_s)\) and period \((T_p)\) for each of the four separate forcing cases is shown in Figure 5.23.

HURRICANE BONNIE
The most energetic wave case was observed during hurricane Bonnie. Wave height ranged from 0.25 – 3 m with a mean of 1 m. Peak wave periods ranged from 5 –17 s with a mean of 10 s. For more than 90 hours wave height exceeded 1 m with periods between 10 and 17 s. At the peak portion of the storm, significant wave height was greater than 3 m with peak spectral period of 15 s.

SOUTHWESTERLY WINDS

The second test case comprised a period of persistent southwesterly winds (Sou’wester). During this period, wave heights were between 0.2 – 1.1 m with a mean of 0.5 m. Wave periods varied between 5 and 11 s with a mean of 7 s. Wave heights exceeded 1 m two times with attendant wave periods of approximately 7 s.

NOR’EASTER

Due to the orientation of the coastline around Beaufort Inlet and sheltering by Cape Lookout, extratropical winter storms (Nor’easters) have a limited impact on this site (McNinch et al., 2001). The Nor’easter recorded in this dataset was no exception and thus represented the third most energetic model wave case. In this dataset, wave height ranged from 0.2 to 1.1 m with a mean of 0.44 m. Wave periods were between 5 and 12 s with a mean of 8.3 s. Wave period and wave height ranged from 5 to 12 seconds and 0.5 to 0.75 m respectively. One brief episode included a wave height of ~1 m and period of 7 s.

FAIR-WEATHER
The fair-weather case was the least energetic condition tested, comprising a period of very calm and essentially negligible wave conditions. Wave height ranged from 0.05 to 0.5 m with a mean of 0.25 m. Wave period varied between 5 and 17 s mean of 9 s.

Figure 5.22 shows a comparison of measured \( (U_{ab}) \) and estimated \( (U_b) \) orbital velocities. There is good agreement between the two with \( U_b \) frequently providing a conservative estimate of the measured conditions. Similar studies (Friedrichs and Trembanis, 2003; Briggs et al., 2002;) have used linear regression to improve the fit between observed and linear theory derived near bed orbital velocities.

5.9.4 SCOUR PREDICTIONS

The time series of scour depth (in cm) for each of the artifacts during all four wave cases are shown in Figure 5.25 and summarized in Table 5.3.

HURRICANE BONNIE

The Whitehouse-Soulsby model predicts complete scour and burial of all three artifacts based on the forcing conditions of hurricane Bonnie (Figure 5.25a). The peak portion of the storm initially induces scours around all three artifacts, which subsequently are buried during the waning portion of the storm. A second energetic wave event then partially re-exposes the objects before they are buried again.

SOUTHWESTERLY WINDS
The test case with southwesterly waves resulted in mixed scour conditions for the three artifacts (Figure 5.25b). As in the case of hurricane Bonnie, both the cannon ball and the cannon were predicted to undergo complete scour and burial. The conditions, however, were not sufficiently energetic to induce complete scour of the large rubble mound. The rubble mound was predicted to receive only around 40 cm of scour.

NOR’EASTER

The Nor’easter test case included three separate scour episodes. The cannon ball was predicted to undergo complete scour and burial from each episode. The model suggests that the nor’easter would produce near total scour for the cannon with a maximum scour depth of 21 cm (84%). The waves in this case were only capable of scouring the rubble mound to a minor depth of 25 cm (12.5%).

FAIR-WEATHER

The mild waves of the fair weather period (Figure 5.25d) produced negligible scour (< 3 cm) in the case of all three artifacts.

5.10 INCLUDING THE EFFECTS OF SHALLOW STRATIGRAPHY

The effect of shallow stratigraphy on scour depth was introduced into the model simulation for the case of hurricane Bonnie. Shallow stratigraphy was incorporated into the model by including vertically varying sediment characteristics into the model. Based on diver observations of shallow stratigraphy from the site (Figure 5.20), an erosion resistant layer was added at a depth of 40 cm below the ambient seabed. The resulting
A conceptual model showing a hypothetical sequence of local scour and overall bed level changes together with the influence of underlying geology is shown in Figure 5.27. At time $t = 0$ the ship has just run aground. Waves and currents would quickly break up large portions of the wreck and scatter debris in the local vicinity. Next, time $t = 1$, the processes of local scour act on the individual artifacts and the central mound of the shipwreck and proceed to scour objects to varying depths based on the object size and hydrodynamic conditions. Subsequent storms would then readjust the artifacts to newer depths. Following equilibration with storm conditions overall bed level changes due to movement of the ebb tidal delta would lower the artifacts *en masse*. Cycles of tidal delta switching would then variously bury or expose the artifacts to further scour. At any point in this sequence shallow underlying sedimentary units would alter the rates or extent of scour based on the geotechnical properties (erosion resistance) of the layer.
5.11 DISCUSSION AND CONCLUSIONS

Field observations indicate 1) partial exposure of the main rubble mound above the seafloor, 2) scour depressions activated during storms with substantial waves but negligible settling of the main rubble mound, 3) smaller, individual artifacts at varying levels of exposure, yet all lying on roughly the same depth horizon, and 4) most importantly, all artifacts have been discovered in a coarse, shell layer lying directly above an erosion-resistant, stiff silty sand. Results from the model simulations are consistent with field observations and support the episodic scour-settling hypothesis. The three objects used in this model study (cannon ball, cannon, and rubble mound) succumb to varying degrees of burial under conditions ranging from fair-weather to severe storms. Although varying burial rates by themselves likely will leave the objects at different levels in the seabed at any given instant in time, over the long-term occasional severe events would reset the artifact depths to a normalized horizon relative to the surrounding seafloor. Simply put, a large storm such as the direct passage of a hurricane would wipe out the record of previously minor events leaving artifacts at a depth in the seabed in direct adjustment to the hurricane conditions. Scour alone cannot entrench an artifact through layers of fine sand deeper than the size of the object itself, since once the artifact has settled and no longer protrudes above the surrounding seafloor the scour mechanism shuts off. The tops of all the artifacts, including the main rubble mound, will therefore reach the same depth horizon episodically whenever a severe wave event occurs at the site.
A significant contradiction between the general scour model simulation and the actual resting depth of the main rubble mound is apparent following hurricane Bonnie. The model predicts full scour (2 m) and subsequent settling and burial, whereas the rubble mound has remained perched above the seafloor throughout the years of observation. This discrepancy occurs because the rubble mound is resting on a more scour resistant layer, the cohesive silty sand, and continued excavation is unlikely even under the most severe wave conditions. As suggested conceptually by McNinch et al. (2001) the maximum settling depth appears to be controlled by the magnitude of near-bottom currents and the characteristics of the underlying sediment. Incorporating shallow stratigraphy into the model produces scour depth estimates consistent with this theory of geologic control.

These results suggest that the short-term fate of artifacts in sandy, wave-dominated environments can be predicted with knowledge of the hydrodynamic regime and the underlying stratigraphy. If an erosion resistant layer is present at a depth in which flow remains strong, the artifacts likely will become exposed on this layer and eventually be transported away or be exposed to degradation, depending on the size and transportability of the artifacts. This factor may explain the many anecdotal stories of wrecks suddenly appearing on beaches following a severe storm decades or centuries after the vessel sank (Table 5.4). If a wreck occurs in the outer surf zone, the remains will quickly become scoured and then settle into the sandy substrate. Episodic erosion of the surrounding seafloor would gradually cause the remains to settle in-place to lower and lower horizons until either they reached a depth in which fluid flows were no longer
strong enough to scour or they encountered an erosion-resistant layer in which case they would degrade in-place or possibly be transported shoreward and left on the beach.

These results suggest that the Whitehouse-Soulsby model can be successfully used to predict the maximum settling depth of artifacts when near-bed flow conditions and underlying sediment characteristics are known.
Figure 5.1 South Korean minesweeper struck by mine, 1950. Photo courtesy Dr. P. Elmore
Figure 5.2 Map of NOAA Wave Model Grid Locations, West-Central Florida

$X = \text{WaveWatch 3 Grid Cell}$
Figure 5.3 Regional Side-scan Sonar Survey of Inner Shelf Surrounding Indian Rocks Beach, Florida Mine Burial Field Site
Figure 5.4 Geophysical Data from the Sand Ridge System at the Indian Rocks Beach mine Burial Field Site (a) Side-scan sonar mosaic (high return = dark shade; low return = bright shade). (b) Boomer seismic profile line 44 (see Figure 5.2 for location). Courtesy Dr. P. Howd.
Figure 5.5 15m Gridded Swath Bathymetric Data from IRB Mine Burial Experiment Field Site
Figure 5.6 Side-scan Sonar Mosaic of IRB Mine Burial Field Site. High backscatter return is bright, low return is dark.
Figure 5.7 15m Generalized Grain Size Distribution from IRB Mine Burial Experiment Field Site
Figure 5.8 Side-scan sonar image of Acoustic Instrumented Mines (AIMs) and German FWG mines and instrumented quadpod used in this study. Courtesy Dr. D. Naar
<table>
<thead>
<tr>
<th>Mine Type/#</th>
<th>Deployed Date/Time on Bottom</th>
<th>Recovered Date/Time on Surface</th>
<th>Site Depth (m)/Grain Size (mm)</th>
<th>Sediment Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM #1</td>
<td>8 Jan 03/12:05</td>
<td>14 Mar 03/16:37</td>
<td>12/0.18</td>
<td>Fine-Sand Plain (FSP)</td>
</tr>
<tr>
<td>AIM #2</td>
<td>8 Jan 03/13:37</td>
<td>14 Mar 03/14:15</td>
<td>12/0.18</td>
<td>Fine-Sand Plain (FSP)</td>
</tr>
<tr>
<td>AIM #3</td>
<td>8 Jan 03/09:50</td>
<td>14 Mar 03/15:05</td>
<td>12/0.18</td>
<td>Fine-Sand Plain (FSP)</td>
</tr>
<tr>
<td>AIM #4</td>
<td>8 Jan 03/11:00</td>
<td>14 Mar 03/15:47</td>
<td>12/0.18</td>
<td>Fine-Sand Plain (FSP)</td>
</tr>
<tr>
<td>FWG #5</td>
<td>11 Jan 03/18:50</td>
<td>15 Mar 03/13:05</td>
<td>12/0.18</td>
<td>Fine-Sand Plain (FSP)</td>
</tr>
<tr>
<td>FWG #6</td>
<td>11 Jan 03/18:35</td>
<td>15 Mar 03/11:30</td>
<td>12/0.18</td>
<td>Fine-Sand Plain (FSP)</td>
</tr>
<tr>
<td>FWG #7</td>
<td>11 Jan 03/18:20</td>
<td>16 Mar 03/12:50</td>
<td>13/0.8</td>
<td>Rippled Scour Depression (RSD)</td>
</tr>
<tr>
<td>FWG #8</td>
<td>11 Jan 03/18:05</td>
<td>16 Mar 03/12:40</td>
<td>13/0.8</td>
<td>Rippled Scour Depression (RSD)</td>
</tr>
</tbody>
</table>

Table 5.1 Summary of Mine Deployment
Figure 5.9 Comparison Between Observed and NOAA WW3 Model Wave Height Transformed to Local Estimates During IRB Field Deployment Winter 2003. (a) Time-series of $H_s$ Observed (blue) and Modeled (red); (b) cross-plot between observed and modeled $H_s$, black line denotes 1:1.

\[
H_{s(\text{IRB})} = 0.9545 \cdot H_s(\text{WW3}) + 0.0450
\]

\[r^2 = 0.84; \ p = 0.00001\]
Figure 5.10 Burst Average Oceanographic Conditions at Indian Rocks Beach, Mine Burial Field Site 1/16/03-3/13/03
Figure 5.11 (a) Observed and modeled wave conditions at the IRB Field Site. (b and c) Model predicted burial and scour for a 0.53 m diameter mine resting on fine sand plain and within RSD. Observational data courtesy Dr. P. Howd, USF.
<table>
<thead>
<tr>
<th>Substrate</th>
<th>Observed Burial: *Ambient Depth</th>
<th>Observed Burial: #Surface Area</th>
<th>Modeled Burial: Ambient Depth</th>
<th>Modeled Burial: Surface Area</th>
<th>Observation Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-Sand Plain (FSP)</td>
<td>75-100%</td>
<td>20-75%</td>
<td>60%</td>
<td>53%</td>
<td>Lots of end scour; large shallow pits; sorted accumulations of coarse shell material in pits</td>
</tr>
<tr>
<td>Rippled Scour Depression (RSD)</td>
<td>20-30%</td>
<td>30%</td>
<td>0%</td>
<td>10%</td>
<td>No scour pits; Prominent ripple fields ($\eta=$ 15-20 cm; $\lambda=$ 100-120 cm); cyclic burial/exposure related to ripple migration</td>
</tr>
</tbody>
</table>

Table 5.2 Summary of Observed and Modeled Mine Burial

* Burial Ambient Depth refers to depth of the mine relative to far-field seabed level
# Burial Surface Area indicates amount of mine surface area that remains uncovered
Figure 5.12  Diver Photos of Mine and Seabed Conditions During Recovery. Photos courtesy Dr. M. Richardson
Figure 5.13 Wave height and near bed orbital velocity (A). Comparison between measured and modeled mine burial (B) from Second MVCO Deployment 2002. Courtesy of Dr. Mike Richardson NRL.
Rapid scour occurs for increasing $U_b > 1.25 \; U_{cr}$

Rapid burial follows when $U_b$ drops below $0.75 \; U_{cr}$

Thin colored lines = hindcasts/forecasts updated every 12 hrs

$\circ$ = Latest available hindcast/forecast as of hour 384

Figure 5.14 Sequence of Hindcast/Forecasts of Waves and Burial for Indian Rocks Beach Field Site
Figure 5.15 Graphical User Interface (GUI) Front Panel for Indian Rocks Mine Burial Field Experiment
Figure 5.16 *Queen Anne's Revenge* Field Site (a) Artist's rendition of QAR at time of grounding; (b) 1733 Wimble Chart of Cape Lookout Region; (c) 1999 NOAA nautical chart of Beaufort Inlet, NC including location of wreck-site; (d) Archaeological site plan of QAR wreckage. Courtesy of Dr. M. Wilde-Ramsing
Figure 5.17 Three-dimensional surface contour plot of QAR wreck site from high resolution swath interferometric bathymetry survey. Courtesy Dr. J. McNinch
Rippled Scour Depressions

Figure 5.18 Side-scan sonar mosaic of Q4R wreck-site Fall 2002 (a); (b) Comparison image of small shore-perpendicular RSDs (facies 4) found off Tairua NZ, (see Chapter 2 for a detailed description).
Figure 5.19 Scour marks commonly associated with shipwrecks. (A) Diagram of single and double scour marks. (B) Scour marks from Mary Rose wreck site.
Figure 5.20. Underwater photographs of the (A) concreted main rubble mound exposed on the seafloor surface (B) an individual cannon (C) and a recovered cannon ball from the *Queen Anne's Revenge* wreck (courtesy of the NC Underwater Archaeology Unit).
Figure 5.21: Diagrammatic cross-section of substrates and relative location of artifacts found at QAR wreck-site. Courtesy Dr. M. Wide-Ramsing
Figure 5.22 Comparison between near bed orbital velocity based on Linear Wave Theory (LWT) (blue) and direct measurement (S4 current meter) (red) during hurricane Bonnie.
Figure 5.23 Observed oceanographic conditions at the Queen Anne’s Revenge wreck-site, Beaufort Inlet, NC under four wave conditions. (a) Significant wave height in meters; (b) Peak spectral period in seconds.
Figure 5.24 Graphical User Interface (GUI) of Interactive Scour Model Using Observations from QAR Field Studies
Figure 5.25 Predicted scour depth (in cm) for QAR artifacts cannon ball (blue), cannon (red), and rubble mound (black) during (a) hurricane Bonnie. (b) Southwesterly Winds. (c) Extra-tropical Nor’easter. (d) Fair weather. *Note the change in vertical scale between plots a, b, c, and d.
Figure 5.26 Variations in scour of QAR rubble mound during hurricane Bonnie (blue line) with inclusion of resistant sediment horizon 40 cm below surface and (dashed re-line) without resistant horizon.
### Table 5.3 Summary of Scour Model Results for Various Artifacts Subjected to Different Flow Conditions

<table>
<thead>
<tr>
<th>Artifact</th>
<th>Diameter (m)</th>
<th>Hurricane Bonnie</th>
<th>Sou’ Wester</th>
<th>Nor’ Easter</th>
<th>Fair-- weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cannon ball</td>
<td>0.15</td>
<td>Complete scour burial</td>
<td>Complete scour burial</td>
<td>Complete scour burial</td>
<td>Negligible scour burial</td>
</tr>
<tr>
<td>Cannon</td>
<td>0.25</td>
<td>Complete scour burial</td>
<td>Complete scour burial</td>
<td>Near complete scour burial</td>
<td>Negligible scour burial</td>
</tr>
<tr>
<td>Rubble Mound</td>
<td>2</td>
<td>Complete scour burial</td>
<td>Moderate scour burial</td>
<td>Minor scour burial</td>
<td>Negligible scour burial</td>
</tr>
</tbody>
</table>
Figure 5.27 Diagrammatic sequence of events leading to present condition of Q4R wreck-site artifacts. Adapted after McNinch et al., 2001.
<table>
<thead>
<tr>
<th>SITE NAME (Year Lost)</th>
<th>Location</th>
<th>Approx. Draft (m)</th>
<th>Current Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bendigo (1864)</td>
<td>Lockwoods Folly Inlet</td>
<td>2.4</td>
<td>3.0</td>
</tr>
<tr>
<td>USS Iron Age (1864)</td>
<td>Lockwoods Folly Inlet</td>
<td>2.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Elizabeth (1863)</td>
<td>Lockwoods Folly Inlet</td>
<td>2.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Ella (1864)</td>
<td>Cape Fear Inlet</td>
<td>2.4</td>
<td>7.6</td>
</tr>
<tr>
<td>La Rosa (1804)</td>
<td>Cape Fear Inlet</td>
<td>3.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Modern Greece (1862)</td>
<td>New Inlet (closed)</td>
<td>3.0</td>
<td>7.6</td>
</tr>
<tr>
<td>Condor (1864)</td>
<td>New Inlet (closed)</td>
<td>2.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Arabian (1863)</td>
<td>New Inlet (closed)</td>
<td>3.0</td>
<td>7.6</td>
</tr>
<tr>
<td>Twilight (1865)</td>
<td>New Inlet (closed)</td>
<td>1.8</td>
<td>6.1</td>
</tr>
<tr>
<td>Flambeau (1867)</td>
<td>New Inlet (closed)</td>
<td>3.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Aster (1864)</td>
<td>New Inlet (closed)</td>
<td>3.0</td>
<td>7.6</td>
</tr>
<tr>
<td>Stormy Petrel (1864)</td>
<td>New Inlet (closed)</td>
<td>2.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Lynx (1864)</td>
<td>Carolina Beach Inlet</td>
<td>2.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Hebe (1863)</td>
<td>Carolina Beach Inlet</td>
<td>2.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Douro (1863)</td>
<td>Carolina Beach Inlet</td>
<td>2.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Venus (1863)</td>
<td>Carolina Beach Inlet</td>
<td>2.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Jetty Wreck (ca. 1864)</td>
<td>Masonboro Inlet</td>
<td>2.4</td>
<td>3.7 (buried)</td>
</tr>
<tr>
<td>Crystal Pier Wreck (ca 1864)</td>
<td>Masonboro Inlet</td>
<td>2.4</td>
<td>4.6 (buried)</td>
</tr>
<tr>
<td>Quadrant Wreck (ca 1864)</td>
<td>Masonboro Inlet</td>
<td>2.4</td>
<td>2.4 (buried)</td>
</tr>
<tr>
<td>Wild Dayrell (1864)</td>
<td>Richards Inlet</td>
<td>2.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Quinebaugh (1865)</td>
<td>Beaufort Inlet</td>
<td>2.4</td>
<td>9.1</td>
</tr>
<tr>
<td>0002BUI</td>
<td>Beaufort Inlet</td>
<td>3.0</td>
<td>7.9</td>
</tr>
<tr>
<td>Queen Anne’s Revenge (1718)</td>
<td>Beaufort Inlet</td>
<td>3.0</td>
<td>6.7</td>
</tr>
<tr>
<td>0004BUI</td>
<td>Beaufort Inlet</td>
<td>3.0</td>
<td>6.1</td>
</tr>
<tr>
<td>0005BUI</td>
<td>Beaufort Inlet</td>
<td>3.0</td>
<td>6.1</td>
</tr>
<tr>
<td>0006BUI</td>
<td>Beaufort Inlet</td>
<td>3.0</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 5.4 Summary of Present Wreckage Depth Relative to Initial Grounding for Historical Shipwrecks in the Cape Lookout Region. Compiled by Richard W. Lawrence, NCUAU
CHAPTER 6

INSIGHTS INTO THE MORPHODYNAMIC COMPLEXITY OF THE INNER SHELF

325
OVERVIEW

This chapter presents a new conceptual model for the observed depth dependent distribution and persistence of features previously referred to as “Rippled Scour Depressions” (RSDs) based on theory developed from the Lenz-Ising complexity model of critical phase transition. Building upon the quantitative analysis of hydrodynamic roughness, object scour processes, and suspended sediment transport behavior developed in the previous chapters, this chapter provides unique insights into the distribution of RSDs across the shelf and also suggests the likely persistence of these features within a given depth interval and inherited geologic framework. The results of this analysis are applicable to understanding the distribution and relative stability of complex, heterogeneous sediment features found within many energetic shelf-systems around the world. The key finding from the modeling effort is that the distinct depth interval of RSD occurrence and persistence is due to the existence of a complex morphological phase-transition system operating across the inner shelf. The results from the overall study of inner shelf morphodynamics indicate that complex, self-organizing features are ubiquitous within energetic, sediment-starved shelf-systems and that complex interactions among scour processes, bed roughness, and hydrodynamics control the delicate distribution and stability of these features in a manner analogous to the Lenz-Ising model of complex phase-transition. Generalized conclusions regarding inner shelf morphodynamics are presented in terms of bottom boundary layer turbulence structure, bed roughness, RSD behavior, and object related scour processes.
MORPHOLOGICAL COMPLEXITY OF THE INNER SHELF - A CRITICAL PHASE
TRANSITION MODEL OF RSD DISTRIBUTION AND PERSISTENCE

This chapter is being prepared for submission to the journal Earth Surface Processes and Landforms under the authorship of A.C. Trembanis
6.1 INTRODUCTION AND MOTIVATION
In recent years, increased attention has been paid to heterogeneous, inner shelf features termed "rippled scour depressions" or RSDs (Murray and Thieler, 2004). RSDs are frequently identified as the dominant morphologic features along many sediment-starved, energetic, inner shelf field sites. Recent studies regarding the distribution and morphodynamics of RSDs (Green et al., 2004; Goff et al., 2003; Hume et al., 2003; Trembanis et al., in press) increasingly show their behavior to be at odds with the initial hypotheses put forth from previous research efforts (Cacchione et al., 1984; Reimnitz et al., 1976). This study is one of the first detailed field investigations into the hydrodynamic and sediment transport characteristics associated with pronounced RSDs. In addition, this study attempts to reconcile the observed behavior with various established analytical models and new exploratory models for bedform and RSD behavior. The purpose of this chapter is to synthesize the recent observational and modeling efforts aimed at understanding the type and relative behavior of RSDs. Furthermore, this chapter postulates a new complexity theory for the distinct across-shelf distribution and variable persistence of RSDs by applying the Lenz-Ising statistical mechanics model of critical phase transitions. Examination of the literature on complexity and analysis from the previous chapters lends support to the hypothesis that within delicately balanced regimes of seabed disturbance, dictated largely by depth and favorable geologic context, persistent RSDs are the modal geomorphic feature of the seafloor. The seafloor seaward (in deeper water) of the critical RSD zone is dominated by a well-ordered zone where fine-sand plains, shelf-sand ridges or exposed rock outcrops present a largely dormant and/or inherited pattern or roughness. Shoreward, in
shallower water depths, intense, frequent disturbance of the seabed precludes the persistent maintenance of RSD. Within these shallow energetic depths, expansive, disordered, mobile, fine-sand plains dominate the seabed morphological configuration state.

To begin this analysis, recall from Chapters 2–4 that RSDs were not observed at all depths within the field site. Furthermore, it was noted that the persistence of RSDs exhibits a strong depth dependency. The shallower, finger-like, nearshore, shore-normal RSDs (Facies 4) were much more ephemeral than the intermediate depth offshore shore-parallel RSDs (Facies 5). Considering the entire Tairua/Pauanui embayment in general, RSDs appear to occur within a discrete depth zone ranging between 12–24 m water depths. It should be noted that the deep water offshore shore-oblique RSDs (Facies 6) are distinct from the other types just mentioned. The Facies 6 RSDs are most similar to the large "sorted bedform" features observed and modeled by Murray and Thieler (2004); they are not sharp, negative-relief "notches" like Facies 4 and 5 RSDs but are more gentle sloping asymmetrical, transverse bedforms. With the exception of Facies 6 RSDs, there is a strong signal of depth-limited RSD distribution within the field-site, possibly suggesting some phase transition is at work across the inner shelf.

From a hydrodynamic/sediment-transport perspective, contrasting occurrences of smooth/rough or fine/coarse facies are similar to each other, whether the morphological packaging of these contrasts comes in a bar/troughs, sorted bedform, or the various notch-like RSDs (Facies 4 and 5). The heart of the morphodynamic process critical to all of these diverse features is the influence of contrasting roughness on boundary layer
turbulence and subsequent sediment transport, forming a tight process feedback loop
whereby a given roughness element influences its immediate neighbors. The interactions
between hydrodynamics and roughness were explored by Trembanis et al. (in press)
(Chapter 3), while the impact of roughness variability on suspended sediment transport
was examined by Green et al. (2004) (Chapter 4).

Three fundamental sets of questions motivate the present study:

1) How can a system made up of components (e.g. heterogeneous sediment
assemblages) and forces (e.g. waves, currents, and scour processes) whose individual
properties we can understand give rise to phenomena such as complex RSDs, whose
patterns and behavior are quite unexpected? In other words, what singular concept
weaves its way through the entire work of the dissertation?

2) Why within certain areas (notably shallower depths) are RSDs much more
ephemeral from one storm to another while in other areas (intermediate depths) they are
quite robust and persistent, while RSDs tend to be completely absent (or of a different
character) in deeper depth zones?

3) What combination of forces contribute to this intermediate depth “critical
zone” of persistent RSDs and how do these forces vary?

So far this study of inner shelf morphodynamics has dealt mostly with complexity
in terms of the sediment heterogeneity or what could be termed spatial complexity. A
notable exception was the brief application of a recently developed exploratory model of
sorted bedforms in Chapter 4. Previously, the notion that these striking seafloor features
are themselves examples of complex systems was dealt with peripherally. This chapter
attempts to explore the variability in persistence between RSDs at various depths and locations in terms of a Lenz-Ising critical phase-transition model.

The present modeling approach differs markedly from the recent work and insights offered by Murray and Thieler (2004) in several ways. First, this study introduces depth-dependent behavior into the model system. In the present analysis, depth is used as a surrogate for energy or more specifically bed disturbance force. It was established in the exploratory model simulations (detailed in Chapter 4) that sorted bedform features developed under all of the depth and hydrodynamic conditions tested as opposed to the more limited observed occurrences of RSDs at the site. Second, the role of underlying geology in helping to set the stage for RSDs in some areas and not others is considered. Third, the present effort not only considers multiple types of RSDs (Facies 4, 5 and 6) but also embraces a wide spectrum of seabed configurations, including end member cases (ordered and disordered zones) along with transient and persistent intermediate state configurations. The model presented by Murray and Thieler (2004) only considers one class of RSD or sorted bedform feature.

The hypothesis underlying the present analysis is that the most complex and persistent active morphological features of the shelf are found within a delicate, critical-depth dependent zone where energy minimization and entropy maximization are balanced in a manner analogous to the Lenz-Ising model of ferromagnetic complexity. Outside of this critical phase transition region lie better organized, less active, deeper water zones and highly disordered, intensely active, shallow water zones that make up the end
member morphological configuration states. The existence and long-term persistence of Rippled Scour Depressions is postulated to be highly dependent on where a given features is found within the phase transition spectrum (i.e. ordered zone; critical-complex zone; or disordered zone).

6.2 BACKGROUND

6.2.1 MORPHOLOGIC COMPLEXITY OF THE INNER SHELF

We must now ask the question, what are the facets or behaviors that, morphologically speaking, make the inner shelf complex? This study of inner shelf morphodynamics suggests that the inner shelf satisfies all of the criteria described for a complex system previously (Chapter 1). First, as detailed in Chapter 2, the inner shelf is a highly heterogeneous sedimentary setting. Second, in Chapters 3 and 4, both the fluid flow and the sediment transport behavior were observed to be spatially and temporally dynamic. Third, the processes controlling the morphologic behavior of the inner shelf are non-linear (Chapters 3–5). Fourth, changes to the geometry of the seafloor are the results of tight feedbacks between seabed roughness and fluid hydrodynamics as were noted in Chapters 3–5. Fifth, the seabed is frequently self-organized into well-defined patterns, which were documented in Chapters 2–5. A sixth and final feature making the inner shelf complex is that distinct spatial and temporal phase transitions are observed in the behavior of the self-organized features within distinct zones of the inner shelf (Chapters 2–5). In other words, while portions of the inner shelf are complex all of the time and other portions are complex some of the time, part of what makes the inner shelf a
complex system, to paraphrase Lincoln, is that the system is not complex everywhere all the time.

6.2.2 Lenz-Ising Model

The Lenz-Ising model, more commonly known as the Ising model, is one of the simplest and most fundamental models of statistical mechanics (Hayes, 2000). The model was first proposed by Lenz (1920) and then taken up and developed by his student Ising (1925) as a way to explain the origin and macroscopic behavior of magnetism within material containing interacting magnetic dipoles. Development of the model was based on the observation that above a critical temperature (the Curie point), dipoles are randomly arranged so that no bulk field is present, while below the critical temperature the interaction between neighboring dipoles leads to structured alignment and the formation of a magnetic field. In this highly idealized model, space is divided into discrete points or “spins” with a magnetic value that takes on one of two discrete values either +1 (up-spin) or −1 (down-spin). Each spin can be thought of as an atom of the ferromagnetic material that interacts with its nearest neighbors and also, if present, to an external magnetic field. Although, we shall see that complex behavior is not predicated on an external field. In “non-magnetic” matter or magnetic material above the Curie point, the atoms are arranged in a random orientation with some pointing up and others pointing down. Thus (in a bulk averaged sense) the orientations of the individual components (atoms) cancel out, and there is no macroscopically perceived magnetic field. However, under the right conditions, it is possible for a large number of neighboring components to take on the same orientation and thus produce perceptible
patterns of magnetism. The Lenz-Ising model attempts to explain how and under what conditions these aligned patterns develop and behave. The Lenz-Ising model is widely used throughout the field of physics (Nicholls, 2003; Sole and Goodwin, 2000; Onsager, 1944; Peierls, 1936) and has been applied directly to questions regarding granular systems, including the formation of ripples (Vandewalle and Galam, 2000) and the compaction of sand (Nicodemi et al., 1997).

At the heart of the Lenz-Ising model is a delicate balance between two opposing physical principles: entropy maximization and energy minimization. In terms of energy minimization, the interaction between the individual components is such that the lowest energy configuration of any two neighboring cells involves them having the same “spin.” Figure 6.1 illustrates a portion of the Lenz-Ising 2D model universe. The center cell (red arrow) is being investigated in terms of spin state relative to the spin state of the four “nearest” neighbor cells (yellow arrows). Thus, from the standpoint of energy, the lowest energy state of a system would have all of the components aligned in the same direction. In the case illustrated by Figure 6.1 the result would be a tendency for the center cell to flip orientation and reach an upward pointing configuration state. While energy tends to minimize the differences between neighbors, the principle of entropy tends to accomplish the opposite. Unless the energy interaction is very strong, there is a tendency, especially amongst systems with a large number of components, for things to move into a progressively more disordered state. Temperature plays a critical role in the balance between entropy maximization and energy minimization. High temperatures introduce lots of energy into the system, perturbing the individual components from one
state to another. If the temperature is high enough, local interactions (energy minimization) cannot overcome the entropy and order the system. At low temperatures, neighboring cells exert an influence on each other, causing cells to spontaneously align together. Therefore, the development of a complex structure within a system, be it magnetic fields or morphologic patterns, depends on the relative contributions of energy minimization and entropy maximization.

A theoretical phase plot of the anticipated morphological configuration state transition across the energy/entropy spectrum of the inner shelf is shown in Figure 6.2. This figure suggests that a narrowly constrained critical zone in which dynamically complex features exist should be found at intermediate depths between an energy minimization dominated, low energy input, ordered zone in deeper water and an entropy dominated, high energy input, disordered zone in shallow water. Our field observations suggest that on the Tairua shelf this phase transition zone occurs between 15 m and 35 m water depth.

For the case of a system without an external magnetic field, the energy \( E_s \), of a state is given by

\[
E_s = -J \sum_{(i,j)} s_i s_j
\]

(6.1)

where \( s_i s_j \) is the state of the cell at point \( i,j \) in the grid and \( J \) represents the interaction strength between the neighboring cells. Low values of \( J \) indicate weak interaction between neighbors while high values indicate strong interaction. In the
ferromagnetic case, where states seek to align together, $J$ can take on values between 0 and 1.

The probability of any state occurring is given by the Boltzmann distribution function

$$p_r(s) = \frac{1}{Z} \exp \left( -\frac{E(s)}{k_B T} \right),$$

(6.2)

Where $T$ is the temperature in degrees Kelvin, $k_B$ is the Boltzmann constant, and the constant $Z$ is the probability distribution. For computational convenience, units are chosen so that $k_B = 1$, in which case $T$ is measured in energy units. From equation 6.2 it is clear that the probability of any given state depends upon the relative balance between the energy interaction from the neighboring cells and the entropic contribution of temperature. From a modeling standpoint, testing the phase transition behavior can be accomplished by varying either the interaction strength ($J$) or the temperature ($T$) of the system.

Equation 6.2 can be rewritten as

$$p_r(s) = \frac{1}{Z} \exp(-2J\#x),$$

(6.3)

where $\#x$ is the number of neighbors of unequal value relative to the cell in question (Nicholls, 2003, 2001).

6.3 METHODS AND RESULTS

With the goal of exploring the applicability of the Lenz-Ising model to the case of RSD behavior, it was necessary to implement the model in a useful computational form.
To this end, a version of the Lenz-Ising model was written using Matlab® computational software. The Lenz-Ising model code used in this study is included for reference in the Appendix.

6.3.1 Quantifying Shelf Complexity

In order to conduct morphology simulations with the Lenz-Ising model, one must first quantify the spatial complexity of the model domain, in this case the Tairua/Pauanui shelf system, for a set of initial conditions. Determination of spatial complexity was accomplished by utilizing the bathymetry and composite facies maps developed in the previous chapters at 20 m x 20 m cell size. The composite facies map for the field site was idealized into a binary system of either rough/coarse or smooth/fine species at each grid cell. This simple binary classification delineates between smooth, fine-sand plains and rough, coarse-sand or rock outcrops. Next, following the convention of the standard Lenz-Ising model, each binary class was arbitrarily assigned a value of +1 for the rough/coarse-sand class or −1 for the smooth/fine-sand class. The resulting composite binary roughness map is shown in Figure 6.3. Shoreface rock outcrops are treated carefully, because while the presence of outcrops adds markedly to the heterogeneous complexity of the system, they are fixed roughness elements and therefore do not qualify as dynamically complex elements like mobile sand. The geologic history of the region thus sets the stage for the role rock outcrops play in the complex morphologic evolution of the inner shelf at Tairua/Pauanui and elsewhere.
Before moving directly to model simulations it is possible to make use of the simplified roughness map (Figure 6.3) to quantify the morphological complexity of the inner shelf. As mentioned earlier, an appropriate metric of complexity is required in these situations. Here the standard deviation of roughness within equal bathymetric intervals was chosen for the complexity index. The morphological complexity index can thus be expressed by the familiar formula

\[ C_I = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x}) \]  

(6.4)

The Complexity Index \((C_I)\) is thus a normalized measure of the variation (simply the square root of the variance) within any given set of values. Since bathymetric data are available for each grid cell in the idealized roughness map (Figure 6.4), it is possible to extract all of the cells within a given depth interval in the model domain. A subset of cells within 5 m depth intervals from the shoreline to 45 m water depth was extracted from the binary roughness map from which the complexity index was calculated. Figure 6.5 shows the resulting cross-shore profile upon calculation of the complexity index. Values were plotted at the mid-point in each depth interval. If the two end intervals are ignored, a parabolic trend of complexity emerges, exhibiting a mid-depth maximum between 22 - 32 m of water. The high \(C_I\) value within the 0 - 5 m interval is due to the headland associated rock reefs next to shore, previously noted. The headland rock-reef is a form of inherited fixed heterogeneity and can therefore be ignored. The high \(C_I\) value within the deepest interval (40 - 45 m) is due to the presence of the large "sorted bedform" shelf sand ridge features (Facies 6). As noted earlier, these features are a distinct RSD type and are therefore excluded from the present analysis as well.
Additional information about the complex configuration of the shelf is obtained from a profile plot of a depth-averaged roughness index (Figure 6.6). In the extreme case a value of $-1$ would indicate that the given depth interval was entirely composed of fine-sand. Conversely, an average roughness value of $+1$ indicates a completely coarse-sand/rock outcrop interval. In general, the inner shelf is dominated by fine-sand (values less than 0). Exceptions include the nearshore, which is influenced by the rock-reefs and the 22 m isobath where large RSDs occur persistently. Beyond the intermediate water depths, there is an increase in fine-sand as the mid-shelf mud belt is approached and RSDs become less common.

The complexity index profile was coupled with the suite of observational data from the previous chapters in order to categorize each depth interval into one of three broad states: 1) Disordered; 2) Complex; and 3) Ordered. Figure 6.7 shows the relationship between the configuration states and the shelf complexity index. A further distinction was made within the complex state between transient complexity (varies over storm intervals) and persistent complexity (stable over annual to decadal time-scales).

The key characteristics of each state are described below:

**Disordered State:** This state occurs between the shoreline and depths of 10 m. In this zone, disturbance of the seabed is intense and frequent. Roughness features within this zone include rock reefs, sand bars, rip-channels, and fine-sand plains. RSDs are completely absent within this zone.

**Complex State:** This state extends from 10 m out to 32 m water depth and contains two distinct sub-groups
Complex Transient- This state occupies the shallow portion of the complex interval, ranging from ~10 to 22 m water depth. The intensity and frequency of bed disturbance is less than that of the disordered state but higher than that of the Complex Persistent state. Fine-sand plains and small ribbon or finger-like RSDs (Facies 4) are found here. The shore-normal RSDs are quite ephemeral disappearing and re-appearing from one storm to the next.

Complex Persistent- This state ranges between 22 to 32 m water depths. This is the zone of highest complexity within the inner shelf. The intensity and frequency of bed disturbances contribute to the formation and maintenance of large shore-parallel RSDs (Facies 5). These complex patterns interrupt otherwise fine-sand plains. RSDs within this zone are morphologically stable over annual time-scales.

Ordered State: This state occupies the deepest portions of the field site in water depths between 32 to 45 m. Disturbance of the bed is weak and infrequent in comparison to the other depth zones. Fine-sand plains dominate the seabed with the exception of rock outcrops and large asymmetrical “sorted bedform” features.

The depth distribution of each morphologic state is plotted against the shoreface profile off of Tairua Beach in Figure 6.8.

6.3.2 MODEL SIMULATIONS

The entire field-site domain grid (Figure 6.3) is 520 x 416 cells in size and therefore too large for rapid model simulation. Therefore, a smaller 128 x 128 cell subset was extracted for modeling purposes (Figure 6.9d). The new model domain was taken from a region off of Tairua Beach in water depths of approximately 12 – 25 m and included the area surrounding and inclusive of the large RSD from the tripod study (Chapters 3 and 4). The mapped binary roughness values from the domain sub-grid were used as the initial conditions in each model run. The only parameter adjusted from
equation 6.3 between model runs was $J$, the interaction strength. No external field was included in any of the model simulations.

The aim of the modeling exercise was to see how the initially complex pattern of roughness would respond to various energy levels as are hypothesized to exist in a depth-dependent manner across the shelf (Figure 6.2). The results from three distinct energy level simulations are summarized below. Each simulation was run until a steady state pattern developed.

LOW-ENERGY LEVEL (COLD) SIMULATION

For the low-energy or "cold" temperature simulation interaction strength factor, $J$ was set to a value of 0.8. This setting gives a greater weight to the energy minimization force analogous to a condition with low external entropy input. The final model-run results are plotted in Figure 6.9a. The low-energy simulation took the longest computational time to reach an equilibrium condition of any model run. The shape of the initial complex roughness pattern (Figure 6.9d) was very slowly degraded. The ultimate configuration of the model grid by the end of the test was an almost completely homogeneous well-ordered system. The initial RSD features were eventually wiped out and replaced by an expansive fine-sand plain with a few scattered coarse cells. Under low energy conditions such as those considered to control deeper settings, the ability to organize into RSDs is dwarfed by slow diffusive energy minimization. Even when RSDs are initially imposed in this setting they eventually get buried, as there is simply not enough energy being fed to the system to maintain the roughness gradients.
HIGH-ENERGY LEVEL (HOT) SIMULATION

For the high-energy or “hot” temperature simulation the interaction strength factor, \( J \), was set to a value of 0.2. This setting gives a greater weight to the entropy maximization force analogous to a condition with high external entropy input. The final model-run results are plotted in Figure 6.9b. The high-energy simulation took the shortest computational time to reach an equilibrium condition of any model run. The shape of the initial complex roughness pattern (Figure 6.9d) was rapidly degraded. The ultimate configuration state of the model grid by the end of the test was a completely disordered heterogeneous system with no complex structures. The initial RSD features were quickly wiped out (within a few iterations) and replaced by a randomly mixed domain of coarse and fine material. Under high-energy conditions such as those considered to control shallow settings, the ability to organize into RSDs is dwarfed by intense entropy maximization. RSDs exposed to these conditions are rapidly obliterated as the entropy maximization force swamps the interaction strength (energy minimization), and any fledgling features get wiped out before they get very large.

CRITICAL-ENERGY LEVEL SIMULATION

For the critical-energy or “intermediate” temperature simulation, the interaction strength factor, \( J \), was set to a value of 0.42. This setting gives a balanced weighting between entropy maximization and energy minimization analogous to conditions with moderate bed disturbing forces input. The final model-run results are plotted in Figure 6.9c. The computational time required to reach an equilibrium condition for this simulation was in between the other model simulations. The shape of the initial complex
roughness pattern (Figure 6.9d) was degraded at a moderate rate. The ultimate configuration state of the model grid by the end of the test was complex. The initial RSDs were eventually wiped out (not as quickly as the high-energy level) and replaced by similarly sized complex patterns of coarse material in between homogeneous areas of fine-sand. Under critical-energy conditions such as those considered to control intermediate depth settings, the ability to organize into RSDs is balanced by intense entropy maximization. RSDs exposed to these conditions are capable of thriving. At moderate energy levels, (intermediate depths) the setting is just right to keep either full-order or full-disorder at bay and thus allow complex structures to emerge and persist.

6.4 DISCUSSION

The results from the Lenz-Ising model simulations provide a host of unique insights into the distribution and behavior of RSDs that are supported by our previously detailed observational studies. The key finding from the modeling effort is that the distinct depth interval of RSD occurrence and persistence is consistent with the existence of a complex morphological phase-transition system operating across the inner shelf. The energy related phase transition behavior of the model is highly analogous to the spatial (largely depth-dependent) variability in seabed disturbing processes that biases end-member zones towards either long-term order or disorder. Within a critical range, the energy input into the system, morphologic roughness elements, and geologic setting are sufficiently balanced against order and disorder to allow complex RSD features to exist and maintain themselves.
6.4.1 IMPLICATIONS FOR OTHER SHELF SYSTEMS

The overall results from this study suggest that the modal configuration of shelf morphology within moderately energetic intermediate depths is the presence of strikingly persistent RSDs bordered by well-ordered and disordered fine-sand plain zones on the seaward and shoreward sides respectively. This shelf behavioral spectrum might be thought of as somewhat similar to the modal state of beaches proposed by Wright and Short (1984), but operating over the longer temporal and spatial scales that mold the inner shelf. Another similar spectrum of behavior exists at even smaller spatial and temporal scales in regards to ripple behavior. At low energy regimes ripples will not form. Conversely, when flow energy is too severe, ripples get wiped out and possibly transformed into other types of upper flow regime bedforms (chutes, antidunes, hummocks, etc). However, within a delicately balanced morphodynamic zone, ripples develop in complex and varied forms. This study suggests that inner shelf sediment assemblages are capable of the same range of dynamic behavior as both ripples and beaches.

The concepts and dynamic processes of complex morphological behavior detailed in the field sites examined in this study are also broadly applicable to other systems around the world. Depth-limited distribution and behavior of RSDs, similar to that seen and modeled for the Tairua/Pauanui embayment, has been encountered at slightly different depth ranges at sites such as Martha’s Vineyard, Massachusetts (10 -- 16 m) (Goff et al., 2003); East Gippsland, Australia (20 – 45 m) (Black and Oldman, 1999); Monterey Bay, California (10 – 20 m); Gulf of Mexico, Florida (15 – 30 m) (Fleischer et
al., 1996); (Hunter et al., 1988); Northern California (20 – 40 m) (Cacchione et al., 1984); and Mexico (15 – 30 m) (Reimnitz et al., 1976). The specific depth interval and precise location of Complex Rippled Features is likely to vary, given local hydrodynamic regimes and geologic settings.

Armed with the knowledge presented in this study it might be possible to develop classification maps similar to Figure 6.10. Maps such as this could be used to determine the likely existence and/or long-term persistence of RSDs within a given shelf system. Furthermore, one potentially could examine transitions out of the modal configuration in terms of the large-scale system wide changes in climate and/or sea-level that would be necessary to upset the previous configuration.

6.4.2 ISSUES OF NOMENCLATURE

At this point, some discussion must be given to the crisis of nomenclature gripping the community of researchers presently exploring the behavior of dynamically complex seabed features. As mentioned in previous Chapters (2–4), the original term “Rippled Scour Depressions” has long been surrounded by critics, keenly aware of the genetic limitations implied by the term. Consequently, many researchers have simply dropped the term and adopted their own ad hoc names for these types of features. One possible solution to the difficulties presented by the term RSD would be to simply drop the word scour (S). To be sure, most (but not all) occurrences of these features contain ripples (R) within depressions (D). So then should we call them Ripple Depressions (RDs)? Other features, like those associated with shipwrecks, rock outcrops or some other seabed object, have a definitive scour process at work. In these cases, use of the
full term RSD seems quite permissible: they have ripples, a scour agent, and depressions. The pool of available terms has increased with the recent work by Murray and Thieler (2004) who suggested the term “sorted bedforms” as a replacement for RSD. While sorted bedforms is an apt term for the kinds of features encountered in their study off of Wrightsville Beach, North Carolina and the deeper water (Facies 6) features at Tairua, it fails to adequately encompass the many other kinds of “RSD” features described in this study and elsewhere. These “RSD” features are simply too broad and diverse a phenomenon to fall under the umbrella of the “sorted bedform” model alone. While the central feedback mechanism is supported by our observational data, some features are clearly neither “sorted” nor “bedforms.” Further evidence of the need to develop a more fitting and consensus vocabulary for these features is the fact that no single model has been able to adequately predict the various types, distributions, and behaviors of features encountered in the field. For instance, the orientation of Facies 4 and 6 RSD features is not perpendicular to the observed weak mean currents as Murray and Thieler’s (2004) sorted bedform model requires. If there is a single consensus starting to emerge among researchers, it may be the recognition of the feedback mechanism between roughness and enhanced suspension, which may provide the formation and maintenance of these various features. Perhaps some term that speaks only to this general feedback mechanism and does not mention scour or bedforms will provide a meaningful commonality amongst the various features such as Complex Organized Rippled Features or Complex Rippled Patterns. Alternatively, there may not be a clean catch-all term to tie these varied complex features together.
Regardless of what the scientific community ends up calling these features, the present study indicates that careful consideration must now also be given to the role of depth disturbance (energy disturbance) in setting the conditions for or against their existence and persistence in a given location.

6.5 CONCLUSIONS

6.5.1 COMPLEX MORPHOLOGICAL PHASE TRANSITIONS

What we are documenting in this study is the existence of a modal morphological configuration state in an energetic sediment starved inner shelf system in which dynamically balanced complex features develop and persist. Figure 6.11 shows, conceptually, the various features and processes examined in this study. Outside of the optimal depth range where bed disturbance is neither too intense nor too infrequent, striking patterns of contrasting roughness are self-organized into various discrete types of morphologic patterns that fall under the blanket term of Rippled Scour Depressions.

At some critical point, which is guided by the initial biases introduced from the geological history of the system, the shelf forms into a new, self-organizing structure. Various short and long-term destabilizing processes (storms, climate change, sea-level change) many seek to push the system into or out of the previously balanced configuration. Three distinct configuration states are identified from detailed field and numerical modeling studies, namely: 1) The well-ordered state in which local gradients in roughness are slowly eliminated by the diffusive influence of the neighboring seabed type; 2) The disordered state in which entropy promotes a randomly fluctuating
roughness field and; 3) The complex state in which persistent intermediate-scale roughness features develop and are maintained.

A consistent underlying theme throughout this study, whether in regards to RSD behavior, barrier island retreat, mine burial, or shipwreck scour, is the understanding that shelf morphology interacts with fluid flow via non-linear dynamics to form complex sedimentary features. This study shows that contrasting morphological states can co-exist in close proximity to each other within a dynamically complex system.

6.5.2 BOUNDARY LAYER CHARACTERISTICS

This study has shown that the bottom boundary layer over complex shelf settings constantly adjusts to changes in forces (shoaling waves, non-steady currents, storms) and features (ripples, hummocks, seabed objects). In response, the bottom boundary layer is continually expanding and contracting; gaining and losing both momentum and mass in ways not usually accounted for in classical models.

This study shows that roughness has profound effects on nearbed turbulence in the form of structured vortices that were documented to occur with wave orbital ripples and hummocky bed configurations. Variations in wave friction factor, $f_w$, and mean current drag due to physical (ripples/hummocks) and biologic roughness (peat/shell beds) were observed to be large during background swell conditions and increased dramatically during storm conditions.
Classically, turbulence due to wave orbital motion is constrained within the thin wave-boundary layer (Grant and Madsen, 1986). In contrast, the observations in this study suggest that pronounced momentum exchange due to structured turbulent vortices takes place well beyond the confines of the wave boundary layer.

This study concludes that the inner shelf, bottom boundary layer cannot be understood simply as the product of instantaneous adjustments between hydrodynamics and bed micromorphology. Heterogeneous exposures of geologic deposits and hysteresis phenomena of bedform dynamics mean that both the present configuration and future morphologic development of the inner shelf are strongly influenced by geologic inheritance that needs to be accounted for in models.

6.5.3 BED ROUGHNESS

Predicting the geometry and evolution of ripple roughness is an important topic for modeling sediment transport and morphologic evolution (Doucette and O’Donoghue 2002). As shown in Chapters 3 and 4, bedforms play an important role in shelf morphodynamics, but present models of bedform behavior insufficiently account for observed configurations, especially during critical storm events.

The observations in this study suggest some surprising bedform behavior not captured by models, including transition to hummocky bedforms during peak storm flows and a hysteresis phenomenon between ripples and fluid flow during the waning portions of storms. Considerable work remains to be performed in order to understand the
dynamics of hummocky bedforms, which developed during the Tairua field experiment and have been observed by a growing number of studies (Traykovski and Goff, 2003; Black and Green, 1999).

A lack of sufficient understanding regarding ripple behavior, particularly in coarse RSD deposits, is also a key shortcoming in present models of local scour.

6.5.4 RIPPLED SCOUR DEPRESSIONS

Morphodynamically active and persistent, heterogeneous patches of sediment, which fall under the general, though admittedly unsatisfactory, name of Rippled Scour Depression (RSD) are ubiquitous along sand depauperate shelves worldwide. In this study, RSDs were encountered at all three field sites. RSDs occur on active as well as passive margins, stable and rapidly transgressing shorefaces subject to a range of energies, though generally wave dominated and sand deficient.

This study demonstrated that the stratigraphic signature of RSDs can be misinterpreted if not carefully considered. Furthermore, underlying geology plays an important role in some circumstances on the location of RSDs. In addition, RSDs, because of their common occurrence, frequently interact with and help to mediate the scour of seabed objects ranging from military mines to archaeological artifacts.

Observations from this study indicate that RSDs have multiple origins. Some RSDs result from geologic influences and are partially palimpsest; others are more
recently formed; all are actively involved in contemporary morphologic exchange processes.

Attempts to model the formation and maintenance of RSDs using Murray and Thieler’s (2004) exploratory model yielded mixed results. The exploratory model is simple and robust leading to the development of bedforms under all tested conditions. However, the model generates bedforms throughout the entire model domain, whereas observations indicate only limited occurrence of RSDs. Furthermore, field studies indicate that RSD sediments are poorly sorted with surrounding well-sorted fine-sand plains, whereas model results produce both well-sorted fine and coarse domains. Nonetheless, Murray and Thieler’s (2004) simple model based on an assumed of enhanced suspension and hindered settling mechanism offers a plausible explanation for one of the types of RSDs encountered at Tairua/Pauanui, namely the offshore, shore-oblique RSDs (Facies 6).

Suspended sediment data (Chapter 3) suggest that under certain flow dynamics, conditions are favorable for the transport and limited deposition of fine-sand on the coarse sand beds, which would lead to progressive burial of the feature. However, under certain conditions the reverse is true. Namely, the deposition of fine-sand on the coarse site is highly unlikely while the transport of coarse material into the fine domain is more likely, which might serve to maintain and possibly lay the seeds for new or larger RSDs. These insights add to the development of improved exploratory or rules-based models for the formation of the other RSD types identified in this study.
A new complexity model to explain the critical phase transition behavior of RSDs across the shelf was developed from the Lenz-Ising model of ferromagnetism. The Lenz-Ising model gives insight into the observed depth variation in RSD occurrence and persistence suggesting that a critical balance between entropy maximization and energy minimization allows RSDs to develop. Outside of the critical depth region, disturbance of the seabed is either too weak or too intense for RSD growth and maintenance. Application of the Lenz-Ising model introduces the idea of depth dependent RSD behavior.

Development of a new complexity theory of RSD distribution based on the Lenz-Ising model suggests that depth dependent bed disturbance plays a critical role in the existence and persistence of complex seabed features.

6.5.5 SCOUR ABOUT SEABED OBJECTS

Scour processes have been documented under moderate to energetic conditions at all of the shelf sites in this study. Reliable predictions of scour for various objects have been calculated with a simple empirical model of complex scour processes. The model does a reasonable job at predicting short-term, event-scale scour of objects associated with fine-sand plains. Difficulties in predicting scour behavior associated with RSD deposits are products of missing bedform behavior in the model. The presently available suites of numerical bedform models are insufficient to the task of predicting ripple geometry and dynamics, particularly during storms.
Another important theme that has emerged from the study of scour processes is the potential influence of underlying geology. This insight was first brought to light in the analysis of surface facies off Tairua where exposure of underlying geology was critical to certain facies (Facies 3 - rock related RSDs) but was not a key determinant in others (Facies 4 - nearshore shore-normal RSDs and Facies 5 - offshore shore parallel RSDs). Shallow variations in vertical composition of the seabed can also control the rate and maximum extent of scour as was seen in the case of artifacts from the QAR wreck-site.

6.6 FURTHER RESEARCH

The focused study of dynamic, spatially heterogeneous, inner shelf, sedimentary systems, is largely nascent and therefore issues remain poorly understood and constrained. The results of this study point to several lines of investigation that should and likely will be explored in the coming years.

The study of surficial and sub-surface facies is informative for the interpretation of the rock record and for diagnosing RSD types in active modern shelf settings. This information helps to understand the behavior of RSDs at other locations such as the Queen Anne's Revenge (QAR) shipwreck and the Indian Rocks Beach (IRB) field sites where similar prominent and persistent RSDs were encountered. Both of the QAR and IRB locations could serve as meaningful locations for experiments on the dynamics of hummocky bedforms associated with the fine-sand plain facies.
A strong need for quantified measurements of the development and behavior of hummocky bedforms exists. Improved models of ripple geometry that include non-equilibrium time-dependent behavior (hysteresis and biodegradation) are needed to better account for field conditions. A study to examine the role of sediment availability in controlling the conditions under which RSDs form or fail to form should be conducted. Attempts to forecast scour with RSD deposits should include bedform dynamics, which will depend on the improvement of bedform models.

Many opportunities exist for the continued development of the Lenz-Ising based model of RSD behavior. These could include the effects of adding an external field to the model, which might replicate the influence of underlying geology within discrete zones of the inner shelf. In addition, the model could be initiated using the entire field site at once with the inclusion of depth dependent energy distribution. This imposed energy distribution could be accomplished by spatially varying the interaction strength \( J \) thus making certain regions cooler or hotter than others and then running the model to assess spatial phase transition patterns.
Figure 6.1 Lenz-Ising model cellular interactions
Figure 6.2 Idealized morphological phase transition
Figure 6.3 Composite Shelf Roughness Index Tairua/Pauanui (20 m grid)
Figure 6.4 Shelf Bathymetry Tairua/Pauanui New Zealand (20 m grid)
Figure 6.5 Inner Shelf Complexity Profile
Figure 6.6 Profile of mean roughness index
Figure 6.7 Depth dependent complexity states
Figure 6.8 Depth dependent morphologic regimes.

- Low energy/infrquent disturbance
- Ordered/Complex
- Infrequent disturbance
- Low energy
- High energy
- Infrequent disturbance
- High energy
- Disordered/Chaotic
Figure 6.9 Lenz-Ising complexity model simulations
Figure 6.10 Inner shelf morphological regime map
Figure 6.11 Diagram of Shelf Processes Examined in this Study Modified after Nittrouer and Wright (1994)
APPENDIX

Matlab Code of Lenz-Ising model developed for application to rippled scour depression behavior

%Matlab script file to run the Lenz-Ising model simulation
%ising.m
N = 128;
X = roughgrid4ising3;
%uses the combined roughness grid for Tairua +1 rough (RSD or rock) -1 smooth (FSP)
figure(1);
h1 = image(32+24*X); colormap cool; shading flat;
J=0.42;
iter = 0;
nbrs=GetNbrs(N);
while 1,
pixel = ceil(rand*N^2);
hashfn=(X(nbrs{pixel})==X(pixel));
agree = sum(hashfn);
disagree = sum(~hashfn);
if rand < min(1,exp(2*J*(disagree - agree)))
    X(pixel) = -X(pixel);
end
iter = iter + 1;
if rem(iter,10000)==0,
    iter
    set(h1,'CData',X);
    axis equal; axis square; axis off; drawnow
end
end

%Subroutine to index neighbors surrounding each cell
function nbrs=GetNeighbors(M,N)
if nargin==1, N=M; end
nbrs=cell(1,M*N);
for k=1:M*N
    [i,j]=ind2sub([M,N],k);
    subnbr=repmat([i,j],1,4)+[0 0 -1 1;1 -1 0 0];
    II=find(subnbr(1, :)>M | subnbr(1,:)<1);
    JJ=find(subnbr(2,:)>N | subnbr(2,:)<1);
    subnbr(:,union(II,JJ)]=[];
    nbrs{k}=sub2ind([M,N],subnbr(1,:),subnbr(2,:));
end
LITERATURE CITED


Hume, T.M., Beamsley, B., Green, M. O., de Lange, W., and Hicks, D. M., 1995. Influence of seabed topography and roughness on longshore wave processes in Dally, W.R. and Zeidler, R.B. Coastal Dynamics '95 Proceedings of the International Conference on Coastal Research in Terms of Large Scale Coastal Experiments, Gdansk, Poland.

Waterway, Port, Coastal and Ocean Division of ASCE, NY: 975-986


Li, M.Z. and Amos, C.L., 1999. Field observations of bedforms and sediment transport


National Center for Environmental Prediction (NCEP), 1998. GRIB. Office Note 388, NOAA/NWS/NCEP. Available by anonymous ftp from ftp://ncardata.ucar.edu/libraries/grib/gribdoc.pdf


Short, A. D., 2002 in press., Large-scale behavior of topographically-bound beaches. International Conference on Coastal Engineering, Cardiff, American Society Civil Engineers.


bedforms at the Martha’s Vineyard Coastal Observatory in *Proceedings of the International Conference on Coastal Sediments* 2003, CD-ROM (Corpus Christi, TX: World Scientific/East Mets West).


Vincent, C.E. and Green, M.O., 1990. Field measurements of the suspended sand concentration profiles and fluxes and of the resuspension coefficient $\gamma_0$ over a rippled bed. *Journal of Geophysical Research* 95: 11,591-11,601.


VITA

Arthur Chris Trembanis


"This is not the end... 
It is not even the beginning of the end... 
...but it is, perhaps, the end of the beginning."
-Winston Churchill