A Geophysical Investigation
of the Derwent Estuary

David J Gibbons
B. Sc.

UNIVERSITY OF TASMANIA

A research thesis submitted in partial fulfillment of the requirements of the Degree of Bachelor of Science with Honours

School of Earth Sciences, University of Tasmania
November, 2001
Acknowledgements

Michael Roach, my supervisor and chief guru for your assistance, expertise and support (even if you did reckon the funny bits in the seismic were basalt!). Thanks especially for scraping together the funds for the project after the grant application got rejected. I hope you enjoyed your holiday, you certainly deserved it.

James Reid - stand-in guru and all-around good guy - for your help and good humour, particularly in Michael’s absence. Thanks also for your lessons in the dark art – fortran 77.

Alan Jordan and Miles Lawler from the Tasmanian Aquaculture and Fisheries Institute, without whom this project could not have proceeded. Alan for providing ‘mates rates’ for the vessels and Miles for piloting them back and forth, back and forth, back and forth....thank you both.

David Mitchell from the University of Sydney, for his willingness to come to Hobart in the colder months (straight from the North West Shelf!) to conduct our seismic survey. His good humour and patience with my clumsiness (“Please don’t stand on the eel, Dave!”) certainly made the seismic survey a more pleasant experience than it might otherwise have been.

Pat Quilty for his willingness to help whenever required (particularly in terms of my literature review). Thanks also to Peter Harris, for looking at my seismic data early in the year and allowing me to use his carbonate distribution map in my thesis.

Mineral Resources Tasmania for their support both personally (through a State Government Mining Scholarship) and for their support of the project. Thanks particularly to the staff who attended and gave input at the mid-year thinktank, aka ‘Roachy’s presentation’ (“Hi Roachy, we’ve come for your presentation”). Thanks also to Dr. David Leaman for his attendance and input at ‘Roachy’s presentation’, and for other valuable discussions throughout the year.

The library staff at the SciTech and Morris Miller libraries here at Uni, the Mineral Resources Tasmania library at Rosny, and the CSIRO Marine library at Salamanca.

Cheers to my fellow honours students and any staff member or undergrad that said anything nice about me or helped me during the year. Special thanks to those who offered to review my chapters in the absence of Michael and James during the latter part of the year – Ben Jones, Luisa D’Andrea, Nolene Dorn, Geoff Peters and my brother Geoff Gibbons. Perhaps I should have taken up the offers! Special thanks also to Jodie Cutler and her friend George for their help with my fieldwork.

Thanks,

Dave.
Table of Contents

ABSTRACT I
ACKNOWLEDGEMENTS II
LIST OF FIGURES V
LIST OF TABLES VIII

CHAPTER 1 INTRODUCTION 1
THE DERWENT RIVER 1
AIMS 4
TECHNIQUES (FOR MARINE SURVEYS) 5
POTENTIAL FIELD METHODS 5
ELECTRICAL AND E/M 5
SEISMIC 6
SONAR 6

CHAPTER 2 GEOLOGY 8
INTRODUCTION 8
PREVIOUS WORK 8
PREVIOUS GEOPHYSICAL SURVEYS 9
GEOLOGY OF THE HOBART AREA 12
STRATIGRAPHY 14
LOWER PARMEENER SUPER-GROUP 14
UPPER PARMEENER SUPER-GROUP 14
TERTIARY 18
QUATERNARY 20
IGNEOUS ROCKS 22
JURASSIC DOLERITE 22
TERTIARY BASALT 24
STRUCTURE AND STRUCTURAL HISTORY 26
PETROPHYSICAL PROPERTIES 26
MAGNETIC PROPERTIES 27
ACOUSTIC PROPERTIES 28

CHAPTER 3 MAGNETIC SURVEY 30
FIELD WORK 30
SPACE WEATHER 33
DATA PROCESSING 35
HEADING TEST 43

CHAPTER 4 MAGNETIC MODELING 50
INTRODUCTION 50
SENSITIVITY TESTING 51
MODELING 57

CHAPTER 5 SEISMIC SURVEY 71
SEISMIC TERMS 72
ACOUSTIC TURBIDITY 77
THE BASALT THEORY 77
DISPROVING THE BASALT THEORY 79
THE EVIDENCE FOR SHALLOW GAS 79
ACOUSTIC TURBIDITY 82
ENHANCED REFLECTIONS 82
ACOUSTIC BLANKING 83
PHASE REVERSALS 83
GAS SEEPS 85
VELOCITY PULLDOWN 85
INDIRECT EVIDENCE 85
REFERENCES

APPENDIX 1 LITERATURE REVIEW ‘GLOBAL SEA LEVEL CHANGE OVER THE LAST 250,000 YEARS’
APPENDIX 2 SOURCE CODE FOR FORTRAN 77 PROGRAM ‘HEADING’ (WRITTEN BY D. GIBBONS)
APPENDIX 3 SOURCE CODE FOR FORTRAN 77 PROGRAM ‘GEO2UTM’ (WRITTEN BY D. GIBBONS)
APPENDIX 4 SOURCE CODE FOR QUICKBASIC PROGRAM ‘LOCATE.BAS’ (WRITTEN BY M. ROACH)
APPENDIX 5 SEISMIC UNIX SHELL SCRIPT FOR ACOUSTIC FINITE DIFFERENCING
### List of Figures

<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Title/Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Overview map of study area (in the context of Tasmania)</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Detailed map of study area</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Traverse map and contours of the vertical component of magnetic intensity for the southern portion of a magnetic survey conducted in the Derwent Estuary in 1974/1975. Reproduced from Leaman (1975b).</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Geological cross section from the Bowen Bridge alignment. Modified from Colhoun and Moon (1984)</td>
<td>12</td>
</tr>
<tr>
<td>2.3</td>
<td>Simplified geological map of the Hobart area</td>
<td>13</td>
</tr>
<tr>
<td>2.4</td>
<td>A photo of an exposure of Lower Parmeener Super-Group rocks at Opossum Bay (sparingly fossiliferous marine siltstone)</td>
<td>14</td>
</tr>
<tr>
<td>2.5</td>
<td>A map of the distribution of Lower Parmeener Super-Group rocks in the Hobart area</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>A photo of an exposure of Upper Parmeener Super-Group rocks at Second Bluff, Bellerville (current bedded sandstone)</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>A map of the distribution of Upper Parmeener Super-Group rocks in the Hobart area</td>
<td>17</td>
</tr>
<tr>
<td>2.8</td>
<td>A photo of Tertiary boulder beds exposed on the foreshore at Taroona</td>
<td>18</td>
</tr>
<tr>
<td>2.9</td>
<td>A map of the distribution of Tertiary sediments and sedimentary rocks in the Hobart area</td>
<td>19</td>
</tr>
<tr>
<td>2.10</td>
<td>A photo of Pleistocene marine sediments exposed at Arm End, South Arm</td>
<td>20</td>
</tr>
<tr>
<td>2.11</td>
<td>A map of the distribution of Quaternary sediments in the Hobart area</td>
<td>21</td>
</tr>
<tr>
<td>2.12</td>
<td>A photo of a thermal contact between a dolerite sill and Lower Parmeener Super-Group rocks near Blackmans Bay</td>
<td>22</td>
</tr>
<tr>
<td>2.13</td>
<td>A map of the distribution of Jurassic Dolerite in the Hobart area</td>
<td>23</td>
</tr>
<tr>
<td>2.14</td>
<td>A photo of a Tertiary basalt lava flow overlying a tuffaceous deposit exposed at Sandy Bay</td>
<td>24</td>
</tr>
<tr>
<td>2.15</td>
<td>A map of the distribution of Cenozoic volcanic rocks (i.e. Tertiary basalts) in the Hobart area</td>
<td>25</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Photo of the FMV Nubeena, a TAFI research vessel. Taken near Electrona in North West Bay</td>
<td>30</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Photo of the FMV Poolta, a TAFI research vessel. Taken near Electrona in North West Bay</td>
<td>31</td>
</tr>
<tr>
<td>3.2</td>
<td>A map of magnetic survey lines for 2000 and 2001 used for gridding (i.e. not all of the survey lines – some were removed prior to gridding. See also figure 3.9)</td>
<td>32</td>
</tr>
<tr>
<td>3.3</td>
<td>Chart of variation in horizontal magnetic intensity measured by the Hobart IPS gradiometer for 4 days in March 2001, demonstrating the magnetic effects of a magnetic storm</td>
<td>34</td>
</tr>
<tr>
<td>3.5</td>
<td>Chart of the G856 base station record for day 2 of the magnetic survey, 2001 (i.e. 21st of March 2001)</td>
<td>35</td>
</tr>
<tr>
<td>3.6</td>
<td>Profile of magnetic intensity on line 5400 from the 2001 magnetic survey, showing drop outs</td>
<td>36</td>
</tr>
<tr>
<td>3.7</td>
<td>Profile of magnetic intensity on line 5400 after drop out editing</td>
<td>37</td>
</tr>
<tr>
<td>3.8</td>
<td>Profiles of magnetic intensity (after drop out editing) for all profiles used for gridding</td>
<td>38</td>
</tr>
<tr>
<td>3.9</td>
<td>All survey lines for the 2001 and 2000 magnetic surveys</td>
<td>39</td>
</tr>
<tr>
<td>3.10</td>
<td>False colour image of total magnetic intensity (TMI) grid</td>
<td>40</td>
</tr>
<tr>
<td>3.11</td>
<td>False colour image of total magnetic intensity grid from regional dataset for comparison to new data</td>
<td>41</td>
</tr>
<tr>
<td>3.12</td>
<td>Contour map of TMI, generated from gridded survey data</td>
<td>42</td>
</tr>
<tr>
<td>3.13</td>
<td>Schematic image of the magnetic response of a sphere of susceptible material, used to illustrate the effect of boat heading on magnetic measurements</td>
<td>43</td>
</tr>
<tr>
<td>3.14</td>
<td>Heading test data (raw) plotted as a function of time. Field and base station records shown</td>
<td>45</td>
</tr>
</tbody>
</table>
3.15  Diurnally corrected heading test data and northings from GPS log as a function of time, illustrating low resolution of non-differentially corrected GPS position data
3.16  Observed and calculated heading test data. Calculated data used to apply corrections
3.17  Comparison of magnetic data from 2000 and 2001 surveys – selected points from line intersections
4.1.1  Sensitivity testing example chart 1
4.1.2  Sensitivity testing example chart 2
4.1.3  Sensitivity testing results chart 1
4.1.4  Sensitivity testing results chart 2
4.1.5  Potent model for sensitivity testing number 1
4.1.6  Potent model for sensitivity testing number 2
4.1.7  Potent model for sensitivity testing number 3
4.1.8  Potent model for sensitivity testing number 4
4.2   Traverse 1 model results
4.3   Traverse 2 model results
4.4   Traverse 3 model results
4.5   Traverse 4 model results
4.6   Traverse 5 model results
4.7   Traverse 6 model results
4.8   Traverse 7 model results
4.9   Traverse 8 model results
4.10  Traverse 9 model results
4.11  Traverse 10 model results
4.12  Traverse 11 model results
4.13  Traverse 12 model results
4.14  Traverse 14 model results
5.1   Photo of the boomer seismic source catamaran (on land)
5.2   Photo of the seismic receiver array (eel) in the water
5.3   Photo of the electrostatic printer used to output the seismic profiles
5.4   Photo of the FMV Mallama (the vessel used for the seismic survey)
5.5   The two boats used for the seismic survey at Bridgewater. Two boats were used because of the shallow water depths.
5.6   Map of the seismic trackpaths, for 2000 and 2001
5.7   Calculated magnetic response of a thin sheet of basalt
5.8   Example of a 'blanket' of acoustic turbidity from Taylor (1992)
5.9   Map of the distribution of acoustic turbidity in the Derwent Estuary as defined from the seismic reflection profiles
5.10  Example 1 of a possible phase reversal on one of the seismic reflection profiles
5.11  Example 2 of a possible phase reversal on a seismic reflection profile
5.12  Example of probable gas seepage and velocity pulldown
5.13  Example of a pockmark from the Derwent Estuary
5.14  Example of a pockmark from the literature (Taylor, 1992)
5.15  Map of water column disturbances defined from the seismic reflection profiles
5.16  Schematic of possible chemical and biological boundaries and conditions necessary for the bacterial production of methane
5.17  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.18  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.19  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.20  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.21  Schematic of some seismic energy travelpaths – primary reflections
5.22  Schematic of some seismic energy travelpaths – simple multiples
5.23  Example of seafloor multiples
5.24  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.25  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.26  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.27  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.28  Schematic of some seismic energy travelpaths – primary reflections
5.29  Schematic of some seismic energy travelpaths – simple multiples
5.30  Example of seafloor multiples
5.31  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.32  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.33  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.34  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.35  Schematic of some seismic energy travelpaths – primary reflections
5.36  Schematic of some seismic energy travelpaths – simple multiples
5.37  Example of seafloor multiples
5.38  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.39  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.40  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.41  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.42  Schematic of some seismic energy travelpaths – primary reflections
5.43  Schematic of some seismic energy travelpaths – simple multiples
5.44  Example of seafloor multiples
5.45  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.46  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.47  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.48  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.49  Schematic of some seismic energy travelpaths – primary reflections
5.50  Schematic of some seismic energy travelpaths – simple multiples
5.51  Example of seafloor multiples
5.52  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.53  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.54  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.55  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.56  Schematic of some seismic energy travelpaths – primary reflections
5.57  Schematic of some seismic energy travelpaths – simple multiples
5.58  Example of seafloor multiples
5.59  Map of the distribution of calcium carbonate in the shallow sediments of the Derwent Estuary (provided by Dr. Peter Harris)
5.60  Photo of the 'Craic' corer owned by TAFI and used for shallow sediment sampling
5.61  Photo of borosilicate glass sample bottles used for the collection of wet sediment samples
5.62  Map of the location of sediment samples, coded according to measured methane concentration (normalised by sample mass)
5.63  Schematic of some seismic energy travelpaths – primary reflections
5.64  Schematic of some seismic energy travelpaths – simple multiples
5.65  Example of seafloor multiples
Schematic of some seismic energy travel paths – complex multiples

Example 1 of multiple reflections from the Derwent Estuary seismic profiles

Example 2 of multiple reflections from the Derwent Estuary seismic profiles

Example of how a multiple reflection can interfere with the interpretation of primary reflections

The seismic profile taken alongside the southern side of the Tasman Bridge

The input velocity model used for acoustic finite difference (AFD) modeling

High frequency model output (i.e. a 'pseudo-boomer' record) from the AFD modeling

Example 1 of multiple reflections from the Derwent Estuary seismic profiles

Example 2 of multiple reflections from the Derwent Estuary seismic profiles

Example of how a multiple reflection can interfere with the interpretation of primary reflections

The seismic profile taken alongside the southern side of the Tasman Bridge

The input velocity model used for acoustic finite difference (AFD) modeling

High frequency model output (i.e. a 'pseudo-boomer' record) from the AFD modeling

Moderate frequency model output from the AFD modeling

Low frequency model output from the AFD modeling

Low frequency 'pseudo-boomer' record calculated by acoustic finite differencing

Trackpaths map for 'long' seismic lines (i.e. lines 3, 5, 7, 12, 21, 22, 23, 16 and 17)

Trackpaths map for 'short' seismic lines (i.e. lines 24 to 34 inclusive)

Line 3 raw seismic profile

Line 3, interpretation

Line 23, raw seismic profile

Line 23, interpretation

Line 22, raw seismic profile

Line 22, interpretation

Line 5, raw seismic profile

Line 5, interpretation

Line 16, raw seismic profile

Line 16, interpretation

Line 17, raw seismic profile

Line 17, interpretation

Line 21, raw seismic profile

Line 21, interpretation

Line 7, raw seismic profile

Line 7, interpretation

Line 24, raw seismic profile

Line 24, interpretation

Line 25, raw seismic profile

Line 25, interpretation

Line 26, raw seismic profile

Line 26, interpretation

Line 27, raw seismic profile

Line 27, interpretation

Line 28, raw seismic profile

Line 28, interpretation

Line 29, raw seismic profile

Line 29, interpretation

Line 30, raw seismic profile

Line 30, interpretation

Line 31, raw seismic profile

Line 31, interpretation

Line 32, raw seismic profile

Line 32, interpretation

Line 33, raw seismic profile

Line 33, interpretation

Line 34, raw seismic profile

Line 34, interpretation

False-colour image of bathymetry, generated from gridded data

Contours of bathymetry, generated from gridded data

Combined geological interpretation map

Image of gridded magnetic data, reduced to the pole. Used for qualitative interpretation

Image of first vertical derivative of reduced to pole magnetic data. Used for qualitative interpretation
### List of Tables

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Title/Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>List of sonic velocity ranges for common geological materials found in the Hobart area</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>Results of headspace gas analysis</td>
<td>98</td>
</tr>
</tbody>
</table>
The Derwent River

The Derwent River is one of the largest rivers in Tasmania by any measurement standard. It drains Lake St Clair in the southern central highlands, and meanders over 200km down to Storm Bay south of Hobart where it eventually joins the Tasman Sea.

The modern river deposits most of its suspended sediment load between New Norfolk and Bridgewater, and an area of fluvio-deltaic mud flat is developed north of the Bridgewater causeway. South of the causeway is the Estuary proper, and this extends to the entrance of Storm Bay, marked by the significant widening of the water body just south of the Iron Pot. The length of the Estuary between Bridgewater and Storm Bay is nearly 60km, and it is up to 6km wide.

The bulk of this study was conducted in the southern portion of the Estuary, between Hobart in the north and Betsey Island in the south, excluding Ralphs Bay to the east and North West Bay to the West. Some seismic data were collected further upstream, as far north as the Bowen Bridge. See the location maps for details.

Since the city of Hobart is built on the banks of the Estuary, access is excellent. There are major roads and numerous boat launching and mooring points along both shores of the river. The boats used for this study were launched near Electrona in North West Bay, at the Regatta Grounds near the Cenotaph and at the Derwent Sailing Squadron (DSS) in Sandy Bay. Access to the DSS ramp and mooring facilities was arranged by Dr. Michael Roach. The other launching points are freely accessible to the public, via good quality sealed roads.
Figure 1.1. General location map of study area.
Figure 1.2. Detailed study area map. Note that some seismic profiles were obtained outside of the main study area.
Chapter I

Introduction

Aims

The purpose of the study was to investigate some aspects of the geology of the lower Derwent Estuary. This kind of study requires specialised techniques because the rocks are covered by water and mud, i.e. direct mapping is impossible. Geophysical techniques enable us to map the hidden geology, provided that certain conditions regarding the physical properties of the rocks are satisfied.

Different geophysical techniques exist for the remote detection and/or mapping of different geological features or ‘targets’. By limiting the techniques that we use in any given study, we automatically place some restrictions on what we can learn. But we are also limited by the techniques themselves, in terms of the equipment, logistics and geological conditions they require to be used successfully.

As a result, the outcomes that can be reasonably expected are in part dependent on the type of techniques to be applied, and the techniques to be applied are chosen based on what you are trying to achieve and what you can afford.

Having said that, the aims of the project were to determine, where possible:

- some aspects of the Cainozoic sedimentation history of the river, and half-graben basin in general
- bedrock depth and distribution of bedrock types beneath the Cainozoic sediments
- location of structures and structural relationships
- tectonic and/or geological history of the Estuary (with implications for the greater Hobart area)

There are a number of reasons why this kind of work can be useful. First and foremost it can be used as an aid for mapping (i.e. to extend the existing maps). Secondly, it can assist in the interpretation of the geological history of the Hobart area. Thirdly, the Derwent is polluted by heavy metals and other contaminants, and knowledge of where sediment has been accumulating in the recent geological past could be useful for pollutant studies. Finally, there is interest in some aspects of the geology of the Derwent Estuary from a geotechnical perspective because the city of Hobart is build around the Estuary. This last
point is particularly noteworthy, because some of the data collected during this project are already being used as part of a land stability study at Taroona (this is being conducted by Coffey Geosciences on behalf of Mineral Resources Tasmania, one of the project sponsors).

Techniques

There are a number of techniques that are routinely applied in geophysical investigations – some of these can be used on land and over water, some are only suitable for land use and some are specifically for use in the marine environment. It is worth briefly considering the applicability of the common techniques to this study, and explaining why we chose the techniques that we did. For the purposes of the following discussions I will use the terms 'seafloor' and 'riverbed' interchangeably, and the term 'marine' includes the estuarine environment.

Potential Field (Magnetic and Gravity) Methods

Potential field techniques are efficient (large coverage for low cost), well understood techniques used for both geological mapping and mineral exploration. Measurements of both the magnetic and gravity fields can be done from the ground, sea or air. For these reasons, we conducted a magnetic survey over the entire lower Derwent Estuary. While it is not particularly difficult to deploy a magnetometer designed for land use from a marine platform, this is not the case for a gravimeter. The specifics of the gravity technique require that acceleration of the deployment platform be removed from the measurements, and this requires specialised equipment (which we do not have). As a result, we did not conduct a gravity survey. While the magnetic data is informative by itself, the lack of gravity data precludes the use of the traditional coupled interpretation method. This has implications for the interpretation of the data, particularly for modeling (see chapter 4).

Electrical/Electromagnetic Methods, including MT and GPR.

Electromagnetic and electrical methods are used in situations where ground conductivity contrasts can be used for mapping or exploration. They are designed for use over land, where ground conductivities are generally low. The (highly conductive) saline water that
exists in all marine settings has traditionally precluded the use of electrical methods, with a few notable exceptions. Magneto-tellurics (MT) and a variation of the MMR method have been applied in marine settings for deep crustal work, but these techniques would not have provided sufficient resolution for this study. Time-domain and frequency-domain EM methods for marine use are under development. Some methods (such as GPR) have successfully been applied in areas of shallow freshwater cover (Reynolds, 1997).

**Seismic Techniques**

Seismic methods (reflection and refraction) are very commonly used in land and marine studies, particularly for petroleum exploration and geotechnical surveys. High resolution seismic reflection profiling is a method used to investigate the structure and sedimentation history of the shallow subsurface in the marine environment, and we applied this technique in the Derwent Estuary. There are a variety of energy sources available for this kind of work – the most common are sparkers, boomers and pingers. For this project, we used a 200J boomer source with analogue data recording.

We did not conduct any seismic refraction surveying, for several reasons. Firstly, in order to get data about deep refractors, a large source – receiver offset is required. This requirement is limiting because it can be difficult to keep a sonobuoy string straight and in line with the source when long offsets (and long cables) are involved. This is especially the case in the presence of strong currents and leads to uncertainty in positions. Secondly, the expected complex subsurface structure would have demanded a large data volume (sufficient for tomographical inversion) and hence a lengthy, expensive survey. These factors suggested that seismic refraction was probably inappropriate for this study. This assessment is in agreement with Leaman (1975), who stated "The refraction technique is not an ideal approach to the problems of the River Derwent..." (page 1).

**Sonar (Side-Scan, Multibeam and Single-Point)**

Similar in principle to seismic reflection profiling but with greatly increased operating frequencies and essentially no sub-bottom penetration are single point bathymetric profiling and side-scan (or multibeam) sonar mapping. These techniques are commonly applied in marine investigations as part of integrated studies, but only provide information
about the seafloor (structure ± some compositional information about the surficial sediments). Single point sonar bathymetric data is easily and cheaply obtained with a depth sounder and logging equipment. Side-scan sonar or multibeam sonar require specialised equipment. We did not have ready access to side-scan or multibeam equipment, so we collected single point sonar data. This was satisfactory for our purposes.
CHAPTER 2  GEOLOGY

Introduction

The Tasmanian settlements were amongst the earliest European colonisations in Australia, and Hobart was settled in the early 1800’s (Leaman, 1999). Despite not being known for any mineral or petroleum resources (industrial resources and coal have been sourced from in and around Hobart historically), this relatively long history of European occupation and large population base has meant that the geology of the Hobart area has been extensively studied over a long period.

Previous Work

The earliest published references to aspects of the geology of southern Tasmania (and Hobart in particular) can be found in works by Charles Darwin from the mid 1840s, such as *Geological Observations on Volcanic Islands* (1844) where he makes reference to the basalts exposed around Hobart (Spry, 1955). Darwin gives a more general treatment to the geology of Hobart in his *Journal of Researches into the Natural History and Geology of the Countries visited during the voyage of HMS Beagle round the world, under the command of Captain Fitz Roy, RN.* (Leaman, 1999).

The first specific guide to the geology of the Hobart area was Thomas Harrison’s *Notes of the Geology of Hobart Town* published in the Transactions of the Royal Society of Victoria in 1865 (Lewis, 1946). This was followed by R. M. Johnston’s *Systematic Account of the Geology of Tasmania* in 1888 (Lewis, 1946).

A number of more specific papers were also published in the late 1800s – these typically related to industrial resources such as coal. The earliest specific work on the Derwent Estuary was also produced around this time – R. M. Johnston’s *Notes Showing that the Estuary of the Derwent was Occupied by a Fresh-Water Lake During the Tertiary Period* (1881).
Following Johnston's 1888 work, the next – and most comprehensive – was A. N. Lewis' book *The Geology of the Hobart District*, published in 1946. This gave a thorough treatment to many aspects of the geology, and included a detailed map.

In the mid to late 1960's a detailed geological mapping program was undertaken by the Department of Mines, and the resulting Hobart 1:50,000 map sheet and accompanying explanatory notes *Hobart* (Leaman, 1976) subsequently became the major reference for the district.

As a more general reference, Burrett and Martin (1989) provides a guide to the geology of Tasmania, (including Hobart) in the same vein as Johnston's *Systematic Account*.

Dr. David Leaman’s recent publication *Walk Into History in Southern Tasmania* (Leaman, 1999) contains updated information on much of the geology of the Hobart area, and is perhaps now the best general guide despite not being a specifically geological text.

**Previous Geophysical Surveys**

Previous geophysical work in the lower Estuary has been relatively limited. The majority of the work has been associated with site investigations for the river crossings, all of which are north of the main study area. Some limited geophysical surveying has been carried out in the lower Estuary, mainly by the Tasmanian Department of Mines in the 1970s.

Seismic refraction surveys were carried out at the sites of the Tasman Bridge (Spry and Carey, 1962) and Bowen Bridge (Leaman, 1975). A seismic refraction survey was also conducted in the area between Kellys Point and the Iron Pot to investigate some aspects of the riverbed structure (Leaman, 1974).

The only previous seismic reflection work in the Estuary was a small 'sparker' survey done for geotechnical purposes – the results were not published (Joe Giedl, pers comm 2001). A major seismic reflection survey just outside of the Derwent Estuary was undertaken by the Amoco Australia Exploration Company in the summer of 1969-1970. This survey obtained approximately 600 miles of 24 fold CDP “Aquapulse” data, with the
closest line to the Estuary (TW322) running due east from the southern tip of Adventure Bay on Bruny Island through Storm Bay. Amoco concluded that the thickness of sediment over the "economic basement" was small, and that hydrocarbon potential was unlikely – in Storm Bay on line TW322 the thickness of "sediment" (ie. Tertiary and younger) was found to vary from around 300 to 900 feet (ie. 90 to 270m).

Figure 2.1. Traverse map and contours of the vertical component of magnetic intensity for the southern portion of the 1974-75 survey. Reproduced from Leaman (1975b).
Regional, airborne magnetic surveying has been carried out in south-eastern Tasmania by a number of exploration companies, but the only prior high resolution (marine) magnetic surveying in the lower Derwent Estuary was a small scale investigation of some known anomalies near Betsey Island in 1973 (Leaman, 1973). In the northern portion of the Estuary, more extensive work has been done. For example, a survey was conducted near Dowsings Point as part of the second river crossing site investigation (Leaman, 1975b), and a much more detailed study of the northern part of the Estuary (from Sandy Bay to Bridgewater) was undertaken between January 1974 and May 1975 by the Tasmanian Department of Mines. This survey used a McPhar fluxgate magnetometer mounted on a wooden gimbal to measure the vertical field component. Locations were provided by surveying but the surveyed lines were irregularly orientated and the data were not corrected for boat heading. The data were used to produce contour maps, and interpretations of the geology from Bridgewater to the John Garrow light were made by Dr. David Leaman (Leaman, 1975b). Some magnetic traverses were also done around the site of the Wrest Point casino as part of the site investigation (Stevenson, 1969 in Burrett and Martin, 1989).

There is reasonable ground gravity station coverage around Hobart, but no ship-borne gravity coverage.

The only significant coring within the Estuary was undertaken as part of the river crossing site investigations. Geological cross sections drawn from the core logs are available for both the Tasman Bridge (Trollope et al., 1966) and Bowen Bridge (Colhoun and Moon, 1984) alignments. Other sediment sampling and coring that has been done by various groups (such as TAFI) has been surficial (ie. less than one metre core length).
The following discussion of the geology of Hobart is designed to give a background regarding the types of rocks and sediments that we might expect to be present in the study area. This is based on the assumption that all rock types that might be present beneath the river are present on shore or are known from the coring that has been done. I do not make any claims as to the validity of this assumption.

The exposed geology of the study area (ie. most of the area covered by the 1:50,000 Hobart and Kingborough Geological Atlas sheets – see Leaman, 1976 and Farmer, 1985) consists entirely of rocks of the upper Paleozoic to Cainozoic – there is no exposure of pre-Permian rocks in the area. Both Cambrian volcanics and Precambrian rocks are known to underlie the more recent geology (Leaman, 1999). Broadly speaking, there are five groups of rocks exposed in the Hobart region. The oldest of these are Carboniferous and Permian sedimentary rocks of the Lower Parmeener Supergroup. These are disconformably overlain by Triassic sedimentary rocks of the Upper Parmeener Supergroup. Intruding the Permian and Triassic sequences are bodies of Jurassic Dolerite. Attaining a maximum sill thickness in excess of 300m, the dolerite forms many prominent hills and ridges in the modern topography. Unconformably overlying these older rocks are Tertiary volcanic rocks, sedimentary rocks, and unconsolidated sediments of variable association, and the Tertiary sequences are in turn overlain by Quaternary deposits.
Figure 2.3. A simplified geological map of the Hobart area, showing six divisions based on age. This map is derived from the 1:250,000 digital geology coverage of Tasmania.
Stratigraphy

Lower Parmeener Supergroup
As mentioned, the oldest exposed rocks in the Hobart-Kingborough quadrangle are of the Lower Parmeener Supergroup, of late Carboniferous to Permian age (commonly referred to as Permian). The earliest part of this Supergroup is a sequence of glaciogenic rocks, which are overlain by a thick succession of mainly marine siltstones and mudstones with lesser sandstone, limestone and carbonaceous rocks including some coal. These rocks are variably fossiliferous and form a largely conformable sequence (with disconformities between some Formations). The ‘Permian’ succession is entirely marine, with the exception of the transitional/terrestrial Faulkner Group.

Upper Parmeener Supergroup
Disconformably overlying the Lower Parmeener Supergroup rocks are those of the Upper Parmeener Supergroup. While Leaman (1976, 1999) assigns the Cygnet Coal Measures to the Lower Parmeener Supergroup, Farmer (1985) asserts that they are in fact part of the Upper Parmeener Supergroup. Both agree that they are latest Permian.
Figure 2.5. The simplified Lower Parmaener Supergroup (ie. Permian) geology of Hobart.
The younger, less contentious parts of the Upper Parmeener Supergroup have been split into a number of different associations based on rock type, and range in age from late Permian to late Triassic (commonly referred to as Triassic). These rocks are entirely of terrestrial origin and range from conglomerate to mudstone and coal seams, but the most important rock type is sandstone — either clean quartz, feldspathic or lithic (Farmer, 1985). Often, these Triassic sandstones exhibit current bedding (commonly overturned). Overall, there is a transition up section from clean quartz sandstones to more micaceous and feldspathic rocks, accompanied by a reduction in average grainsize (Leaman, 1976).

Figure 2.6. Triassic sandstones showing typical cross bedding at Second Bluff, Bellerive. Lens cap is 52mm diameter.
Figure 2.7. The distribution of the Upper Parmeener Supergroup rocks in the Hobart area.
Tertiary Sediments and Sedimentary Rocks

Tertiary deposits (with varying levels of consolidation) unconformably overlie the Parmeener Supergroup rocks at a number of localities in the Hobart-Kingborough quadrangle. There are boulder beds, gravels, silts, sands and clays, and localised occurrences of ferricrete and silcrete (Farmer, 1985). Also of Tertiary age are various deposits associated with basaltic volcanism – notably sub-basalt tuffs and super-basalt gravels (Leaman, 1976).

![Figure 2.8. Tertiary boulder beds (matrix supported polymictic boulder conglomerates/breccias) containing large clasts of dolerite, exposed on the Taroona foreshore. Lens cap (centre of photo) is 52mm diameter.](image)
Figure 2.9. Distribution of Tertiary sediments around Hobart.
Quaternary Sediments

There are a number of deposits of probable Quaternary age around Hobart. Included among these is the Mary Ann Bay Sandstone, a friable, fossiliferous marine deposit dated by Amino-Acid Racemisation at around 125,000 years old (Murray-Wallace and Goede, 1995). This corresponds to isotopic sub-stage 5e, when global sea level was equal to or slightly higher than present. This deposit is presently exposed some 24m above the high water mark at Arm End – implying significant uplift rates. Other Quaternary deposits include talus, scree, silts and beach sands.

Figure 2.10. Fossiliferous marine sands of Late Pleistocene age exposed at Arm End. Lens cap is 52mm diameter.
Figure 2.11. Distribution of Quaternary sediments around Hobart.
Igneous Rocks

Jurassic Dolerite
Jurassic dolerite is very common in the Hobart-Kingborough quadrangle. It crystallised from a tholeiitic basalt magma (Leaman, 1976), and varies in grain size and intrusion form. Differentiation effects can be observed in larger sills and dykes. No Jurassic volcanic rocks are known in this area – the dolerite exposed presently was all emplaced in the (relatively) shallow subsurface. Emplacement was multi-phase, with up to five magma pulses (Leaman, 1999).

Figure 2.12. Intrusive contact between a dolerite sill (lower) and Permian sedimentary rocks (upper) exposed near Blackmans Bay.
Figure 2.13. Distribution of Jurassic dolerite around Hobart.
Cretaceous Alkaline Intrusive Rocks
These occur only in the far south of the Hobart-Kingborough quadrangle, and are not relevant to this discussion.

Tertiary Volcanic Rocks
There is some controversy about the ages of the rocks I have named here as Tertiary (i.e. some may be younger), and Leaman (1976) refers to them simply as Cainozoic. I will refer to them as Tertiary (following common usage), but I recognise that this is perhaps not strictly correct. A large number of relatively small volcanic centres are recognised in the Hobart area, and petrographic studies have revealed a range of compositions from typical tholeiitic and alkali olivine basalts to more undersaturated varieties (Leaman, 1976). There are pyroclastic deposits, coherent lavas and minor intrusions associated with the various volcanic centres.

Figure 2.14. Basalt lava flow overlying a tuffaceous deposit, exposed on the foreshore near Blinks Billy Point, Sandy Bay. Lens cap is 52mm diameter.
Chapter 2
Geology

Tertiary (igneous) Geology of the Hobart Area
From 1:250,000 scale digital coverage of Tasmania

Figure 2.15. Distribution of Tertiary (Cainozoic) basalt around Hobart.
Structure and Structural History

The following notes regarding the structure and structural history of the Hobart area are greatly simplified and, of necessity, very brief. Only Jurassic and younger structures are considered here.

Work by Berry and Banks (1985) on fault striations of the Parmeener Supergroup rocks concluded that a NW to NNW compressional event formed the fracture pattern associated with dolerite emplacement, and involved strike-slip and possibly reverse movement. This event must therefore have commenced prior to the mid-Jurassic, and they suggest that it remained active after the dolerite emplacement. The other major event they interpreted was Cainozoic normal faulting associated with extensional tectonics that led to the development of the Derwent graben, and they suggest that this later event involved reactivation of many of the older Mesozoic faults. This event occurred in the early to mid Tertiary (Berry and Banks, 1985). Their work did not provide support for an independent fold phase.

Leaman (1995) does not support the contention of Banks and Berry (1985) that there was regional NW compression prior to or during dolerite emplacement, stating that “Inspection of all faults and contacts, however, does not support this view.” (page 153). Rather, he suggests that the emplacement of the dolerite was part of a rifting (ie. extensional) event that broadly defined the position of the modern Tamar, Coal and Derwent Rivers (Leaman, 1999). He concurs with Berry and Banks regarding the Cretaceous-Tertiary extension.

Suffice to say that there are at least two generations of faulting and all recent (Tertiary and younger) movement has been normal. There are a variety of fault orientations (dominated by NW/NNW and SE/ESE trends), but exposed faults are generally steeply dipping. Generally, sedimentary dips are low (< 25°) but can be highly variable, particularly in the area of the monocline defining the Cascades Fault Zone (Leaman, 1976).

Petrophysical Properties
Since this study involved the use of magnetic and seismic data, it is useful to discuss the relevant petrophysical properties of the materials likely to be present in the study area.

**Magnetic Properties**

The following discussion of the magnetic properties of rocks from Hobart is partly based on a similar discussion in *River Derwent Magnetic Survey, John Garrow Light – Bridgewater* by Leaman (1975b).

**Parmeener Supergroup (Permian and Triassic) Sedimentary Rocks**
The Permian glacio-marine sedimentary rocks of the Hobart area are essentially non-magnetic, and the same can be said of the Triassic freshwater series. Leaman (1975b) felt that the younger, feldspathic division of the Triassic might have slightly more intense remanent magnetisation than the older rocks, but not enough to make them particularly magnetic.

**Cainozoic Sedimentary Rocks and Sediments**
These are regarded by Leaman (1975b) as non-magnetic, and in general this is probably true. However, channels of probable Tertiary age in the Fingal valley that contain significant volumes of dolerite (as boulders and smaller clasts) are apparent in aeromagnetic data and the anomalies appear to be due to the dolerite clasts (Gregg, 2001). Therefore, we could infer that the coarse Tertiary sediments containing large proportions of dolerite around Hobart could also potentially have a significant bulk susceptibility. Sediments with this potential (boulder beds containing large numbers of dolerite clasts) occur on-shore at Taroona. Note that any magnetic anomalies due to these features would presumably be from induced magnetisation only, since the thermo-remanent components would be randomly orientated (see below for discussion of dolerite). Certainly I agree that the finer sediments such as clays and sands are effectively non-magnetic.

**Jurassic Dolerite**
Leaman (1975b) describes this as "A petrologically and magnetically variable rock with intense remanent magnetisation and high volume susceptibility" (pages 2 and 3, after Irving, 1956). In a later work he states that the most magnetically susceptible parts of an intrusion are commonly the granophyric sections – near feeders and/or in the upper section.
Chapter 2

Geology

of a sheet, and that the most intense remanent effects typically occur in the fine grained margins of the intrusion (Leaman, 1997). Irving (1956) measured the direction and intensity of remanent magnetisation in 30 samples of dolerite, and found a mean inclination of $-85^\circ$ ($-72^\circ$ modern value) and mean azimuth of $325^\circ$ ($14^\circ$ modern value). None of his samples were found to be reversely magnetised. Irving also took measurements from 9 irregularly arranged boulders in a Tertiary fault scarp breccia from Cartwright Point. He demonstrated that the magnetic orientations within these samples were random, ie. the remanent magnetisation in the boulders had been acquired prior to the breccia formation. Leaman (1975b) gives a range of susceptibilities from $1 \times 10^{-3}$ to $40 \times 10^{-3}$ SI units, and remanent magnetisation intensities ranging from 0.4 to 7 A.m$^{-1}$ directed at $-85^\circ/325^\circ$ (after Irving) for the Jurassic dolerites.

Tertiary Basalts

Leaman (1975b) states that the "...range of properties of the basalt are considered to be greater than for the dolerite." (page 3), implying a large range of values from highly magnetic to effectively non-magnetic. However, he goes on to state that the variation is dependent on the degree of weathering. The basalts exposed around Hobart are all deeply weathered, and the weathered basalts tend to have lower susceptibilities than the dolerite. To this, we can add that some of the basalts are reversely magnetised – ie. they have a thermo-remanent component that is (broadly speaking) opposed to the modern field orientation. This means that they can appear as anomalous lows in magnetic survey data. However, there are no published data regarding the intensity or orientation of the thermo-remanent component of the basalts. Since the geomagnetic field changed orientation numerous times in the Tertiary, there are likely to be basalts with their remanent components aligned with the modern field, ie. they are not all reversed.

Acoustic Properties (ie. sonic velocities)

The following table of sonic velocity ranges is taken from appendix 1 of Leaman (1975a), *The River Derwent: Elwick Bay to Macquarie Point. Geology: Facts, deductions and problems* and is relevant to the discussion of seismic data.
<table>
<thead>
<tr>
<th>Material</th>
<th>Seismic Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1500</td>
</tr>
<tr>
<td>River Silt (suite 1)</td>
<td>~1400-1500</td>
</tr>
<tr>
<td>Sand, clay (suite 2)</td>
<td>1600-1800</td>
</tr>
<tr>
<td>Weathered Basalt</td>
<td>1700-2500</td>
</tr>
<tr>
<td>Basalt (fractured-massive)</td>
<td>2200-6000</td>
</tr>
<tr>
<td>Weathered Dolerite</td>
<td>1700-2500</td>
</tr>
<tr>
<td>Dolerite (fractured-massive)</td>
<td>2200-6000</td>
</tr>
<tr>
<td>Sandstone (weathered-massive)</td>
<td>2000-4500</td>
</tr>
<tr>
<td>Siltstone (weathered-massive)</td>
<td>2000-5000</td>
</tr>
</tbody>
</table>

*Table 1. Sonic velocity properties.*

Leaman (1975a) also states that prior surveys had suggested a velocity of less than 1500 m/s for some river silts.
CHAPTER 3  MAGNETIC SURVEY

Field Work

2001
The survey was conducted over three days (the 19th, 20th and 21st) in March 2001. East-west lines at 300m line spacing were surveyed, with navigation by differentially corrected GPS. North-south tie lines were also surveyed. Diurnal corrections were applied using a base station record collected at the Tasmanian Aquaculture and Fisheries Institute (TAFI) labs at Taroona with the EG&G Geometrics G856X magnetometer. The roving magnetometer was a GEM Systems GSM-19 Overhauser magnetometer. Both of these instruments measure total magnetic intensity (TMI). The GSM-19 was set to fast sampling auto mode with a one-second sample interval. At boat speeds up to around 40km.hr\(^{-1}\), this equates to a maximum spatial sampling interval (along line) of around 11m. The vessel used for the data collection was the \textit{FMV Nubeena}, an aluminium monohull approximately 16 feet long.

![Figure 3.1. The FMV Nubeena at North West Bay.](image)

The GSM-19 sensor would normally be mounted on a pole attached to a backpack and used on land. For this survey we mounted the sensor on a long aluminium pole, which was
then lashed to the vessel. When mounted in this fashion, the magnetometer sensor extended several metres from the front of the boat. The sensor itself and the cable connections were wrapped in plastic and sealed so they would be watertight, to protect against spray, rain and possible dunkings.

2000

Magnetic data were collected in 2000 as part of a trial survey – the instruments were the same as for 2001, but a slightly smaller vessel was used. The survey lines were not regular as in 2001, see figure 3.2 (next page, also figure 3.8 page 38). Bathymetric data were not collected in 2000, but were collected in 2001 (see chapter 8). The survey was run from the 25th of August to the 28th of August.

Figure 3.1.2. The FMV Poolta (another TAFI research vessel), with the GSM-19 magnetometer mounted in place and sealed for water-tightness. Note that the pole is not fully secured in this photo. An identical mounting method was used on the FMV Nubeena.
Figure 3.2. Location map of all magnetic survey lines for both the 2000 and 2001 surveys. The 2001 lines are east-west and north-south (ties) and the 2000 lines are north-east and north-west.
Space Weather

The purpose of collecting magnetic data from a geological perspective is to gain an insight into the sub-surface distribution of magnetic susceptibility. This can then be combined with geological knowledge to produce an interpretation of rock type distribution and geological structure. This means that we, as geologists, are generally only interested in magnetic fields associated with the geology. Naturally occurring fluctuations in the earth’s magnetic field due to non-geological sources need to be removed from our data in order to ensure we are only considering the magnetic fields associated with the geology (and the main field of course). Such fluctuations can be generated by thunderstorm activity and by ionospheric currents resulting from the interaction of the solar wind with the ionosphere.

Occasionally, solar activity increases and the solar wind flux increases accordingly. A peak of solar activity occurs approximately once every 11 years. This heightened solar activity can result in abnormally strong ionospheric currents – producing auroras and interfering with geophysical techniques. Techniques that can be affected by these currents include some electromagnetic methods and magnetics. The magnetic expression of abnormal ionospheric currents is a component of magnetic intensity that varies rapidly, both spatially and temporally. It may have large amplitudes (i.e. greater than the geological component). Such variations cannot typically be removed from survey data by a diurnal record due to their rapid spatial variation.

A period of heightened solar activity occurred during the magnetic survey in 2001. Fortunately, the most extreme fluctuations occurred during the night rather than during the day when the data were being collected.

IPS Radio and Space Services (a division of the Federal Government Department of Industry Science and Resources) maintains a magnetic gradiometer in Hobart that measures the horizontal and vertical field components (plus the declination) every second, on a continuous basis.
The horizontal field component as measured by the IPS gradiometer is shown in figure 3.3 as a function of time. Note the relatively low frequency, low amplitude variation towards the left of the chart (0 to 48 hours), and compare this to the high frequency, high amplitude variation later in the week (commencing at around 64 hours) associated with the storm activity. Although the amplitude of variation is fairly high it is relatively systematic, and therefore could be removed using a base station record. The base station record for day 3 shows nearly 500nT variation in total magnetic intensity (TMI) – this is nearly an order of magnitude more than “normal”.

Figure 3.3. The horizontal magnetic field component as measured by the IPS gradiometer (see text) for around four days from the 18th to the 22nd of March 2001. Boxes indicated approximate survey times.
Figure 3.5 shows the base station (G856) record for the 21st of March. Note the large but systematic variation in TMI. If the survey had been conducted several hours later or earlier on the 21st, the data might have been terminally corrupted by the magnetic storm. At one point it looked as if the survey might need to be postponed, but fortunately this was not necessary. Clearly, this survey was an example of a near miss and demonstrates the prudence of checking the space weather forecasts!

**Data Processing**

Typically, geophysical data requires some processing before they can be used constructively. For magnetic data, this might include diurnal corrections and various forms of data editing such as tie line levelling. The data for both the 2000 and 2001 surveys was diurnally corrected, but more processing was required before it could be used.

One of the problems associated with the 2001 magnetic survey data was the relatively large numbers of “drop-outs” experienced when the swell was strongest (on the 20th). As mentioned, the sensor was mounted on a rigid pole. Although the pole was lashed down as tightly as possible, during heavy swell conditions the pole would occasionally lift slightly and then slap on the deck. The jarring induced by this slapping caused the signal to drop...
out. After day 2, the pole was padded to reduce the number of drop-outs and the data quality improved noticeably.

Fortunately, drop-outs are relatively easy to remove from the data because they are always negative, and have relatively high frequencies compared to most geological features (often the drop-out is only a single sample). The aeromagnetic processing program ChrisDBF was used to remove drop-outs from the raw survey data. This program enables the use of linear or cubic-spline interpolation for profile editing. Rarely, it was difficult to determine whether a particular negative excursion on a profile was geological or a drop-out, so some subjective data editing occurred. Examples of raw and edited profiles are shown below. Some drop outs were also present in the 2000 data, and these profiles were also edited.

Figure 3.6. Line 5400, prior to drop-out editing. Note the high frequency, negative excursions superimposed on the otherwise low frequency profile. These negative excursions are drop-outs.
Figure 3.7. Line 5400, after drop-out editing. Note the removal of the high frequency negative excursions.

The final gridded dataset is shown as a series of maps on the following pages. The regional dataset is also shown (for comparison).
Figure 3.8. Profiles of total magnetic intensity for selected traverses from the 2000 and 2001 surveys. Note the extremely high amplitude anomaly near Betsey Island.
Figure 3.9. Location of gridded magnetic traverses - i.e. the traverses from the 2000 and 2001 surveys used to create the grid of total magnetic intensity shown in figure 3.10 (page 40).
Figure 3.10. Image of TMI from gridded data (2000 and 2001). Grid cell size is 50m; units are nanoTelsas (nT). The grid was interpolated using a spline algorithm and 650m scan distance in ChrisDBF.
Figure 3.11. Image of TMI from regional grid. Units are nanoTelsas (nT), base has been subtracted. Note the lack of resolution compared to the new data (figure 3.10)
Figure 3.12. Contours of total magnetic intensity generated from the gridded magnetic survey data (see figure 3.10 for a false colour image of the grid). Units are nanoTelsas.
One of the difficulties associated with deploying a magnetometer from a marine platform is the ferrous material (ie. iron) associated with the platform. Unless the scale of operation is very small (ie. a rowboat or canoe) some iron will almost certainly be present, particularly in the boat engines. Although the sensor is mounted away from the boat, a component of magnetic intensity measured at the sensor is due to the vessel. Furthermore, the measured component varies according to the orientation of the boat. This is because the main field of the earth (the \textit{inducing} field) is a vector field, and the induced magnetic field associated with a susceptible body will be aligned with the main field even if the body is rotated. So as the boat changes direction, the measured component of magnetic intensity due to the boat changes.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{image.png}
\caption{Image of TMI calculated for a sphere of magnetically susceptible material (see text). Colours indicate relative intensity (red = high values, blue = low values). North is grid north. The anomaly peak is not centred on the causative body because of the declination (14°) and inclination (-72°) of the inducing field.}
\end{figure}

Figure 3.13 shows the magnetic response of a sphere of susceptible material of one metre diameter, and 0.1 SI units susceptibility (the black dot). The image has extents of around 30 by 30 metres and the inducing field has a magnitude of 62000nT. The induced magnetic response associated with the sphere is mildly asymmetric, and the maximum is displaced...
relative to the centre of the sphere (these effects would be more significant at lower magnetic latitudes). If we imagine that this sphere represents the motors of the FMV Nubeena, and the black circle represents all possible sensor positions (relative to the motors), then we can see how the sensor will measure different field strengths associated with the motors depending on their relative positions.

We can quantify this in terms of field strength as a function of angle -- ie. the angle of the long axis of the boat relative to a datum angle, such as magnetic or grid north. The long axis of the boat is used to calculate the angle, because the bulk of ferrous materials (ie. the motors) and the sensor are mounted in line with this long axis. Furthermore, the boat travel direction (expressed as an angle relative to north) is the same as the angle of the long axis of the boat, assuming the boat is moving forward along line, which it was at all times during data collection.

Since the interest lies only in the magnetic response of the rocks (and not of the boat, or magnetic storms!), it is useful to correct for effects such as the one described above. This requires a heading test, which is a means of quantifying the effects of the orientation of the deployment platform. It is done by rapidly sampling the magnetic field, while slowly rotating the deployment platform relative to the sensor, which should remain in a fixed position throughout the test. In this case, the test was performed by driving the boat into shallow (knee-deep water) and raising the motors. The sensor was held firmly in place while the boat was slowly pushed around the it. Several rotations were performed and a GPS record was obtained simultaneously. Note that the sensor remained attached to the mounting pole throughout this exercise.
Figure 3.14 shows the raw heading test data, plotted as a function of time. The data was diurnally corrected using the base station record prior to any further processing. There are nearly three full boat rotations shown here – note the periodicity of change in orientation with time (in this case, a proxy for angle). The variation in intensity with boat orientation covers a range of around 22nT.

It is useful to conduct the test in an area with low magnetic gradients, so any inadvertent lateral movement in the sensor does not significantly impact on the results. Our heading test was performed in the northern end of North-West Bay, where the gradients are relatively low. Unfortunately the test was not performed with the FMV Nubeena, but with the FMV Poolta instead. The Nubeena had been decommissioned by the time we performed the heading test. This will have some influence on the applicability of the heading test to the data collected with the Nubeena, but both vessels have motors of similar size and design so the difference should not be substantial. Both vessels are constructed of aluminium and carry little ferrous material apart from that in the motors.
Figure 3.15 shows the diurnally corrected heading test record and northing from the GPS log. The GPS positions could not be differentially corrected because we couldn’t receive the differential beacon signal, so the resolution is poor. This lack of resolution means that direct calculation of the boat orientation from the GPS record would not provide a satisfactory result. Further, this method would mean that estimates regarding the absolute sensor position and sensor-GPS antenna separation would be required – these could not be made (without significant errors) from this GPS log.

Fortunately there is another way to calculate the angles without reference to the GPS log. Theory dictates that the maximum response due to the boat motors would be experienced with the sensor due north (ie. magnetic north) of the motors. This is also demonstrated from the calculated response due to the sphere shown earlier – the peak response of the anomaly is offset to the north by the inclination, and to the east (away from grid north) by the declination of the main field. Given this, it is possible to assign angles to the measured response based purely on the amplitude of the magnetic field. The method used involved calculating a sinusoidal function of angle, and fitting it to the measured response over one rotation interval. It was not possible to fit the function to multiple rotations simultaneously because they were performed at different speeds, meaning phase differences became significant.
Figure 3.16 shows the results of fitting a calculated curve to the observed data. The fit was calculated over the interval 280 degrees to 640 degrees (one full cycle), and this region was used to produce the look up table of correction as a function of angle. Note the phase difference between the calculated and observed curves for the other cycles due to the difference in rotation speed. Although the angles were only calculated from the one cycle, the amplitude of the sinusoidal function was chosen by assessing all three rotations. The advantage of using the sinusoid is a regular and rapid sample interval, and the elimination of high frequency noise. The variation between the measured and calculated responses is never more than 2nT (~10%) over the fitted interval and typically much less. The measured response shown in figure 3.16 is in a diurnally corrected but raw state – if it had been used to apply the corrections (rather than the calculated response), it would have required filtering to remove some of the high frequency variations. The filtering process would have produced an output which would more closely approximate the calculated response than the raw observed data does (in terms of RMS error).

Once the look up table of correction as a function of azimuth was calculated, a Fortran 77 program *(heading)* was written to apply the heading test corrections. This program uses publicly available subroutines to interpolate (using cubic splines) a correction for any arbitrary angle based on the look up table values. Angles relative to grid north were
calculated using the arctangent of the change in northing: change in easting ratio, and then corrected for declination. The source code for this program (head.f) is at appendix 2.

Once the diurnally corrected, drop-out edited data was heading test corrected, it was re-gridded. The same heading test corrections were also applied to the magnetic data collected in 2000, which used a different vessel again (but still aluminium, with twin two-stroke outboard motors).

Although the variation in magnetic intensity due to boat direction changes is small relative to the larger geological variations – tens of nanoteslas compared to thousands of nanoteslas – the heading corrections did result in a noticeable reduction in data striping in regions of low magnetic gradients, and improved the meshing of the two surveys (note these had different survey line orientations – east/west for 2001, and dominantly north-east/south-west for 2000).

On that note, it is worth mentioning the variation between the two surveys. The magnetic data collected in 2001 was of generally good quality, with regular line spacing and orientation. The data collected in 2000 was of considerably lesser quality, with irregular line spacing and orientation. The two surveys do not mesh together well. To demonstrate this, I have selected a line from the 2000 survey that crosses several lines from the 2001 survey. I checked the measured TMI at the intersection points after heading test corrections and drop out editing, and plotted the difference in TMI between the 2001 survey and 2000 survey for each intersection point. The results are shown below.
The 2000 survey does not grid well in an unmodified form (i.e., it requires significant levelling), and even after removal of some of the 2000 survey lines the combined grid of both surveys is low quality in the northern section (where there are no 2001 data). For this reason, the image and contours generated from the grid appear "noisy" in the north. The interpretation and models from the northern portion of the study area are also less reliable as a result, even though the heading test corrections did improve things somewhat.

The gridded images (and contours generated from the grid) were generated using ChrisDBF. The grid has a 50m mesh, and was made using a spline interpolation algorithm with a scan distance of 650m.

Figure 3.17. Not only is the difference in TMI inconsistent across the different lines, it also covers a very large range: from $-391\text{nT}$ to $221\text{nT}$, or a total of $612\text{nT}$! I can only attribute this massive discrepancy to poor data quality for the 2000 survey.
CHAPTER 4 MAGNETIC MODELING

Introduction

One of the great advantages of potential field data (magnetics and gravity) is the availability of modeling programs that enable real time calculation of complex model geometries. One of the great downfalls is that it is virtually impossible to find a unique model solution for any given real-world potential field measurement. It is vitally important to constrain models as tightly as possible by utilising existing geological data such as outcrop locations, and by using realistic petrophysical properties measured either on the rocks whose geophysical response is being modelled, or by equivalent rocks from nearby areas. If possible, combined interpretations of magnetics and gravity are preferred to interpreting one in the absence of the other.

In this case, there are no hardrock core logs south of the Tasman Bridge and no gravity data is available, so the modeling performed on the magnetic data is poorly constrained. I have used realistic magnetic susceptibilities and remanent magnetisation intensities, but the magnetic properties of the Tasmanian dolerites and basalts overlap significantly (see chapter 2).

Potential field modeling should, ideally, be constrained according to the five criteria described by Leaman (1994). He states that acceptable solutions should:

1. Honour geologic or other control
2. Not contain discontinuities in geometry or properties that are not justifiable
3. Use rock properties (i.e. magnetic susceptibility, density) that are within known ranges or that can be inferred from the data
4. Be based on several interlocking profiles across the data set
5. Have a consistent (or correct) base level for the entire data set

I have attempted to meet these criteria where possible, but the particulars of my study have meant that criterion 1 has little meaning, and I have not met criterion 4 due to the difficulties associated in modeling along strike using 2D models (where the ‘infinite extent perpendicular to section’ approximation does not apply).
Sensitivity Testing

Sensitivity testing is a means of assessing the suitability of various model solutions during forward modeling of potential field data. A sensitivity test can be performed by varying a model parameter and assessing the change in fit between the observed and calculated data. The sensitivity can then be assessed by plotting the (systematically varying) model parameter against a measure of the model fit (such as RMS error).

Figure 4.1.1. In this example, the parameter being varied is magnetic susceptibility. This is for a small section of the 2001 data, modelled as a sill. In this case, the sill is modelled as being 200m thick, and with a depth-to-top of 350m. The RMS error reaches a minimum at a susceptibility of around 0.024 SI units – this is the susceptibility that produces the best model fit for the specified geometry.

The model sensitivity is approximated by the slope of the sensitivity function adjacent to the minimum. If the function has a shallow slope adjacent to the minimum, this means that a small change in the modelled parameter has only a small effect on model fit, and therefore the model is not very sensitive (to changes in that parameter). On the other hand, if the function has a steep slope adjacent to the minimum, then a small change in the modelled parameter will have a large effect on the model fit, and therefore the model is highly sensitive (Roach, 1994).
In general terms, a highly sensitive model solution is preferred. This is because highly sensitive solutions permit only a small range of feasible properties and geometries compared to insensitive solutions.

Of course, for complex models or where geological constraint is poor, the sensitivity testing method described above is inadequate. This is because of the multi-dimensional nature of the sensitivity functions. For example, model fit will typically be influenced by body geometry (shape and orientation), body size and susceptibility. For a simple body (e.g., a dyke), this could be broken down to: depth to top, width, dip, strike extent and susceptibility (i.e., five parameters). Testing of each parameter individually, while keeping the others constant, would be unfeasibly time-consuming.

To illustrate the sensitivity of my models (actually, the lack thereof), I have conducted limited sensitivity testing on a geologically simple section. I deliberately chose a transect that could be modelled effectively with one* simple body. This section is from the southern portion of the field area, and can be modelled reasonably well with a single sill of dolerite (*plus one other body almost off section that was not varied at all). I calculated
sensitivity functions for various sill thicknesses, depths and magnetic susceptibilities. The results are shown below.

![Figure 4.1.3. Sensitivity test results A – constant magnetic susceptibility. See below for discussion.](image)

![Figure 4.1.4. Sensitivity test results B – constant depth to top. See below for discussion.](image)

The sensitivity function curves shown above indicate two things. Firstly, since the slopes of individual curves are all relatively shallow adjacent to their respective minimum, there is a range of feasible values for each parameter for each model. Secondly, the minimum
for adjacent curves have similar values – so the model fit for a 200m thick sill at 350m depth and with a susceptibility of around 0.0225 SI is equivalent to that for a 400m thick sill at 350m depth with a susceptibility of around 0.013 SI. Equally, both of these solutions are equivalent to that for a 300m thick sill at 400m depth with a susceptibility of 0.018 SI and so on. Furthermore, all of these solutions are geologically feasible and none can be disregarded based purely on geological arguments. It is also perhaps worth re-iterating here that this is a particularly simple model (effectively only one magnetic source), and that in terms of body geometry, only the thickness was varied in this testing. When more complicated shapes are modelled, the range of available solutions increases. We can generalise by saying that: since there is effectively no geological control for the lower Derwent Estuary, and there is a wide range of magnetic properties for the materials that are likely to be present, the modeling results should be regarded with caution.

Another way of considering the equivalence of varying model solutions is by constructing models with equivalent model fits but varying source geometries and/or properties (Roach, 1994). The following four models are all constructed with uniform model susceptibilities – only the geometries change.

Figure 4.1.5. Example #1 of alternative model geometries producing equivalent observed responses.
Figure 4.1.6. Example #2 of alternative model geometries producing equivalent observed responses

Figure 4.1.7. Example #3 of alternative model geometries producing equivalent observed responses
Figure 4.1.8. Example #4 of alternative model geometries producing equivalent observed responses

Note that no serious attempt has been made to fit the data over the 0-2000m interval—some sources influencing this section of the data probably lie off section.

All of these models are geologically possible, although some are perhaps more likely than others. Although some of the solutions are similar in general body form, they differ in terms of depths, thicknesses and detailed shapes.

Finally, although I have been emphasising that a range of possible solutions exists for any particular potential field model, I still believe that forward modeling is a useful interpretive tool. Although the models shown above do differ in detail, the gross form of the modelled geometries are reasonably similar, particularly in lateral extent. Since this modeling is used to help with geological interpretation, the lateral extents of bodies is important since the geological map is presented in plan view. The models also enable us to make estimates regarding the range of potential depths-to-top, and are useful in terms of defining fault or contact positions and possibly fault dips etc.
Modeling

As I have been emphasising, the magnetic models are poorly constrained and should be taken as indicative only. I have used estimates from these models to suggest the depths of some interpreted magnetic bodies on the geological interpretation (see chapter 9), but these depth estimates are based on assumed body properties and therefore could vary significantly (if the actual body properties are different to the modelled properties). They do, however, provide relative depth estimates for different bodies because the bodies are generally modelled with the same susceptibilities and basic forms. This enables some sense of relative block displacement (i.e., fault movement) to be gained.

Most of the models I have shown have a good fit between the calculated and observed data—this does not imply they are correct, even if they appear plausible geologically. The models that do not have a good fit are from areas where the assumptions used in the modeling break down, i.e., from where the geology cannot be approximated by two or two-and-a-half dimensional models. In these cases, sources that have margins just off section or are entirely off section influence the observed response. On selected sections I have modelled bodies that occur off section—their bodies are shown in solid colours. I did not perform any regional/residual extraction prior to modeling.

I cannot determine the distribution of the non-magnetic lithologies from my models and in general I do not know this independently, so it would be misleading to include sediments or sedimentary rocks on my modelled sections. For this reason, I have only shown the magnetic bodies on the model profiles. I have added some approximate fault positions and displacement sense indicators on the profiles. In terms of general presentation, dolerite is shown in orange and basalt in grey.

Apart from that, the sections really require no further explanation—they are all very simple. The inducing field for all model profiles has a intensity of 62000 nT, inclination of -72° and declination of 0° 14.

Note that traverses 13 and 7 are not shown, although they do appear on the location map.
Traverse 1. Figure 4.2
Traverse 2. Figure 4.3
For Help, press F1

Traverse 9. Figure 4.9
In Traverse 10, Figure 4.10, the graph illustrates the magnetic field strength in nano-Teslas (nT) against distance. The magnetic field values are depicted on the y-axis ranging from -160.0 to 160.0 nT. The horizontal axis represents distance, with markers at 0, 2000, and 4000 units. The data points show fluctuations in magnetic field strength, with some peaks and troughs indicating variations in the field. The graph also includes annotations for specific locations, such as 'Suse = 0.03000' and 'Rem H = 0.00', which highlight particular measurements or observations at those points.
Traverse 11. Figure 4.11
Traverse 12. Figure 4.12
Figure 4.14. Location map for modelled magnetic traverses. Although the locations of traverses 13 and 7 are shown here, the modelled sections have been omitted.
The seismic source used for the Derwent Estuary work was an EG&G Geometrics Uniboom “boomer” operating at 200J and 4Hz. As with all types of seismic reflection surveying, source selection is a trade off between resolution and depth of investigation. Depth of investigation is dependent on both the properties of the materials under investigation and the frequency content and amplitude of the source pulse. Higher amplitudes and lower frequencies provide greater depth of investigation, but at the cost of resolution. High frequencies provide better resolution, but with reduced depth of investigation. Chirper systems are designed to get around this limitation by using a linear frequency modulation sweep (eg. from 2 kHz to 16 kHz), but these systems are less readily available at low cost. The survey specifications (and budget) are typically the controlling factors in the choice of source.

The boomer plate was mounted in a catamaran and powered by a 6.9kVA petrol generator. The boomer source consists of a coil of wire mounted in a rigid, non-conducting medium (eg. epoxy resin) that sits flush with an aluminium plate. A high voltage discharge from the power source energises the coil, and the magnetic field associated with the electrical flow in the coil induces eddy currents in the aluminium plate. The eddy currents induce magnetic fields which oppose those produced in the coil, and the aluminium plate sharply pushes away from the coil – producing a short, broad spectrum pressure pulse.

The seismic equipment was hired from the University of Sydney, and operated by Mr. David Mitchell (the seismic technician from USyd).
The receiver array consisted of a hydrophone streamer (or “eel”) containing ten hydrophones wired in series, inputting to a single channel analogue recorder with output onto electrostatic paper. The paper record has time (ie. along line time) on the horizontal axis, and two-way time (a proxy for depth) on the vertical axis. The source-receiver offset was around 4 metres. Time varying gain and uniform ‘trace’ amplification with clipping were applied prior to output. A bandpass filter with a low cut frequency of 700Hz or 1.5kHz and a high cut frequency of 5kHz was also applied, with the low frequency cut off being changed as required. Navigation was via Ashtech and Garmin 48 GPS systems, without differential corrections.

Seismic Terms
At this point it is worth introducing some terms for those not used to seismic data. In terms of seismic profiling, a reflection is a return of transmitted energy from a physical boundary within the earth. A reflection can only occur at a boundary between two substances with differing acoustic impedances. The acoustic impedance (AI) of a material is the product of the sonic velocity (the speed at which the sonic pulse travels through the material) and the density of the material. The proportion of energy transmitted and reflected at any particular boundary depends on the AI contrast across the boundary. More energy will be reflected if there is a large AI contrast than if there is a small AI contrast. We can quantify this using...
the reflection coefficient and the transmission coefficient. These coefficients give the proportions of energy reflected and transmitted (respectively) at a particular boundary.

![Image of hydrophone streamer](image)

*Figure 5.2. The hydrophone streamer (eel) trailing behind the boat. A bamboo outrigger was used to move the streamer out past the boat wash.*

The paper record was regularly time stamped, and positions were referenced from the GPS logs (see appendix). With the system operating at 4Hz, the maximum recorded two way time was 0.25 seconds, but typically the record is interpretable for a maximum of around 0.125 seconds.
The seismic survey lines were not pre-planned in detail, and are not on a grid as such. See the trackpaths map for traverse locations. The vessel used for the main seismic survey in 2001 was the *FMV Mallanna*, an aluminium sharkcat approximately 16 feet long.

A preliminary seismic survey using the same equipment (but a slightly smaller boat) was carried out over 3 days in August 2000. The trackpaths map shows the locations of the traverses for this trial survey. A small two-boat survey was also carried out at the Bridgewater mudflats prior to the commencement of the 2001 survey – although I have not interpreted any of the data collected near Bridgewater, I have shown the line locations on the trackpaths map. This survey was conducted as part of the proposed gas pipeline site investigation. Two boats were required due to the very shallow water at this locality – each boat carried half of the equipment.
Figure 5.4. The FMV Mallanna, with Mr. David Mitchell on board.

Figure 5.5. The two boats used for the Bridgewater survey.
Figure 5.6. Seismic trackpaths map showing locations of all seismic reflection profiles (2001 and 2000 surveys).
Acoustic Turbidity

It quickly became apparent during data acquisition that a large portion of the Derwent Estuary was characterised by a shallow subsurface with acoustic properties that we had not expected. Rather than seeing clear, coherent reflectors at most locations, we observed expansive zones of chaotic reflections (noise-like) that appear as dark smears on the seismic record. These zones tend to have sharp lateral boundaries, so the transition from coherent reflections at large two-way times to loss of detail is essentially instantaneous. These zones typically appear to extend to the seafloor, but sometimes have a thin veneer of sediment overlying them. Rarely, they terminate vertically at a horizontal reflector. The vertical extent of these zones is difficult to judge in almost all cases – it is exceptionally rare to find a coherent reflector beneath them. This could mean one of two things – the zones could be quite thick, or they could be relatively thin but their acoustic properties prevent the imaging of the underlying reflectors. I consider the latter scenario more likely, for reasons that will become apparent.

The Basalt Theory

As mentioned in chapter 2, there are a number of basaltic volcanic centres known around Hobart including some bordering the Derwent Estuary (eg. at Blinking Billy Point in Sandy Bay). It was initially suggested that the zones of chaotic seismic response could be due to the presence of basaltic lavas and associated rocks within the stratigraphy. A large acoustic impedance contrast would exist between hard basalts and soft sediments, and it was thought that this could be sufficient to prevent the propagation of the seismic signal through the basalt (ie. it would all be reflected off the upper surface of a flow). This suggestion has a reasonable theoretical base, and would explain the inability of our seismic system to image reflectors beneath the upper surface of the zones of chaotic response. It was also favoured because a general co-incidence between the areas of unusual seismic response and regions of anomalous magnetic intensity had been noted. This correlation was not perfect, but several factors combine to suggest that it need not be. Firstly, some of the Tertiary basalts are effectively non-magnetic. Secondly, a thin sheet of magnetically susceptible basalt might be enough to degrade the seismic signal but not be detectable by the magnetometer with sensor heights typically greater than 15m above the seafloor. Forward modeling confirms that with a susceptibility of 0.02 SI units, a 5m thick sheet of
basalt at 15m depth (with an inducing field of 62000nT, declination 14° and inclination – 72°) produces negligible magnetic response, assuming thinning margins. Finally, where the magnetic field is anomalous but the seismic response is not, we could argue that the magnetic sources are buried below the depth of investigation of the seismic signal.

Figure 5.7. The magnetic response of a 5m thick sheet of basalt (see text for discussion). Note scale on TMI axis – this is typical of the scale for the profiles extracted from the Derwent Estuary magnetic grid.

These arguments do not explain some features associated with the anomalous seismic response. Firstly, we observed that it typically occurs in the deepest portions of the river. Secondly, the upper surface of the anomalous zone is always restricted to the shallow subsurface – it does not occur deep within the stratigraphy. Thirdly, the lateral margins typically have coherent reflectors dipping into them – suggesting that whatever causes the anomalous seismic response was emplaced into low relief areas of the palaeotopography. These factors can be explained in terms of the basalt theory using the following arguments. High temperature, fluidal basalt lavas typically flow freely under the influence of gravity, and are often emplaced along topographic lows. This explains why we see the ‘basalt’ in channels, and may explain why it occurs in the deepest portion of the river – i.e. perhaps the modern channel profile records Tertiary/Pleistocene relief. Alternatively, erosion could
have removed poorly consolidated post-basaltic cover to expose the more resistant lavas — this could also explain the first observation.

**Disproving the Basalt Theory**

These arguments are all reasonable and plausible geologically, but are not necessarily correct. To answer the question regarding basalt, it was necessary to consult the core logs. As mentioned, no deep coring has been performed in the Derwent Estuary except as part of the studies regarding the two bridges — the Bowen Bridge and the Tasman Bridge. Although these were outside the principal study area, seismic profiles were recorded alongside both of these bridges. The profiles from both bridge sites contain zones of the anomalous seismic signal. At the Bowen Bridge site, basalt occurs adjacent to both abutments. However, *no basalt was intersected in any of the bore holes*. At the Tasman Bridge site, basalt was intersected in over half of the bore holes, and occurs beneath the zone of anomalous seismic response. However, the basalt at the Tasman Bridge occurs deeper in the stratigraphy — *well beneath the upper surface of the acoustically anomalous zone*. In both cases, the anomalous seismic response begins at a two way time that places it *within the youngest, fine grained sediments of the section*. Clearly, the anomalous seismic response that had been observed was *not* due to basalt within the stratigraphy. Furthermore, although the youngest muds extend right across both sections (with laterally varying thicknesses), the anomalous acoustic response does not. Yet no change in sediment characteristics is noted on either section at or near the boundaries of the anomalous seismic response. This suggests that the property of the sediments causing the seismic signal degradation was not apparent to the core loggers.

**The Evidence for Shallow Gas**

Obviously, this raised the question: what property of the fine grained sediments might be causing the seismic response that we had seen? One clue came from Colhoun and Moon (1984), who noted that at the Bowen Bridge site the uppermost formation of massive estuarine clays is “rich in colloidal organic matter (10-22.5%)” (page 224), suggesting an organic process could be responsible. After studying the literature and the data, I have formed the opinion that the observed seismic response of the acoustically chaotic portions of the Derwent Estuary can be explained by the presence of disseminated gas bubbles.
within the sediments. The seismic evidence for the presence of gas is compelling, and is discussed below.

We can obtain a significant body of evidence for the presence of gas in shallow sediments from high resolution seismic data, and we can break this into two kinds of evidence — "direct" and "indirect" (Judd and Hovland, 1992). Direct evidence is the acoustic expression of physical phenomena associated with gas, and indirect evidence is the morphological and/or structural expression of the presence (or former presence) of gas. Firstly, I will consider the direct evidence.
Figure 5.9. Map of acoustic turbidity distribution as defined from the high resolution seismic profiles (for 2000 and 2001).
Acoustic Turbidity

Gas in shallow marine sediments can be expressed in a number of ways. One of the most common is as acoustic turbidity on high resolution seismic profiles. Acoustic turbidity is defined by Judd and Hovland (1992) as the scattering of acoustic energy by disseminated gas in fine grained sediments, recorded as dark smears on the seismic profile. Taylor (1992) and Yuan et al. (1992) define acoustic turbidity in a similar way, but extend the definition to include absorption effects as well as scattering. Bouma et al. (1987) do not use the term acoustic turbidity but refer to acoustical voids or wipe-out zones that they attribute to bubble phase gas occurrences in the shallow sub-bottom.

Acoustically turbid zones have been classified according to their morphology and other characteristics into three types (blankets, curtains and plumes) by Taylor (1992). The descriptions and examples of acoustic turbidity from the literature are strikingly similar to the acoustic response observed in the Derwent Estuary. The nature of the response (noise-like, but with higher amplitudes) is more satisfactorily explained by scattering and attenuation by gas than by a strong reflection from the surface of a lava flow. Both “curtains” and “blankets” occur within my data, although blankets are more common. The distribution of this acoustic turbidity is shown on figure 5.9.

Enhanced Reflections

Gas can also be manifested as enhanced reflections. These are the equivalent of bright spots in petroleum exploration seismic data, and result from the accumulation of gas in porous horizons e.g. in a sand layer beneath an impermeable clay. The accumulation of gas has the effect of lowering the acoustic impedance of any given sediment type compared to water saturated sediment, enhancing the reflection from the boundaries of the gas charged horizon. It is common to find enhanced reflectors extending from the margins of acoustically turbid zones (Judd and Hovland, 1992).

There are enhanced reflections present within my data, particularly extending into the edges of acoustically turbid zones. These reflections occur at the upper surface of the gas charged zones and I interpret them to indicate an increase in reflection coefficient due to a decrease in the acoustic impedance of silts caused by gas build up.
Acoustic Blanking

*Acoustic blanking* is a phenomenon characterised by faint reflections, or an absence of reflections on a record where gas is inferred to be present (Judd and Hovland, 1992). Blanking by itself is not sufficient to demonstrate the presence of gas, but in combination with other evidence such as acoustic turbidity, it can be used to infer the presence of gas. It can result from the mixing (homogenisation) of sediments by migration of pore fluid (i.e. gas) or by absorption without scattering in overlying gas rich sediments (Judd and Hovland, 1992). Acoustic blanking does occur in my data, but as I have mentioned this cannot be unequivocally attributed to the presence of gas.

Phase Reversals

If gas is present within a package of sediments, a *phase reversal* may be evident in the seismic data. This occurs when the energy pulse is reflected from an interface where the upper layer has a higher acoustic impedance than the lower layer (note that in the general case, acoustic impedance will increase with depth). Of course, gas charged sediment will tend to have a very low acoustic impedance (since gas will tend to lower both the bulk velocity and density of any given sediment type), so we could reasonably expect to see seismic phase reversals associated with gas. Phase reversals do appear to be present on some of my seismic profiles, but it is difficult to be certain in the interpretation of these features. Taylor (1992) states (in regard to ‘blankets’ of acoustic turbidity) that there is “...rarely any evidence of phase reversal at the upper surface of the feature.” (page 1140). Furthermore, attempting to pick a phase reversal from an *analogue* record can be difficult (James Tayton, pers. comm.). Nevertheless, where the acoustic turbidity has clearly defined margins and does not extend quite to the riverbed, I believe phase reversals can sometimes be detected.
Figure 5.10. Phase reversal example 1. See notes below.

Figure 5.11. These two small sections show possible phase reversals associated with acoustic turbidity. The white/black reflector change at the indicated positions is suggestive of a phase reversal (the analogue record represents different signal polarities with different shades). Note the ‘trapping’ of the acoustic turbidity beneath faint horizontal reflectors in these sections. In detail, the acoustic turbidity is marked on the upper surface by a strong reflection (black). This strong black line passes laterally into a white line approximately in the positions of the arrows. This signifies a lateral change in signal polarity, which in these cases is clearly associated with the edge of the acoustic turbidity. This may represent a phase reversal.
Gas Seeps
Sea floor gas seeps can be detected acoustically. These occur as dark smears within the water column on a high resolution seismic record (shoals of fish have a similar acoustic expression). Field and Jennings (1987) studied sediment destabilisation associated with earthquakes and provide example of seepages visible on high resolution seismic reflection profiles. Bouma et al. (1987) state that "Gas escaping through the water column can be clearly seen as vertical "V"s" on high frequency records such as 12kHz." (page 74). Numerous water column disturbances occur on the Derwent Estuary profiles that are not associated with speed, direction or gain changes. These water column disturbances show a strong spatial relationship with the zones of acoustic turbidity (see figure 5.15). At least some of these could be gas seeps.

Velocity Pulldown
A final physical phenomena associated with the presence of gas is velocity pulldown. Dobrin (1976) explains it in the following way: "The low velocity of gas saturated sand...gives rise to lateral anomalies...in the time required for seismic waves to pass through the sand." (page 348). It is recorded as an increase in two way time to all reflectors beneath a layer with elevated gas concentrations. Since variation in gas concentration affects bulk sediment sonic velocities, a lateral increase in gas concentration within a given layer will result in an increase in two way time for reflections from below the upper surface of the gas rich layer. There are excellent examples of pulldown on the Derwent Estuary profiles.

Indirect Evidence
Indirect evidence of the presence or former presence of gas comes from sedimentological and/or structural features that result from the migration or accumulation of gas. If observed on seismic profiles, the reflectors typically do not have unusual acoustic characteristics and could easily be interpreted as being formed by other processes if the interpreter did not realise gas might be present. Indeed, the interpretation of these structures is not always unambiguous even if the presence of gas is suspected or known.
Figure 5.12. This is an example of velocity pulldown and seepage. The dark targets in the water column are probably gas seeps (see text). The signal associated with the seepage is weakest at early two way times – this is due to the gas dispersing as it rises from the seafloor. The position of a curtain of acoustic turbidity is indicated by A. Reflectors B and C appear at earlier two way times away from the curtain, and appear at greater two way times directly beneath the curtain. This does not represent a change in the physical depth of the interfaces imaged as reflectors B and C, rather it is a result of a lateral change in gas concentration within the sediments. The gas concentration is greatest in the position of the curtain, so the bulk sediment sonic velocity is lowest in this position. This causes reflectors to be imaged at greater two way time beneath the acoustic turbidity curtain. Also see text for discussion of pulldown.
Pockmarks are depressions on the seafloor caused by the escape of a pore fluid – in most cases this pore fluid is gas. The pockmark is a result of the escaping gas removing the soft sediments (Hovland, 1982). The formation of pockmarks has been artificially induced by blow outs during drilling (Judd and Hovland, 1992). Pockmarks may be associated with other features, such as columnar disturbances. Although not abundant in my data, there are a few features that appear to be pockmarks, based on the examples reported in the literature.

Seabed domes may predate the formation of pockmarks – they are broad, low relief features possibly caused by the displacement of water by gas in pore spaces, resulting in an inflation effect. They have been associated with gas in several studies (Judd and Hovland, 1992). Columnar disturbances are columns of breached or disturbed reflectors, where the disturbances are attributed to the vertical migration of gas – these may occur directly beneath pockmarks (Hovland, 1982). Mud diapirs are bodies of plastically deforming, gas rich clay or mud that rise buoyantly and may penetrate the seafloor (Judd and Hovland, 1992). Both of these features are caused by the buoyancy of gas and assisted by low confining pressures of the shallow marine environment, and can be recognised on seismic profiles. There is no evidence for seabed doming, but there are disrupted reflectors where the cause of the disruption is not clear on the Derwent Estuary profiles.
Figure 5.13. This is an example of a pock mark (see text) from the Derwent Estuary.

Figure 5.14. This is an example of a pock mark and gas curtain from the literature (Taylor, 1992).
Clearly, the evidence for gas is strong based on the seismic record. Several features that are strongly suggestive of the presence of disseminated gas are definitely present within the data, and others are arguably present. But why does this gas affect the seismic signal?

The attenuation and scattering effects of acoustic signals by bubbles are complex, and only partially understood. Some of the significant factors include: occurrence (bubbles can occur wholly within the pore water between grains, they can displace grains, or they can enclose grains of sediment); bulk sediment shear modulus; bubble size distribution; bubble resonant frequency and acoustic frequency (Wilkens and Richardson, 1998). Suffice to say that the presence of gas bubbles can result in very rapid signal attenuation, with (frequency dependant) acoustic attenuation of hundreds to thousands of dB per metre possible for gas charged sediments.

These recent observations can also be used to help explain and reinforce the long-held view of Leaman (pers. comm., 2001) that the uppermost layer of silts within the Derwent Estuary have low acoustic velocities. The first suggestions that this was the case came during refraction seismic surveying as part of the site investigation for the second Derwent crossing study at Dowsings Point. During this survey, Leaman (1975b) deduced that the silt velocity was approximately 1050m/s. Note that the velocity of seawater is around 1500 m/s, and water saturated sediments would be expected to have velocities equal to or greater than that of seawater. The presence of free gas as bubbles within the sediment has the effect of lowering the bulk velocity significantly – Taylor (1992) states that as little as 0.1% gas (by volume) can lower bulk velocity by up to one third when compared with bubble free, water saturated sediment.

So then, what sort of gas are we are talking about, and where is it coming from? Several lines of circumstantial evidence suggest that if gas is present, it is likely to be biogenic in origin and being produced in situ by bacteria.
Water Column Disturbances

Figure 5.15. Map of water column disturbances as defined from seismic profiles. Note correlation between water column disturbance distribution and acoustic turbidity distribution (see text for discussion). Disturbances known to be side echoes etc are not shown.
As mentioned in the introduction, the modern Derwent River has deposited fluvio-deltaic mudflats near Bridgewater. At this location, the suspended fine grained sediment load of the river is flocculated by the interaction with salt water, and the resulting muds are rich in organic material. Since sea level has fluctuated significantly throughout the Pleistocene (down to around -125m below present twice in the past 250ky), deposition of similar material is likely to have occurred along most of the length of the (modern) Estuary at some point in the last 250,000 years (see appendix 1), providing a source of organic matter for biogenic gas production.

Secondly, there is a remarkable correlation between the bathymetry of the Estuary and the occurrence of the acoustic turbidity – the acoustic turbidity is confined to the deeper portions of the Estuary, particularly south of the Tasman Bridge. While this could be due to confining pressure associated with the deeper water retaining more gas within the sediments, it is more likely that it indicates the area of maximum gas production. This in turn is linked to the first point, regarding the accumulated mass of organic rich sediments (ie. the gas is being produced from channel fill sediments, deposited during periods of lower sea level – these occupy the deepest parts of the bathymetry). Okyar and Ediger (1999) noted a similar correlation between water depth and acoustic turbidity distribution and concluded that this was a reflection of sedimentation patterns.

Thirdly, we can compare the Derwent results to other shallow marine/estuarine sediments that display acoustic turbidity. Park et al. (1999) found that acoustic turbidity in the Korean Sea was likely to be due to the \textit{in situ} production of gas in recent muds, Okyar and Ediger (1999) came to a similar conclusion about acoustic turbidity in Pleistocene sediments of the Black Sea. Mullins et al. (1991) suggested the same cause for acoustic turbidity in the sediments of Lake McDonald in North America. Taylor (1992) states “...it would appear that there is a wealth of evidence for the presence of shallow gas in nearshore marine sediments around the U.K...”, but he goes on to state that acoustic turbidity in the estuaries of the Thames, Mersey and Forth is generally not associated with local structures (implying that it is more likely to be biogenic than thermogenic). And as a final point from the literature: “Most gas in surficial, shallow-water sediments is biogenic and originates from the generation of methane as a by-product of metabolism by methanogenic bacteria” (Richardson and Davis, 1998).
Finally, there does not seem to be a close spatial association between the acoustic turbidity and known structures - or structures inferred from the magnetic survey data - in the Derwent Estuary. This suggests that the gas causing the acoustic turbidity has not migrated up from deep within the basin, and is unlikely to be thermogenic. Equally, the gassy sediment is found in the Derwent Estuary - in a graben. Certainly there are large, deep rooted structures near the acoustically turbid zones, so it is perhaps misleading to suggest there is no spatial association with large structures.

In summation, there is no firm evidence regarding the origin of the gas in the shallow sediments of the Derwent Estuary. It is my personal opinion that it is probably biogenic, but I can not demonstrate this conclusively.

**Biogenic Methane Production**

The term 'biogenic gas' is used to refer to methane produced by bacteria. This is quite different to thermogenic gas, which is gas produced by the thermally driven decomposition of organic material. The bacteria that can produce methane all belong to the Archæbacteria group, and are unusual in that they are strictly anaerobic, albeit with varying toxic responses to oxygen (Floodgate and Judd, 1992). Although there are only a few species, the methanogens are relatively common in muds, soils, and the intestinal tracts of many animals (especially ruminants). Unlike thermogenic gas, biogenic gas production does not require the deep burial of organic material and usually occurs in the shallow subsurface. In relatively impermeable muds, available oxygen is quickly depleted by other bacteria and anoxic conditions may be achievable within millimetres of the surface (Floodgate and Judd, 1992). The methanogens can only produce methane from a limited number of substrates, including acetate, methanol and hydrogen+carbon dioxide, so other bacteria are required to break down polymeric organic substances to these simpler compounds. The terminal electron acceptor from the chemical reactions varies depending on the environment (which influences the available ions), but in brackish or salty water sulphate can be very important – leading to the reduction of sulphate to sulfide, and the production of hydrogen sulfide. Since the interplay between species is complex, and environmental conditions vary greatly it is very difficult to predict exactly which gases will be present in
the muds of the Derwent Estuary, except to say that methane is likely to be most abundant, and some carbon dioxide, hydrogen and hydrogen sulfide may be present.

<table>
<thead>
<tr>
<th>Dissolved Species</th>
<th>Water-Sediment (Biogeochemical zones)</th>
<th>Metabolic Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td>Photosynthesis</td>
</tr>
<tr>
<td></td>
<td>(photic zone)</td>
<td>Aerobic Respiration</td>
</tr>
<tr>
<td>O₂</td>
<td>Water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aerobic zone)</td>
<td></td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>Sediment</td>
<td>Anaerobic Respiration</td>
</tr>
<tr>
<td>HS⁻</td>
<td>(sulfate reducing zone)</td>
<td></td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5.16. Modified from Okyar and Ediger (1999) after Rice and Claypool (1981). Okyar and Ediger (1999) suggest that in cases where the upper surface of an acoustically turbid zone parallels the seafloor, the upper surface may represent the boundary between the sulfate and carbonate reducing zones. If this is correct, then methane and hydrogen will only occur as dissolved species below the upper boundary of the acoustically turbid zone.*

The distribution of acoustic turbidity has been found to vary with oxygen availability on a seasonal basis in some locations. For example, Muller (1976) reported that acoustic turbidity (detected with a 30kHz echosounder, capable of perhaps 1m sub-bottom penetration) became more widespread when the deep water became oxygen depleted. This is almost certainly linked to the anaerobic requirements of the methanogens.

Biogenic methane production and the processes associated with it can lead to carbonate precipitation. Measurements of carbonate concentration in shallow cores taken from the Derwent Estuary indicate generally higher values towards Storm Bay, and a zone of elevated carbonate concentration extending up the centre of the Estuary. This zone of elevated carbonate concentration is broadly coincident with the mapped gas occurrences.
and may in part reflect carbonate precipitation via processes associated with biogenic methane production.

The carbonate concentration map was kindly provided by Dr. Peter Harris from the Antarctic CRC at the University of Tasmania and is reproduced here with his permission. The suggested interpretation I have provided is my own, and in no way linked to Dr. Harris.
Figure 5.17. Map of carbonate distribution in the Derwent Estuary, provided by Dr Peter Harris. There is a general correspondence between the zones of higher carbonate values (20-30%) and the acoustic turbidity distribution. See text for discussion.
Simple chemical arguments dictate that if a gas is present as bubbles within wet sediment, then the aqueous interstitial fluid must be saturated with that gas. This deduction led to the development of the headspace analysis technique of Kvenvolden and McDonald (1986). The technique involves sealing a wet sediment sample in a gas tight vessel, heating to liberate dissolved gases, and analysing the "headspace" gas (i.e. the gas in the container—a mixture of air, water and any gases released from the sediment). A slightly modified version of this technique was applied to the sediment samples taken from the Derwent Estuary in an attempt to determine whether or not gas is present in the shallow sediments (as the seismic data suggests).

**Sediment Sampling**

Samples were collected along a single transect, from Cartwright Point on the western shore to just south of Tranmere Point on the eastern shore. This transect was chosen based on the seismic data, since the acoustic turbidity on the seismic profiles appeared to extend to the riverbed (to the resolution of the seismic system) in this area. The wet sediment samples were collected using the Craic corer belonging to TAFI.

This corer has a rope that is used both for deployment/retrieval and to raise a weight which drives the core barrel into the sediments. The core barrel is plastic and the system is suitable for obtaining short cores in soft sediments. Although the core barrel is around 30cm long, the cores obtained were at most 15cm long. Nine samples were obtained. Positions were obtained using a Garmin eTrex GPS receiver (no differential corrections applied).
The cores were immediately sub-sampled using a 50mL syringe with the end removed, and the wet sediment placed into modified borosilicate glass sample bottles. The bottles had holes drilled into the lids, with Suba seals glued into the holes using a silicon based adhesive. The adhesive was only applied to the outside of the lid, and allowed to cure for several weeks before the bottles were used. These modifications were made so the headspace gas could be extracted (by piercing the seal with a syringe). Since the samples needed to be heated prior to analysis, sample vessel design and material choice was important for several reasons: firstly, we needed to be able to heat the sample vessels without losing gas tightness; and secondly, we needed to be confident the materials used would not evolve light hydrocarbons on heating. A heating and cooling cycle prior to sample collection was performed as a precaution. Around 30mL of wet sediment was retained from each core, and the bottles have 100mL capacity.
Figure 5.19. Modified borosilicate glass sample bottles. The rubber Suba seal inserts in the lids are designed to allow the removal of gas with a syringe.

Typically, headspace gas analysis is performed using a flame-ionisation detector (FID) coupled to a gas chromatograph (GC). In this case, a FID was not available so a high resolution mass spectrometer (MS) was used instead. The GC-MS used was the Kratos Analytical Concept ISQ in the Central Science Laboratory. Analyses were kindly performed by Dr. Noel Davies.

All samples were analysed for methane, and calibrated against authentic standards so results could be reported in parts-per-million (ppm). The results are semi-quantitative at best, since the volume of wet sediment obtained was not consistent and cannot be easily quantified. Several samples were also analysed for hydrogen sulfide, but it was not detected (note that H₂S may have been present below detection limits). All except one sample contained elevated (with respect to a blank and fresh air) concentrations of methane. Results are summarised in table 2 below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Easting (m)</th>
<th>Northing (m)</th>
<th>Mass (g)</th>
<th>Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>529451</td>
<td>5246778</td>
<td>47.03</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>530048</td>
<td>5246987</td>
<td>13.42</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>530546</td>
<td>5246978</td>
<td>33.50</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>531050</td>
<td>5247073</td>
<td>36.83</td>
<td>52</td>
</tr>
<tr>
<td>5</td>
<td>531594</td>
<td>5247249</td>
<td>37.36</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>532102</td>
<td>5247469</td>
<td>49.30</td>
<td>106</td>
</tr>
<tr>
<td>7</td>
<td>532592</td>
<td>5247729</td>
<td>36.84</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>533064</td>
<td>5247862</td>
<td>37.77</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 2. Sample 1 is the only sample that gave an ambient methane concentration – all other samples have elevated concentrations of methane. Although the concentrations of samples 2, 8 and 9 are close to that of sample 1, Dr. Noel Davies considered them significantly different (pers. comm. 2001). Since sample 6 had by far the highest methane concentration, it (along with sample 4) was analysed for hydrogen sulfide, but no hydrogen sulfide was detected.

Sample 1 contained a high proportion of sand and shell material. Sample 9 was partly sandy and partly muddy, and the other samples were of uniform composition – dark grey mud.

The results tend to support the seismic evidence – an elevated concentration of methane is present in the shallow sediments of the Derwent Estuary. Relatively speaking, the highest concentrations (even when scaled for sample mass) occur in the central portion of the Estuary, with reduced concentrations near the riverbanks (this is in accordance with the acoustic turbidity distribution). Although it is impossible to generalise for the entire Estuary based on a single transect of the river, this sampling reinforces the seismic evidence for shallow gas in the Derwent Estuary.
Other Seismic Features

Because the seismic system had an analogue recording and printing process, typical seismic post-acquisition processing could not be performed. This precluded the use of techniques such as automatic gain control filtering or automated migration. While manual migration could theoretically be done, it is impractical to migrate even a small section of the data. One of the great advantages of automated migration is the suppression of multiple reflections. There are a number of multiple types in the Derwent Estuary data, but particularly problematic are the almost universal seafloor multiples. Seafloor multiples are characterised by occurring at exact two-way time multiples of the seafloor reflector. They are common because of the generally large acoustic impedance contrast between water and the seafloor and the large contrast between water and air. These impedance contrasts cause the energy to reverberate in the water column – up to four or five sea floor multiples may occur given the right conditions, but at least one is almost always present. Other multiple types that occur on the Derwent Estuary profiles are ordinary multiples from geological interfaces, and “peg-leg” multiples. These concepts are illustrated below.

![Diagram of primary reflection travelpaths](image)

**Figure 5.21. Schematic of some primary reflection travelpaths.** Note that although this schematic is shown with non-vertical incidence for clarity (and therefore assuming a significant source-receiver offset), the source-receiver offset for the boomer system was small – so the actual seismic travelpaths were largely vertical.
Figure 5.22. Schematic of some simple multiple reflection travelpaths. Although only one multiple is shown per reflector, it is entirely possible to have several multiples from the same interface. These multiples are common on my reflection profiles. The seafloor multiples occur because of the large acoustic impedance contrasts between water and air, and water and sediment.

Figure 5.23. This is a simple example of sea floor multiples (although there are other multiples present). Apart from the primary reflectors near the top of this section, most of the other reflections are multiples. There are two strong (and one faint) sea floor multiples in this section.
Figure 5.24. Schematic of some more complicated (pegleg) multiples. In these examples, the energy reverberates within layers of sediment (the Complex peglegs), or travels within a layer of sediment and reverberates in the water column. "Complex Pegleg 1" is shown as a dashed line for clarity only. These kinds of multiples also occur on the Derwent Estuary seismic reflection profiles.
Figure 5.25. This is an example of a peg-leg multiple that looks like an ordinary multiple. Beneath the broad zone of acoustic turbidity, there are two multiples (marked A and B). While these appear to be simply the first multiples of the seafloor (A) and the zone of acoustic turbidity (B), they are actually the first multiple of the acoustic turbidity (A) and a pegleg where the energy has reverberated once between the top of the acoustic turbidity and the seafloor (B). This can be demonstrated by looking at the two way times of the multiples with reference to the zero time line. If multiple A was in fact the seafloor multiple, it would occur at exactly twice the two way time of the seafloor. However, it actually occurs at a slightly greater two way time (i.e., twice the two way time of the top of the acoustic turbidity). The seafloor multiple in this case is very faint, and lies just above multiple A.
Figure 5.26. In this example of a pegleg multiple, the energy has travelled to and from reflector A and reverberated once in the water column. This means that the pegleg occurs at the two way time of reflector A plus the two way time of the water.
Figure 5.27. This is an example of a multiple interfering with the interpretation of primary reflections. The sea floor multiple is indicated by the positions of the arrows, and in the positions marked as A and B, the multiple occurs at the same position as primary reflections (and with similar strength and dip).
As previously mentioned, geological cross sections are available for the alignments of both the Tasman (Carey and Spry, 1961; also Trollope et al., 1965) and Bowen Bridges (Colhoun and Moon, 1984). The later Tasman Bridge section is slightly more detailed. The availability of these cross sections provided the possibility of conducting acoustic finite difference modeling.

Although I have seismic profiles from both alignments, the Tasman Bridge is more 'interesting' geologically, so it was chosen to be modelled. The section from Carey and Spry (1962) was used to construct the digital representation of the geology used for the models discussed below, although the section from Trollope et al. (1965) was also digitised (there were some difficulties getting the modeling program to accept the more complex section, so it was abandoned).

Figure 6.1 Part of the Tasman Bridge seismic profile, approximately corresponding to the modelled section. The seafloor profile is slightly different to the published cross sections, because of the Lake Illawarra. The Lake Illawarra was a bulk carrier that ran into pylon 17 of the bridge and forms the a lump in the deepest part of the water. The reflections in the water column are side echoes off the bridge pylons.
The finite difference modeling was undertaken to attempt to answer two main questions. Firstly I wanted to know if a low velocity, low density gas charged layer of sediment could produce multiple reflections from its upper surface. Secondly, I had observed that no reflectors were resolvable beneath the acoustically turbid zone on the seismic profile, but the geological sections indicated that there were a number of potential reflectors present (ie. boundaries between various sediment and rock types). I therefore wanted to know if those reflectors would be resolvable on the Tasman Bridge seismic profile if the silt was not highly attenuating.

The acoustic finite difference modeling was carried out using the sufdmod2 routine of Seismic Unix, a freeware seismic processing and modeling package developed by the Centre for Wave Phenomena at the Colorado School of Mines. This routine uses the traditional explicit second order differencing method. The input is a uniformly sampled two-dimensional velocity model (generated using the unif2 routine), and parameters such as the source position and runtime duration can be specified. The timestep is not user specified – the sufdmod2 routine automatically chooses a stable timestep.

As mentioned, the velocity/density model used by sufdmod2 is produced from the unif2 routine. The input for unif2 is an ASCII file containing x,z coordinate pairs defining points on boundaries between media. The boundaries are then constructed as a series of straight lines joining the coordinates as defined in the ASCII file. No boundary can contain more than 200 points, and the upper surface of the model must be flat. In my case, the model was constructed based on actual depths reported in the published Tasman Bridge geological section. The model was 766m long, and around 120m deep. The velocities and densities used fell within known ranges for the materials in question (see table 1), but without petrophysical data directly from the core logs the values used should be regarded as best estimates.
Figure 6.2. The input velocity model for the acoustic finite differencing. Although the velocities appear to increase monotonically with depth, I assigned a velocity of 1050m/s to the silt when building this model with uniF2 (i.e. less than the water, and less than it appears to have in this image). The uniF2 documentation does not indicate that velocities must increase with depth, but I assume that it must be a 'hidden' requirement. The 'distance' label on the top axis is not physical distance (the model is 766m long) – it is scaled automatically by the display subroutine (ximage).
Figure 6.3. The pseudo-high frequency model (see text). Note the scale difference on the vertical axis compared to the other models. This model has some unexpected 'features' - such as the noise at early times near both ends, and the low frequency event at around 1s towards the right of the profile. Since the model was calculated at 5m steps along a 766m input, there are 153 traces. To obtain distance, multiply trace number by 5.
Figure 6.4 The first model — the maximum frequency here is around 500Hz. Several multiples occur on this record, and the upper multiple obscures the primary reflections to some extent. However, some reflections can clearly be seen, and the base of the silt appears to be resolved.
Figure 6.5. This is a low frequency model (peak frequency of around 50Hz). Note that the seafloor is not resolved, and there are what appear to be several multiples. This model suggests that conventional oil-field seismic frequencies would be inappropriate for investigating the detail of the Estuary.

The sufdmod2 routine is able to calculate source point seismograms, and/or the responses from lines of vertical or horizontal seismograms. The geometry of the boomer seismic system is such that the output is effectively a series of closely spaced source point seismograms, since the source-receiver offset is generally small compared to the water depth, and the receiver array is short (several metres only). To effectively simulate the
boomer record, a series of source point seismograms were calculated at 5m increments along the model, starting at one end and "stepping" the source and receiver along together. A shell script was constructed to automate this process (see appendix). Once calculation of the individual source point seismograms was completed, the output files were concatenated in order of their positions on the model – creating a simulated boomer profile.

After the first high frequency model was calculated, it became apparent that the sufdmod2 routine was not performing the acoustic finite differencing with sufficiently high source frequencies, even though I had instructed it to use very high frequencies. The power spectra (calculated using the suspecfx routine) revealed the main frequency content was around 500Hz. This is typical of the maximum frequencies recorded for oil field exploration, but is considerably lower than recorded by the boomer system (as mentioned, the high pass cut applied during data collection was set at around 5kHz). Although the results were informative, source frequency is inversely related to depth of investigation. This means that by calculating the model with (relatively) low frequencies, the 'virtual boomer' output could potentially contain responses from deep reflectors that the actual boomer could not have imaged.

In an attempt to overcome the frequency limitation of sufdmod2, I scaled my model vertically and ran it for longer. The scaling applied was a simple multiplication of all interface depths by ten, and the model was calculated for approximately 3.2s (as opposed to 0.25s). I could then display the first 2.5s of data over the same axis length as for the older 0.25s model, effectively compressing the output and (in theory) 'increasing' the frequencies by a factor of 10 for display purposes. Unfortunately, the output from this model had some unexpected features and it may be that the simple scaling I used was inappropriate, or there may have been errors in the input parameters. Further work would be required to investigate the problem more thoroughly, but long model run times are limiting – for example, to produce the pseudo-high frequency model took around 13 days of continuous calculation time. In the process, sufdmod2 generated nearly 200 gigabytes of data with around 4.5 million individual timesteps. An even more complicated model was stopped after around 18 days of runtime when it appeared to be producing meaningless output.
A model was also run at considerably lower frequencies, to investigate the resolution of conventional oil-field style seismic in this setting. As we might expect, the resolution was much lower, and interfaces between thin sediment packages are not resolved.

**Conclusions**

The final results revealed that multiple reflections can be generated from the surface of the low velocity, low density silt layer. The model also indicates that it should be possible to resolve the base of the silt layer, further reinforcing the suggestion that the silts are attenuating (and probably scattering) the seismic energy. Note that in the accompanying model plots, the only gain functions applied are time varying gain and trace amplification with clipping. Although it is possible to apply for complex gain functions to the model output (such as automatic gain control) it would not be appropriate because these gain functions were not (and could not be) applied to the actual boomer data.