Subcoal Seismic Exploration in the Gippsland Basin (Australia)

by

Jarrod Craig Dunne
B. Sc. (Hons.) The University of Melbourne, Australia

Department of Mathematics
The University of Melbourne, Australia

A thesis submitted to The University of Melbourne
for the degree of Doctor of Philosophy

October 1996

Printed on acid free paper
# Table of contents

ABSTRACT viii
LIST OF PUBLICATIONS x
LIST OF FIGURES xi
LIST OF TABLES xxii
DECLARATION xxiv
ACKNOWLEDGMENTS xxv

1 INTRODUCTION
1.1 Subcoal imaging difficulties in the Gippsland Basin 1
1.2 Review of related studies 5
1.3 Objectives of thesis 8
1.4 Outline of thesis 9

2 DETAILED ELASTIC SYNTHETIC MODELLING
2.1 Introduction 11
2.2 The need for elastic modelling 12
2.3 A modified reflectivity method 14
   2.3.1 Theory and implementation 15
   2.3.2 Advantages and disadvantages 18
2.4 A detailed elastic synthetic for the Gippsland Basin 21
   2.4.1 Building a depth model for Well 3 21
   2.4.2 Prestack field data matching 23
   2.4.3 Stacked field data matching 27
2.5 Conclusions 28
3 IDENTIFYING NOISE IN SEISMIC DATA

3.1 Introduction 29
3.2 Identifying modelled noise events 30
  3.2.1 Modelling selected parts of the wavefield 30
  3.2.2 Depth model variation 33
  3.2.3 Analysis techniques 37
3.3 Identifying coherent non-modelled noise events 39
3.4 Conclusions 41

4 BUILDING A DETAILED ELASTIC DEPTH MODEL WITH LIMITED INFORMATION

4.1 Introduction 43
4.2 P-wave velocity model 45
  4.2.1 Depth sampling 45
  4.2.2 Replacing missing sonic log sections 47
  4.2.3 The sea floor model 49
  4.2.4 Checkshot corrections 50
4.3 S-wave velocity model 51
  4.3.1 The sea floor model 51
  4.3.2 Replacing a missing S-wave velocity log 52
4.4 Density 55
4.5 Q attenuation 57
4.6 Lateral structure 59
4.7 Conclusions 59

5 \( \tau-p \) DOMAIN PROCESSING

5.1 Introduction 61
5.2 An introduction to the \( \tau-p \) domain 62
  5.2.1 The linear \( \tau-p \) transform 62
5.2.2 The transform variables 63
5.2.3 The appearance of seismic events in the linear $\tau$-$p$ domain 64
5.3 Plane-wave decomposition via the proper slant stack 67
  5.3.1 Theory and implementation 67
  5.3.2 Synthetic testing 73
5.4 Hyperbolic velocity filtering during the proper slant stack 79
  5.4.1 Theory and implementation 79
  5.4.2 Synthetic testing 84
5.5 Other $\tau$-$p$ domain processing applications 93
  5.5.1 The inverse transform 93
  5.5.2 The elliptical moveout correction and stack 94
  5.5.3 S-wave elliptical moveout correction 96
  5.5.4 $\tau$-$p$ domain semblance analysis 97
  5.5.5 Deconvolution 97
5.6 Conclusions 99

6 PROCESSING THROUGH TO STACK IN THE $t$-$x$ AND $\tau$-$p$ DOMAINS
  6.1 Introduction 100
  6.2 Processing streams for the Gippsland Basin 101
  6.3 Pre-processing 104
    6.3.1 $t$-$x$ domain 105
    6.3.2 $\tau$-$p$ domain 110
  6.4 Hyperbolic velocity filtering 112
  6.5 Short period deconvolution 118
  6.6 Poststack processing 120
  6.7 Conclusions 125
7 MODEL-BASED VELOCITY ANALYSIS

7.1 Introduction .......................... 126

7.2 Event interpretation in semblance analyses .......................... 127
7.2.1 Field data comparison ........................................ 127
7.2.2 Using additional synthetics ........................................ 129
7.2.3 Using RMS velocity functions ........................................ 131

7.3 Semblance analysis in the $\tau$-$p$ domain .......................... 133

7.4 Field data examples ........................................ 134

7.5 Conclusions ........................................ 136

8 A STRATEGY FOR SUBCOAL SEISMIC EXPLORATION IN THE GIPPSLAND BASIN

8.1 Introduction ........................................ 138

8.2 Noise identification ........................................ 139
8.2.1 Streamlined elastic synthetic modelling ........................................ 139
8.2.2 Line B example ........................................ 141

8.3 Improved imaging ........................................ 147
8.3.1 Line B example ........................................ 147
8.3.2 Line C example ........................................ 153
8.3.3 Gap deconvolution of long period multiples ........................................ 159
8.3.4 Surface multiple stacking ........................................ 160

8.4 Acquisition ........................................ 161

8.5 Conclusions ........................................ 162
9 CONCLUDING REMARKS

9.1 Contributions of thesis

9.2 Future directions

9.2.1 Depth model preparation and elastic modelling

9.2.2 $\tau$-$\rho$ domain processing

9.2.3 Elastic waveform inversion

9.3 Will oil be found?

APPENDIX A FIELD DATA SPECIFICATIONS

A1 Well-logs

A2 Seismic data

APPENDIX B AUTOMATED WELL-LOG BLOCKING

B1 Introduction

B2 Average-resampling

B3 Automated blocking

B3.1 The blocking algorithm

B3.2 Parameter selection

B3.3 Unfavourable geologies

B4 Recommendations

APPENDIX C APPROXIMATIONS TO THE EXACT REFLECTION TRAVELTIME FOR A HORIZONTALLY LAYERED SUBSURFACE

C1 Introduction

C2 Single layer case

C3 Multilayer case

C4 Conclusions
APPENDIX D   FAST HYPERBOLIC VELOCITY FILTERING
DURING THE CYLINDRICAL SLANT STACK

D1  Introduction          189
D2  The cylindrical slant stack  190
D3  Elimination of smeared artefacts  193
D4  HVF during the cylindrical slant stack  196
D5  HVF velocity interpolation in the t-x domain  199
D6  Field data examples  201

APPENDIX E   USING THE UNUSUAL SHAPE OF THE HVF MUTE
E1  Introduction          202
E2  Mute description  202

APPENDIX F   PROCESSING PARAMETERS FOR THE FIELD DATA
EXPERIMENTS

F1  t-x domain processing streams  204
F2  τ-p domain processing streams  205

REFERENCES  206
Abstract

Deep seismic exploration in the Gippsland Basin is hindered by strong, unidentified noise below the Latrobe Group coal sequence. Low velocity events that appeared in field data semblance analyses suggested that an elastic wave modelling study was required to understand the subcoal reflection response. The modified reflectivity method (Kennett, 1980) provided a means for constructing detailed and accurate synthetic seismograms from realistic depth models, under the assumption of an isotropic, plane-layered earth.

A study into the effect of each part of an elastic depth model (upon an elastic synthetic seismogram) resulted in a set of guidelines for obtaining a field data comparison. Excellent ties were then obtained at several wells, often using little more than a partial sonic log. The noise contributions to the synthetics were interpreted using additional synthetics computed from variations upon the depth model and by exercising control over the wave types modelled. Subsequent processing of the synthetics revealed three types of persistent noise in progressively deeper parts of the subcoal image: 1) mode converted interbed multiples (generated within the coal sequence); 2) S-wave reflections and long period multiples (generated between the coal sequence and the Miocene carbonates) and 3) surface-related multiples.

The noise interpretation can also be performed upon semblance analyses of the elastic synthetics to guide a velocity analysis away from a well. RMS velocity functions for the P-wave primaries and specific noise events can be used as overlay to further constrain the velocity picking. The "model-based velocity analysis" procedure helped to avoid picking the interformation long period multiples, whose stacking velocities were only 5-10% below those of the weak target zone primaries. This realisation provided subtle but significant improvements in stacked sections where the noise events had been picked.
An improved subcoal image was obtained by making full use of the versatile noise suppression offered by a $\tau$-$p$ domain processing stream. By separating the strong linear events at the far offsets it was possible to stack a larger portion of the target zone reflections, provided that hyperbolic velocity filtering (HVF) was applied to suppress the $\tau$-$p$ transform artefacts. HVF is a form of time and offset variant filtering that only allows each point in the $t$-$x$ domain to contribute to a small number of $p$ traces during a $\tau$-$p$ transform. HVF can be incorporated into a point source $\tau$-$p$ transform (Harding, 1985), extending previous implementations that applied HVF during the slant stack (Mitchell and Kelamis, 1990). Tests performed upon a detailed elastic synthetic ensured that the benefits of my implementation would carry over to the field data.

Following HVF in a point source $\tau$-$p$ transform, the S-wave reflections and guided waves were well suppressed and the remaining events possessed plane-wave amplitudes. In the $\tau$-$p$ domain, multiples are exactly periodic along $p$ traces and this enabled a far better deconvolution of the mode converted interbed multiples. However, it is not possible to achieve a reliable deconvolution of the interformation interbed multiples primarily because only a few bounces arrive before the end of the trace. Fortunately, these multiples are highly dependent upon the strength of the Miocene carbonate and coal sequence reflections and may only persist in some parts of the Gippsland Basin.

Stacking in the $\tau$-$p$ domain brought further advantages resulting from the elliptical moveout correction (EMO), which minimises wavelet stretch and approximates the exact reflection traveltime better than NMO. Two regional seismic sections were reprocessed using the $\tau$-$p$ domain processing stream and were co-interpreted with the modelling studies performed at nearby wells to avoid the noise events that still remained. Several new structures appeared in both the immediate target zone and the deeper response with the low frequency character expected following transmission through a coal sequence.
List of publications


Dunne, J. C., Beresford, G. and Kennett, B. L. N., 1995a, Detailed elastic modelling to characterise noise contributions to seismic data from the Gippsland Basin: Exploration Geophysics, 26, 37-44.


Dunne, J. C., Beresford, G. and Kennett, B. L. N., 1996a, Identifying and suppressing noise in seismic data from the Gippsland Basin (Australia): The Leading Edge, 15, 993-1000.


# List of Figures

<table>
<thead>
<tr>
<th>Figures</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>2</td>
</tr>
<tr>
<td>1-2</td>
<td>2</td>
</tr>
<tr>
<td>1-3</td>
<td>4</td>
</tr>
<tr>
<td>2-1</td>
<td>13</td>
</tr>
<tr>
<td>2-2</td>
<td>14</td>
</tr>
<tr>
<td>2-3</td>
<td>15</td>
</tr>
<tr>
<td>2-4</td>
<td>16</td>
</tr>
<tr>
<td>2-5</td>
<td>19</td>
</tr>
<tr>
<td>2-6</td>
<td>20</td>
</tr>
<tr>
<td>2-7</td>
<td>22</td>
</tr>
<tr>
<td>2-8</td>
<td>24</td>
</tr>
</tbody>
</table>
The synthetic/data matching procedure corrected the synthetic for the main wavelet differences and included amplitude scaling and bandpass filtering to enhance deeper reflections.

The noise contributions to a supergather (four interleaved CMP gathers) from the Gippsland Basin a) were well matched by the elastic synthetic seismogram computed for Well 3 b).

The spliced stack display contains the elastic synthetic (centre traces) and the adjacent supergather after minimal processing through to stack. The high quality of this synthetic tie resulted in the identification of three zones of persistent noise in stacked data from this region.

The synthetic computed without mode conversions revealed the importance of S-wave contributions at offsets greater than 800 m.

Stacking the synthetic computed without mode conversions suggested that S-wave reflections comprise much of the coal sequence and target zone stack response (1.3-2.2 s).

The 16 m averaged-resampled depth model was used to compute the full reflection response a), a synthetic lacking surface multiples b), a synthetic lacking all multiples c), and a synthetic containing only P-wave primaries d).

Only the S-wave refractions were significantly altered in the elastic synthetics computed from depth models that were representative of harder and softer sea floors.

The complex structure of the Miocene carbonates was simulated by reordering layers in the depth model (P-wave velocity shown) from 600-1100 m.

Zoom displays of the target zone response confirmed the Miocene carbonates' influence upon both the S-wave reflections and long period interbed multiples. Panel a) is the original elastic synthetic from 1.2-2.2 s and between 100-1330 m. Panel's b), c) and d) are the elastic synthetics respectively computed from the "subtle", "moderate" and "large" change depth models.
3-7 Panel's a), b), c) and d) are the stacks for each of the synthetics shown in Figure 3-6. They show enough variation in the target zone to account for the lateral noise variation observed in the field data.

3-8 A $\tau-p$ domain version of the elastic synthetic from Well 3 indicates the interpretational advantages gained from the greater separation of linear events and S-wave reflections in this domain.

3-9 I found strong noise bursts in a supergather from Line A a) but overlooked the forward and backscattered energy indicated in a nearby shot record b). I then found low velocity noise after low pass filtering the same shot record c).

4-1 A spliced stack comparison indicating the dependence of stacked elastic synthetics (centre) on the depth sampling interval and the extent to which thin layering can influence seismic data from this region.

4-2 A graphical analysis of the timing a) and amplitude b) of four key events suggested that the elastic synthetic had stabilised for depth sampling intervals below 1 m. The two-way times (TWT) and amplitudes were normalised for each event using the synthetic computed from the 0.25 m model.

4-3 The absence of the early part of the sonic log can dramatically alter the appearance of the stacked elastic synthetic a). With a shallow 500 m section missing, the coal sequence and its short period interbed multiples (NZ1) suffered only minor changes b). However, the noise events (NZ2) generated in the missing region were significantly altered when a 1000 m section was removed c).

4-4 An S-wave velocity log from Well 1 suggested that formation changes are often accompanied by a change in the locally averaged Poisson ratio a). The $V_S-V_P$ distribution suggested that each formation could be assigned a single Poisson ratio b) to produce an "artificial" S-wave velocity log that closely resembles the measured log c).

4-5 I incorporated the "artificial" S-wave velocity log into a simplistic depth model to study the sensitivity of elastic synthetics to the S-wave velocity model using the strong and isolated PPSP/PSPP events.
4-6 The PPSP/PSPP events computed from the measured log a) compared well to those computed from the "artificial" S-wave velocity log b). The match remained accurate when the Poisson ratio of the lower formation was reduced to 0.20 c) and was increased to 0.30 d).

4-7 The stacked elastic synthetic from the reference depth model a) was quite different within the coal sequence and target zone to the synthetic whose density profile was based on Gardner's equation b). Using only a single density for the entire subsurface gave a synthetic c) that was nearly identical to panel b) suggesting that only large density variations can influence a complex stack response.

4-8 Elastic synthetics revealing the effects of Q attenuation were computed using $Q_p = Q_S = 85$ a), $Q_S = 2Q_p$ b) and $Q_S = 0.5Q_p$ c) for the entire depth model.

5-1 A reflection hyperbola a) maps to an ellipse b) in the $\tau$-$p$ domain.

5-2 S-wave events generated in a marine environment a) are well separated from P-wave events in the $\tau$-$p$ domain b).

5-3 Refractions and direct waves a) often cross reflections in the $t$-$x$ domain b). The linear $\tau$-$p$ transform maps these events to points in the $\tau$-$p$ domain c).

5-4 A flowchart describing my implementation of the proper slant stack (PWD). The runtime is given by the number of times each loop is performed multiplied by the time each loop takes to run.

5-5 A graphical interpretation of aliasing in the forward $\tau$-$p$ transform. If slopes approaching $\phi$ are included in the transform, aliasing results from constructive summation across separate events (redrawn from Turner, 1990).

5-6 The first test model consisted of a single hyperbolic reflection a) while the second contained several isolated P- and S-wave reflections and refractions b).

5-7 The proper slant stack (PWD) applied to the first test model a) showed distinctive edge effects from the near (upper arrow) and far offsets (lower arrow). Its application to the second test model b) only indicated edge effects from the far offsets.
5-8 The proper slant stack (PWD) applied to the elastic synthetic a) and supergather b) revealed strong edge effect artefacts in the field data due to the stronger refractions and guided waves.

5-9 Hyperbolic velocity filtering in action, indicating how the stacking velocity range restricts the summation to a small range of \( p \) values a) and thus suppresses aliasing and edge effects b).

5-10 A flowchart describing my implementation of HVF during the proper slant stack.

5-11 Interpolated RMS velocities for the Well 3 depth model as used in my implementation of HVF during the proper slant stack.

5-12 HVFPWD applied to the first test model a) and the second test model b) without the Bartlett weighting applied to the mute specification. The white arrows indicate the far offset edge effects that fell within the pass zone, while the black arrows indicate the artefacts caused by the sharp edges of the HVF mute.

5-13 HVFPWD applied to the first test model a) and the second test model b) with the Bartlett weighting applied to the mute specification.

5-14 HVFPWD applied to the elastic synthetic a) and the supergather b) without the Bartlett weighting applied to the mute specification.

5-15 HVFPWD applied to the elastic synthetic a) and the supergather b) with the Bartlett weighting applied to the mute specification.

5-16 HVFPWD applied to the elastic synthetic a) and the supergather b) with Bartlett weighting but without velocity interpolation and the velocity corridor reduction at the far offsets.

5-17 Averaged amplitude spectra of the rho filtered, \( \tau-x \) domain elastic synthetic a), its PWD b), its HVFPWD c) and its exact \( \tau-p \) reflection response d), shown from 0-70 Hz.
5-18 The elliptical moveout correction (EMO) reduces the wavelet stretch of shallow, small moveout reflections in the $\tau$-$p$ domain without adverse affects upon deep, large moveout reflections.

5-19 The elliptical moveout correction (EMO) applied to the HVFPWD of the elastic synthetic (Figure 5-15a).

5-20 The exact periodicity of multiple reflections in the $\tau$-$p$ domain b) for the case where first-order water bottom multiples are recorded from a flat sea floor a).

6-1 A $t$-$x$ domain processing stream for marine seismic data a) and its $\tau$-$p$ domain "equivalent" b). The key differences occur in the pre-processing and CMP sorting stages, with options (dashed boxes) to perform FK demultiple, gap deconvolution and velocity analysis prior to stacking.

6-2 Line A, $t$-$x$ domain processing stream 1: No pre-processing, decimated CMP gathers and FK demultiple. Only the strongest reflections are visible amongst the guided wave interference, until 3.0 s where the guided waves reach the end of the cable.

6-3 Line A, $t$-$x$ domain processing stream 2: Mute/FK filter pre-processing, decimated CMP gathers and FK demultiple. Signal and noise reflections are now visible at all times although backscattered noise appears in the deep response.

6-4 Line A, $t$-$x$ domain processing stream 3: Mute/FK filter pre-processing, decimated CMP gathers and FK demultiple with full stack array formed after stacking. The target zone response was unchanged apart from the reduction in the backscattered noise.

6-5 Strong edge effects were generated when HVFPWD was applied to the decimated CMP gather 842 a), but these were well suppressed when HVFPWD was applied to supergather 842 b).

6-6 Line A, $\tau$-$p$ domain processing stream 4: Decimated CMP gathers and PWD with full stack array formed after stacking. When compared to its equivalent $t$-$x$ domain result (Figure 6-4), the greatest difference occurred at the Miocene carbonates where the supercritical reflections were included in the stack. Several new events appeared in the target zone (1.7-2.0 s) possessing the low frequency character expected after transmission through the coal sequence.
6-7 Line A, \(\tau-p\) domain processing stream 5: Supergathers and PWD. Further improvements in the target zone (1.55 s, 1.8-2.0 s) resulted from the reduction in guided wave edge effects.

6-8 Line A, \(\tau-p\) domain processing stream 6: Supergathers and HVFPWD. The new target zone events appeared with greater continuity and strength resulting from the suppression of the guided wave edge effects and the NZ2 reflections, although the NZ3 surface multiples were only slightly reduced.

6-9 Line A, \(\tau-p\) domain processing stream 6, stacked using only the first half of the \(\tau-p\) gather. The changes in this section reaffirm the notion that \(\tau-p\) domain processing is able to exploit a greater portion of reflection events.

6-10 Normalised \(f-x\) and \(f-p\) spectral analyses computed from decimated CMP gather 842 processed in the \(t-x\) domain a) and supergather 842 after HVFPWD in the \(\tau-p\) domain b). The spectral analyses computed after short period gap deconvolution applied in the \(t-x\) domain c) and the \(\tau-p\) domain d) indicated a much better result in the \(\tau-p\) domain.

6-11 Line A, \(t-x\) domain processing stream 3, with a short period gap deconvolution. The "noise contaminated" character of the target zone response remained despite indications that some of the short period multiples were suppressed.

6-12 Line A, \(\tau-p\) domain processing stream 6, with a short period gap deconvolution and stacked using only the first half of the \(\tau-p\) gather. There appeared to be considerable suppression of the NZ1 multiples within the coal sequence and the early part of the target zone, especially near the centre of the section between 1.5-1.7 s.

6-13 Line A, \(t-x\) domain processing stream 3, with short period gap deconvolution and a poststack migration applied. The side-scattered noise appeared partly suppressed by the dip filtering action of the migration.

6-14 Line A, \(\tau-p\) domain processing stream 6, with a short period deconvolution and stacked using only the first half of the \(\tau-p\) gather. The subsequent poststack migration reduced the side-scattered noise and thereby improved the continuity of events in the middle part of the target zone (1.8-2.0 s).
7-1 A detailed and accurate match between the semblance analysis of supergather 842 a) and the elastic synthetic from Well 3 b) allowed the noise events to be interpreted and avoided in the velocity analysis of Line A.

7-2 The full extent of the difficulties in performing a velocity analysis for complex areas such as the Gippsland Basin can be seen in the semblance comparison between a processed CMP gather a) and the "P-wave primaries" synthetic b).

7-3 The RMS velocity function for first-bounce P-wave surface multiples corresponds to semblance peaks at traveltimes where these events are strongest in the synthetic a). Similarly, the interbed multiples and S-wave reflections generated between the Miocene carbonates and deeper horizons can be found along the trajectories indicated by their respective RMS velocity functions b).

7-4 Supergather semblance analyses computed in the t-x a) and τ-p domains b) indicated a 5× resolution improvement at the Miocene carbonates through the use of supercritical reflections, while elsewhere the EMO correction provided a 2× resolution improvement.

7-5 "Production" processing was applied to Line A with the coal sequence and target zone reflections stacked according to a 5% decrease in the velocities obtained from the model-based velocity analysis a). Only minor changes resulted from restacking using the exact model-based velocities b).

7-6 Line A was reprocessed in the τ-p domain to judge the effects of a 5% reduction in the model-based velocities a). Although some noise still persists in the target zone, an overall reduction of incoherent noise and greater continuity in the deeper reflections resulted when the unadjusted model-based velocities were used b).

8-1 Modelling and image processing can be used together to reduce the exploration risk associated with poor quality seismic data from the Gippsland Basin.

8-2 Flowchart describing the elastic synthetic depth model preparation program (ESDM).

8-3 The depth model used to construct the elastic synthetic seismogram for Well 4.
The noise contributions to supergather 2098 from Line B a) were well matched by those in the elastic synthetic computed for Well 4 b).

The depth model used to construct the elastic synthetic seismogram for Well 5.

Apart from the surface multiples and S-wave refractions, most events in supergather 2464 from Line B a) were well matched by those in the elastic synthetic computed for Well 5 b).

Line B with t-x domain "production" processing using the original velocity analysis. The upper coal sequence terminates at the Marlin channel (far right) and overlies a deeper coal sequence that suffers from moderate noise interference.

Line B with τ-p domain processing after a model-based velocity analysis and a short gap deconvolution targeting the mode converted interbed multiples. Significant changes in the lower coal sequence are likely to provide a new interpretation of the faulting that occurs below the elevated part of the upper coal sequence.

Line B region of interest after t-x domain "production" processing a) and τ-p domain processing b). The τ-p section should enable a better interpretation of the stratigraphy in the immediate target zone and of the structural influences upon the lower coal sequence.

Line C with t-x domain "production" processing using the original velocity analysis. The main features are the Barracouta anticline and a small "rollover" feature near SP 2140.

Line C with τ-p domain processing after a model-based velocity analysis and a short gap deconvolution targeting the mode converted interbed multiples. Strong, low frequency reflections appeared in both the immediate target zone (1.75 s, SPs 2300-2600) and the deep response (2.4 s, SPs 2200-2600).

Line C region of interest after t-x domain "production" processing a) and τ-p domain processing b). A roughly horizontal reflection appeared in place of the coal sequence surface multiple (2.4 s) and a set of disjointed reflections replaced the MC/CS interbed multiples (1.75 s).
8-13 Line C semblance analyses computed at SP 2240 from a t-x domain CMP gather a) and a τ-p domain supergather after HVFPWD b). The semblance peaks near 1.7 s and 2.5 s verified the new subcoal reflections in the τ-p domain section.

8-14 Line C with τ-p domain processing applied to enhance the first-bounce surface multiples.

8-15 HVFPWD was applied to the elastic synthetic computed from Well 5 with a maximum offset of 3.8 km a) and 7.6 km b) to suggest that further improvements in the subcoal image are likely to be obtained using an increased cable length.

B1 Sonic and density logs for Well 2 were originally sampled at 0.25 m.

B2 Adequately sampled reflection a) and transmission b) seismograms generated from Well 2 with four reference events marked.

B3 The effect of average-resampling on the Well 2 reflection a) and transmission b) seismograms.

B4 An analysis of the depth sampling dependence of the Well 2 synthetic seismograms.

B5 Flowchart for the blocking program described by Kerzner (1986).

B6 The effect upon blocked velocity and density models from varying the filtering window length for N=0.5 m a), N=1 m b), N=2 m c) and N=4 m d).

B7 The effect upon blocked velocity and density models from varying the cutoff noise level for CNL=0.0001 a), CNL=0.001 b) and CNL=0.01 c).

B8 The effect on the transmission synthetic due to changes in the filtering window length (N) a) and the cutoff noise level (CNL) b).

B9 Automated well-log blocking of transitional layering. The blocked model can be inadequate for a purely artificial scenario a) but tends to be similar to an averaged-resampled model when the input log includes a small amount of noise b).

C1 The model and parameters used to derive the single layer traveltimes.
C2 The model and parameters used to derive the two layer traveltime approximations.

C3 Timing errors associated with the third term in the traveltime approximation for the second reflection from a three layer depth model.

C4 Timing errors associated with the third term in the traveltime approximation for a reflection at the bottom of the Well 3 depth model.

D1 Test model 1 after $\tau-p$ transformation with $\Delta p=0.01 \, s/km$ using the slant stack a), the cylindrical slant stack b) and the proper slant stack c), indicating the smeared artefacts that dominate the cylindrical slant stack at large $p$ values.

D2 Test model 1 after $\tau-p$ transformation with $\Delta p=0.002 \, s/km$ using the slant stack a), the cylindrical slant stack b) and the proper slant stack c), indicating that the smeared artefacts have been well suppressed by finer $p$ sampling.

D3 The elastic synthetic after $\tau-p$ transformation with $\Delta p=0.002 \, s/km$ using the slant stack a), the cylindrical slant stack b) and the proper slant stack c).

D4 Test model 1 after HVF with $\Delta p=0.002 \, s/km$ using a) the cylindrical slant stack, showing how HVF compounded the difficulties associated with the smearing artefacts. Applying a Bartlett window to the HVF mute offered some improvement b), although the artefacts were still worse than those remaining in the equivalent result obtained using the proper slant stack c).

D5 The elastic synthetic after HVF with $\Delta p=0.002 \, s/km$ using the cylindrical slant stack and obtained with an averaged velocity interpolation method a) showed significant errors near supercritical reflections. A vastly improved result was obtained when the "link-listed" velocity interpolation method was applied b) and most of the remaining artefacts were removed using a postmute c).

D6 Brute stacks showing the target zone response of Line A were obtained using HVF applied during the slant stack a) and the cylindrical slant stack b). Weaker target zone events appeared in the slant stack result and residual smearing artefacts persisted in the cylindrical slant stack result when these were compared to the stack obtained using HVFPWD (Figure 6-9).
# List of Tables

<table>
<thead>
<tr>
<th>Tables</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Modelling parameters used to construct the elastic synthetics in this thesis.</td>
</tr>
<tr>
<td>2-2</td>
<td>Key to the annotation used to locate noise events in the elastic synthetics. Where possible, the labels are positioned to the upper right of an event.</td>
</tr>
<tr>
<td>3-1</td>
<td>Elastic modelling strategies for noise identification.</td>
</tr>
<tr>
<td>3-2</td>
<td>The noise contributions to seismic data from the Gippsland Basin and the properties that could be exploited to achieve suppression.</td>
</tr>
<tr>
<td>5-1</td>
<td>Specifications of the single hyperbolic reflection that comprised test model 1.</td>
</tr>
<tr>
<td>5-2</td>
<td>The elastic depth model used to construct test model 2.</td>
</tr>
<tr>
<td>5-3</td>
<td>The parameters used in the proper slant stack (PWD) experiments.</td>
</tr>
<tr>
<td>5-4</td>
<td>The parameters used in the hyperbolic velocity filtering (HVFPWD) experiments.</td>
</tr>
<tr>
<td>5-5</td>
<td>The parameters used to test the elliptical moveout (EMO) correction.</td>
</tr>
<tr>
<td>6-1</td>
<td>Processing parameters used in each flow segment during this chapter.</td>
</tr>
<tr>
<td>8-1</td>
<td>List of synthetic analyses used to perform the noise interpretation and model-based velocity analysis in the streamlined elastic synthetic modelling procedure.</td>
</tr>
<tr>
<td>8-2</td>
<td>Key to the annotation used to locate noise events in the elastic synthetics computed from Wells 4 and 5. Where possible, labels are positioned to the upper right of an event.</td>
</tr>
<tr>
<td>A1</td>
<td>Acquisition information concerning the well-logs used in the thesis.</td>
</tr>
</tbody>
</table>

D1 CPU runtimes using an IBM RISC System/6000 320 for a number of $\tau$-$p$ transformation options using the elastic synthetic as an input model.

E1 ProMAX™ parameter table for the process "Reapply HVF Mutes".

F1 The processes and parameters used in the "production" flow for Lines B and C.

F2 The processes and parameters used in a $t$-$x$ domain flow for Line B that used the model-based (MB) velocities and included a prestack deconvolution for the mode converted interbeds (NZ1).

F3 The processes and parameters used in the core $\tau$-$p$ domain flow for Lines B and C.
Declaration

I certify that this thesis contains only my own original work and that I have made proper acknowledgment of the material published or contributed by others in the text.

I also declare that this thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

[Signature]

Jarrod Dunne
Acknowledgments

I am extremely grateful to a large number of people who have provided me with encouragement, criticism, advice and support during the course of my research and the writing of this thesis. In particular, I would like to thank my supervisor, Dr Greg Beresford, for guiding the research in a challenging, yet practical direction. I would especially like to thank Greg for the role that he has played in my development not only as a researcher, but as a "new age" scientific writer and presenter.

My research began to bear fruit after meeting with Prof. Brian Kennett and discussing the possibility of proving my noise hypothesis. I am in great debt to Brian for allowing me to use his implementation of the reflectivity method and for our subsequent discussions on the modelling results. I would also like to thank Bryan Beresford for his ideas on improving the implementation of HVF during a point source $\tau-p$ transform and for his patience in using the ProMAX™ programming environment. Thanks also to Dr Lindsay Thomas and Steve Carroll for their constructive criticism and feedback during the writing of this thesis. I am especially grateful to Dylan Mair for his help over several years in using UNIX and keeping the "520" running.

Naturally, I would like to thank ESSO and BHP Petroleum for their sponsorship and for providing the well-logs and seismic data used in this thesis. During the course of my research, their feedback served to strengthen my arguments and I owe particular thanks to Adem Djakic, John Moore and John Volaric for their input over a long period of time.

I thank my parents (Graeme and Thelma) for providing me with a stable home life and financial support, without which I would not have reached this level in my education. Thanks also to my sister (Michelle) for being a great mate.

Special thanks to Jackie for making the last three and a half years the best of my life.
Chapter 1

Introduction

1.1 SUBCOAL IMAGING DIFFICULTIES IN THE GIPPSLAND BASIN

With declining reserves in the existing Gippsland Basin oilfields, ESSO and BHP Petroleum are now attempting to find deep oil and gas reservoirs in permits where there exists a proven source of hydrocarbons. Given the existing infrastructure within the Gippsland Basin, new oilfields are being sought to meet the energy needs of both Victoria and New South Wales into the 21st century. This research aims to improve the seismic reflection imaging of deep exploration targets so that new oilfields can be discovered, appraised and developed with reduced risk.

The Gippsland Basin is located near the southeast corner of the Australian mainland and includes both land and marine exploration permits (Figure 1-1). In the 1960's, several large oil and gas reservoirs were discovered in large, folded structures of the upper Latrobe Group (Figure 1-2). These are sealed by shales within the Latrobe Group and by the mudstones that comprise the Lakes Entrance formation. With a proven source of hydrocarbons, current exploration is focussed on the deeper part of the Latrobe Group, below an extensive coal/shale sequence. The play types sought in this region include anticlinal structures, rotated fault blocks and stratigraphic traps (Mebberson, 1989). In searching for these play types, the principal difficulty is that seismic images below the Latrobe Group coal sequence contain strong noise interference.
Figure 1-1. The Gippsland Basin is located near the southeast corner of the Australian mainland and includes several land and marine exploration permits.

Figure 1-2. The Gippsland Basin oilfields are often located in large, folded structures of the upper Latrobe Group, while current exploration is focused on the deeper part of the Latrobe Group, below an extensive coal/shale sequence.
The quality of the subcoal seismic image is so poor that seismic interpreters have been unable to construct maps below the first few coal seams. It has also proven extremely difficult to reconcile well-log measurements taken below the coal sequence with nearby seismic data. The subcoal image deteriorates rapidly below the first few coal seams, so it is likely that the imaging difficulties are somehow associated with the coal sequence. However, the exact noise generating mechanism is not understood and a successful processing solution is yet to be found.

The Latrobe Group coal sequence is present over the entire basin and its upper limits lie near the surface at some onshore locations and as deep as 2000 m in the offshore exploration permits. As a result, the subcoal imaging problem exists over the entire basin, although there appears to be considerable variation in the severity of the noise interference. The highly reflective coal sequence (CS) is easily identified in a 4 km segment of a conventionally processed seismic section (Figure 1-3). This section contains severe noise contamination in the immediate target zone (1.5-2.2 s) despite several indications of strong impedance contrasts in nearby wells.

Other consistent features in seismic data from the Gippsland Basin are the strong primary reflections from the Miocene carbonates (MC) and the first-bounce surface multiple from the coal sequence (CS sm1). Relatively hard limestones exist close to the sea floor, which lies at depths between 40-100 m in the regions of current exploration interest. The presence of a hard and shallow sea floor means that surface-related multiples dominate the deeper part of most offshore seismic sections and are likely to prevent an interpretation of the basement. Further interpretational difficulties result from the influence of complex structure in the Miocene carbonates upon depth conversion procedures (Maung and Cadman, 1992). This formation usually consists of several highly reflective channels, which were formed when submarine valley systems were filled with high velocity carbonates.
Figure 1-3. A seismic section (Line A) from the Gippsland Basin containing strong, unidentified noise contributions in the target zone (1.5-2.2 s). The main reflections are from the Miocene carbonates (MC), the Latrobe Group coal sequence (CS) and its surface multiple (CS sm).
The subcoal imaging problem is perhaps the most serious limitation upon oil and gas exploration in the Gippsland Basin. Despite over 30 years of exploration in the Gippsland Basin, there has been very little progress towards improving the quality of the deep seismic image. However, with the advent of small scale seismic processing systems, such as ProMAX™, it is now possible to simulate an entire production processing scheme and perhaps reduce the severity of this difficult noise problem.

1.2 REVIEW OF RELATED STUDIES

Given the lack of published attempts at imaging below a coal sequence, I now discuss several broadly related studies that had a major impact upon my research. The modelling studies tended to focus specifically on the modelling of coal seams, while the processing studies were more general and dealt with the noise problems that I expected to find. I defer my discussion of the studies that influenced the technical aspects of the research until the chapters where they are used.

A precursor to my research was a feasibility study performed by ESSO Australia prior to their 1992 regional seismic survey of the Gippsland Basin (Volaric, 1991). This study considered both processing and acquisition methods that were cost effective and available at that point in time. The central idea was the simultaneous acquisition of high and low frequency data using two cables towed at different depths. Simplistic processing was proposed for the low frequency data because greater signal penetration was expected into the target zone. This idea originated from studies involving normal incidence synthetics, which showed that a coal sequence acts as a low pass filter on transmission (Rüter and Schepers, 1978). Heavy duty processing was prescribed for the high frequency data to suppress the short period multiples and allow the sections to be co-interpreted to reveal deep structure.
The findings of this feasibility study were based on the assumption that the subcoal imaging problem was largely due to P-wave interbed multiples generated within the coal sequence. However, my early attempts at deconvolving interbed multiples of this type suggested that the noise problem was far more complex than previously thought (Dunne, 1992b). From the field data semblance analyses, I realised that strong, low velocity events were contributing to the stack and also deteriorating the short period deconvolution. I turned my attention to more sophisticated modelling techniques in order to prove the hypothesis that these noise events included surface multiples and S-wave reflections generated at the hard sea floor.

The reflectivity method (Fertig and Müller, 1978; Kennett, 1980) provides a means for modelling all of the seismic wave contributions to prestack seismic data, under the assumption of an isotropic, plane-layered earth. The computation is performed in the frequency domain so that arbitrary layer thicknesses can be input and their multiples computed without dependence upon the time sampling interval (Schoenberger and Levin, 1979). The early studies using this technique were actually attempts to model and interpret coal sequence reflections. In attempting this, Kennett's modified approach proved advantageous as the contribution of specific multiples could be controlled.

These early studies resulted in several conclusions regarding the seismic behaviour of coal seams. Firstly, the major contributions to the reflection response are due to the internal multiples (Hughes and Kennett, 1983). Secondly, considerable mode conversion occurs within a coal sequence so that the delayed S-wave reflections might interfere with the deeper response if sufficiently large offsets are recorded (Fertig and Müller, 1978). These studies also recognised the need for better field data comparisons if the noise contributions are to be fully understood. Achieving this would require more layers to be modelled, as well as the surface-related effects of a complex overburden or sea floor. To achieve an accurate synthetic tie would also require a better representation of the
unknown elastic parameters, along with a simulation of the source and receiver array effects and the field data processing.

An accurate synthetic tie would enable a quantitative interpretation of the noise contributions and allow noise suppression techniques to be specifically developed for this region. Prior to gaining such an understanding, I was forced to consider more general techniques for noise suppression. The excellent separation of different seismic wave events in the $\tau$-$p$ domain held particular appeal given the likelihood of several types of noise interference.

Linear events, mode converted reflections and long period multiples can be suppressed during the $\tau$-$p$ transform itself, using a technique known as hyperbolic velocity filtering (HVF) (Schultz and Claerbout, 1978; Tatham, et al., 1983). I found strong appeal in the notion that deconvolution might also be applied to the velocity filtered gathers to take advantage of the exact periodicity of multiples along the $p$ traces in the $\tau$-$p$ domain (Taner, 1980). Stacking could then be performed with further advantages expected from the use of an elliptical moveout correction (EMO) (Cutler and Love, 1980).

Since 1978, $\tau$-$p$ domain seismic processing applications have been developed extensively, yet my interpretation of the literature indicated several openings for original contributions. Firstly, HVF might be applied during a point source $\tau$-$p$ transform to provide true amplitudes and thereby enable a more accurate deconvolution. Secondly, despite a few attempts at processing through to stack in the $\tau$-$p$ domain (Goodrum, et al., 1986; Brysk, et al., 1987; Wang and McCowan, 1989; Vanic, 1989) it is not clear whether the theoretical advantages of $\tau$-$p$ domain processing are achieved in practice. This concern is primarily related to the generation of artefacts so that a new implementation would need to prove that the transform artefacts are under control. Finally, $\tau$-$p$ domain processing is yet to be tested over a significant volume of seismic data and its effect upon an interpretation is not well documented.
1.3 OBJECTIVES OF THESIS

The primary goal of this thesis is to improve the quality of seismic data from the Gippsland Basin and, in doing so, reveal deep geological structures that might allow new oilfields to be found. However, I conducted the research with several smaller objectives in mind. The first objective was to obtain a detailed understanding of the noise contributions and to use this knowledge to devise a processing strategy appropriate for this region. In attaining this second objective, the processing techniques needed to be robust and practical so that they could be used immediately to process large volumes of seismic data. Finally, I needed to provide hard evidence that my exploration strategy was successful, preferably by identifying deep structure possessing a recognisable geological form.

In the early stages of my research, discussions with Greg Beresford and Jon Claerbout convinced me of the rewards to be gained from "letting the field data observations guide the theoretical development". In adopting this philosophical objective, I found that the Gippsland Basin data contained a wealth of information. I can attribute many discoveries to this scientific method as I attempted to explain peculiarities in the seismic and well-log data. This often led to simplistic but effective solutions thus avoiding an overly mathematical treatment that might prove difficult to implement. As a result, this thesis contains very little mathematics but it does contain processing techniques that work equally well on synthetic models and field data.

I commenced the research under the assumption that the Gippsland Basin geology mostly consisted of sediments with only moderate dips. During the course of the research, I found that my modelling and processing methods were sufficiently robust to the dips encountered in the field data examples. Eventually, the validity of these assumptions will need to be reassessed for exploration permits that contain strongly dipping layers.
1.4 OUTLINE OF THESIS

I have structured the thesis according to the need to understand the noise contributions prior to developing relevant suppression techniques and proving that they work in practice. Chapter 2 can be considered a "materials and methods" section as it provides a layman's description of the reflectivity method and how I used this technique to produce a detailed and accurate elastic synthetic. In Chapter 3, I demonstrate how this synthetic can be used to interpret the noise contributions to seismic data from the Gippsland Basin. The elastic synthetic proved a considerable boon to both seismic interpretation and the development of processing methods, so there was a strong need to ensure that accurate field data comparisons could be obtained elsewhere. In Chapter 4, I present a sensitivity analysis of the elastic synthetic to the underlying depth model and develop guidelines for obtaining accurate synthetic ties from an incomplete sonic log.

Seismic processing in the τ-p domain is well placed to suppress the wide range of noise contributions to seismic data from the Gippsland Basin. In Chapter 5, I build and test the individual processing applications that comprise an entire τ-p domain processing sequence. In Chapter 6, I show how this processing stream operates through to stack and delivers substantial improvements over the t-x domain "production" processing stream. In Chapter 7, I develop a scheme for guiding a velocity analysis away from well control by using the elastic synthetic to interpret noise events in semblance analyses.

The processing techniques developed in Chapters 5-7 delivered gradual improvements to the subcoal image for a short segment of a regional seismic line. In Chapter 8, I combine these techniques into a strategy for subcoal exploration, which I then apply to two lines from the 1992 regional survey. These lines possess quite different structural and noise influences and their associated modelling studies help to quantify the improvement in the subcoal image. Finally, in Chapter 9 I summarise the contributions of the thesis and
discuss further applications of the techniques that I developed to address the subcoal imaging problem.
Chapter 2

Detailed elastic synthetic modelling

2.1 INTRODUCTION

Synthetic modelling is required in order to understand the complex nature of the subcoal imaging problem. Most modelling techniques can be classed into four categories according to their operation (Wason, et al., 1984). Convolutional methods, such as the normal incidence synthetic computed in the time domain, are fast, easy to use and can provide detailed synthetic seismograms. However, these methods only account for a few of the effects upon seismic wave propagation and accurate synthetic ties usually require considerable field data processing and phase matching (Hu and White, 1994). Finite difference and raypath methods are often used to interpret structural influences upon seismic data. Although S-waves and multiples can be modelled using these methods, it is difficult to obtain the detail necessary for a field data comparison. At this stage, only propagator methods are able to provide a detailed representation of the full seismic wavefield and have the best chance of matching prestack seismic data for a subsurface with only moderate dips.

To confirm my noise hypothesis, I require a synthetic that provides an excellent description of prestack seismic data from the Gippsland Basin. The reflectivity method (Fuchs and Müller, 1971) is a propagator method that has provided great insight into the offset dependence of seismic reflections for coal seam geologies (Fertig and Müller, 1978). However, accurate field data comparisons have not yet been achieved. An alternative implementation of the reflectivity method (Kennett, 1980) held significant advantages through the inclusion of Q attenuation effects and the ability to model selected parts of the wavefield and thus interpret the noise contributions.
In this chapter, I show that elastic modelling is required for coal seam geologies where significant mode conversion should be expected at several interfaces. I provide a simple description of the implementation and performance of the reflectivity method prior to computing an elastic synthetic for a well from the Gippsland Basin. I apply a simplistic, prestack matching procedure prior to stacking the synthetic to prove that accurate and detailed synthetic ties can be achieved.

2.2 THE NEED FOR ELASTIC MODELLING

Early indications of strong, low velocity events in the field data semblance analyses (Dunne, 1992b) suggested that surface multiples and S-wave reflections might contribute to the subcoal imaging problem. In addition, I suspected that significant mode conversion might occur within the coal sequence due to the large number of strong impedance contrasts. For the offshore exploration permits there are typically 10-30 brown coal seams in the upper Latrobe Group with thicknesses ranging between 1-10 m. These possess exceptionally low velocities (2.0-2.6 km/s) and densities (1.2-1.8 g/cc), even when buried over 2 km below the sea floor.

I used representative values for coal and shale to model the amplitude variation with angle of P-wave reflections from a thin coal seam (Figure 2-1). The maximum amplitude of the composite P-wave reflection was isolated at each ray parameter \( p \) using a customised version of Brian Kennett's reflectivity method. Similar responses were measured for different values of the S-wave velocity, indicating similar levels of mode conversion within the coal seam for realistic S-wave velocities. However, a dramatic increase in the reflection response was observed in the acoustic case, where S-wave effects were omitted from the computation by letting the S-wave velocity approach zero. The large difference between the elastic (solid) and acoustic (fluid) calculations suggests that substantial mode conversion occurs well before the critical angle is reached for the lower halfspace.
I observed similar behaviour in the reflection response of other low velocity thin layers, with greater mode conversion indicated as the velocity of the thin layer was decreased. In contrast, the reflection response of a thin, high velocity layer (e.g., carbonate in shale) showed only minor differences between the elastic and acoustic results for the same range of ray parameters. These observations suggest that substantial mode conversion occurs within the Latrobe coal sequence and that elastic modelling is required to obtain a better synthetic tie.

![Diagram](image-url)

**Figure 2-1.** For a thin coal seam in shale a) the P-wave reflection response b) suggests that substantial mode conversion occurs well before the critical angle is reached for the lower halfspace.

In a marine seismic experiment, S-wave events can be indirectly recorded provided that they are reconverted to P-waves prior to their return through the sea floor. This reconversion often takes place near the sea floor, where steep gradients in the S-wave
velocity can cause efficient mode conversion (White and Stephen, 1980). Isolated S-wave reflections might be generated from the conversions occurring at the coal sequence and sea floor. Marine S-wave reflections can be classed into three types according to where the mode conversion occurs (Figure 2-2). PPSP/PSPP reflections spend the least amount of time as S-waves and may possess similar stacking velocities to the primary reflections (PPPP). PSSP reflections possess a symmetrical raypath and could be more easily stacked to produce an S-wave section (Carrion and Hassanzadeh, 1985). In using the reflectivity method, I hope to determine whether these noise types account for the abundance of low velocity events in the field data semblance.

![Figure 2-2. Marine S-wave reflections can be classed into three types according to where the mode conversion occurs.](image)

2.3 A MODIFIED REFLECTIVITY METHOD

The reflectivity method attempts to model the full reflection response of a horizontally layered and isotropic subsurface. The implementation used in this thesis was developed by Brian Kennett as a series of modifications to the reflectivity method (Fuchs and Müller, 1971). It has been used to study the upper mantle (Kennett, 1975), earthquakes (Kennett, 1980) and in the exploration of the British Coal Measures (Hughes and Kennett, 1983). In this section, I provide a simplistic discussion of its operation and an assessment of its strengths and weaknesses.
2.3.1 Theory and implementation

Figure 2-3. Flowchart outlining the implementation and features of Kennett's modified reflectivity method.

The modified reflectivity method is implemented in several stages (Figure 2-3), although the actual subroutines used may vary as directed by the parameters that control the computation. Each layer of the input depth model is described according to its thickness \( h \), P-wave velocity \( V_P \), density \( \rho \), S-wave velocity \( V_S \) and the inelastic attenuation quality factors \( Q_P \) and \( Q_S \), with the first entry corresponding to the water (or surface) layer. After making several reasonable assumptions about the frequency independence of Q attenuation, it is possible to compute frequency independent reflection and transmission coefficients for each layer. These coefficients describe the generation of P-
and vertically polarised S-waves (P-SV) and are computed from the force and displacement boundary conditions at each interface (Kennett, 1991).

![Diagram](image)

**Figure 2-4.** P- and vertically polarised S-waves are reflected and transmitted at each interface of a solid medium.

A compact matrix representation is used to describe the coupled P-SV reflection and transmission coefficients at each interface for a given slowness \( p \) (Figure 2-4),

\[
\begin{align*}
    r_j & = \begin{bmatrix} R_{pp} & R_{ps} \\ R_{sp} & R_{ss} \end{bmatrix} \\
    t_j & = \begin{bmatrix} T_{pp} & T_{ps} \\ T_{sp} & T_{ss} \end{bmatrix}
\end{align*}
\]  

(2-1)

where, \( r_j \), \( t_j \) are the reflection and transmission coefficient matrices for the \( j \)th interface, and, \( R_{pp} \) is the coefficient for incident P-waves that remain P-waves upon reflection, etc.

The full reflection response at the sea floor, \( R_q(\omega, p) \), is then built using a matrix recursion that describes the propagation of coupled P-SV waves in each layer, including their respective multiples (Equation 2-2). This computation consists of several 2x2
matrix multiplications and is commenced at the bottom of the depth model where incident waves are assumed not to exist \( (R_n = 0) \). The reflection response at each layer is also described using the same matrix organisation, with the coupling between P- and S-waves controlled by the diagonal terms.

\[
R_{j-1} = r_j^o + \frac{t_j^u \hat{R}_j t_j^o}{1 - r_j^u \hat{R}_j} \tag{2-2}
\]

where, \( r_j^o, r_j^u, t_j^u, t_j^o \) are the upgoing and downgoing reflection and transmission coefficients for the \( j \)th layer,

\( \hat{R}_j = R_j \phi_j \) is the phase shifted reflection matrix for the \( j \)th layer,

and, the phase shift for each wave type through each layer is described by,

\[
\phi_j = \begin{bmatrix} \Phi_{pp} & \Phi_{ps} \\ \Phi_{sp} & \Phi_{ss} \end{bmatrix} \tag{2-3}
\]

where, \( \Phi_{pp} \) is the phase shift for incident P-waves that remain P-waves upon reflection within the layer, etc.

The matrix recursion allows the contribution of specific events to be isolated by preventing the propagation of other events during the recursion. For example, the influence of mode conversions can be assessed by removing the coupling between P- and S-waves during the recursion \((\Phi_{ps}, \Phi_{sp}=0)\) and comparing the result to the full response. Internal multiples can also be omitted by setting the denominator term to unity during the recursion and this can be performed on a layer-to-layer basis.

The reflection response is continued to the surface using reflection and transmission coefficients computed specifically for the fluid/solid interface at the sea floor. Surface multiples can be added according to the source and receiver depths and the air/water reflection coefficient. The final reflection response is modulated according to the desired source spectrum and, if known, source and receiver array directivities can also be applied at this stage. For the experiments in this thesis, I simulated a receiver array by summing
the individual phase delays of the reflection response as it crossed each element of the array. For an array consisting of \( N \) equally weighted elements, the array response can be specified according to the partial sum of a geometric series,

\[
A_N(\omega, p) = \frac{1 - \exp[i\omega p N \Delta x]}{1 - \exp[i\omega p \Delta x]} \quad (2-4)
\]

An inverse FFT can then be applied to the reflection response, \( R_0(\omega, p) \), to analyse the synthetic in the \( \tau-p \) domain. After defining a set of receiver stations, the \( \tau-x \) domain synthetic for a point source excitation is obtained using the Hankel transform. This procedure consists of a trapezoidal rule integration followed by an inverse FFT and is discussed in greater detail in Chapter 5. It is important to note that Q attenuation helps to avoid integrating singularities in the reflection response associated with surface waves (Kennett, 1980). Finally, the elastic synthetic seismogram is output in a simple format that can be readily converted to the SEG-Y standard for subsequent analysis and processing.

2.3.2 Advantages and disadvantages

The advantages of the modified reflectivity method are clear when compared to the normal incidence modelling methods that are still in common use. Firstly, the elastic synthetic seismogram provides a 2D representation of the full seismic wavefield for a point source excitation. In comparison, a normal incidence synthetic usually contains only non-dissipative P-wave events from a plane-wave source. As a result, substantial data processing is usually required to match a normal incidence synthetic. Synthetics computed using the reflectivity method provide a means for interpreting the raw field records and the ability to control the contribution of multiples and S-waves should assist in this endeavour.
The reflectivity method also improves synthetic ties by performing the recursion in the frequency domain where the exact layer thicknesses are used to compute the multiples within each layer (Figure 2-5a). In contrast, synthetics computed in the time domain force the input depth model into layers possessing the same transit time so that the reflections arrive precisely at time samples. As a result, the computation of intrabed multiples is highly dependent on the time sampling interval (Schoenberger and Levin, 1979). For a time sampling interval $\tau$ (where $\tau > h/v$), the multiples generated by the actual layer are quite different to those synthesised in the time domain (Figure 2-5b,c) using layers with averaged acoustic properties. For highly reflective thin layers, the intrabed multiples transmit the majority of energy. Therefore the cumulative effect of inaccuracies in their computation is likely to result in poor ties to deeper reflections.

![Diagram](image.png)

Figure 2-5. The time sampling dependence of multiples modelled in the time domain.

By recomputing an elastic synthetic in single precision, I confirmed that stable full wavefield synthetics can be obtained for more than 3000 layers of a highly active depth model. However, numerical errors overwhelm the synthetics when a large number of intrabed multiples are excluded. This problem is related to the enormous primary transmission loss, which is of the order of $10^{-13}$ for the Gippsland Basin depth models. It is worth noting that I also observed similar problems in normal incidence synthetics when small time sampling intervals were used to model highly active depth models. At this stage, I am yet to find an acceptable solution to this problem. In this thesis, I simply avoid the problem by only computing primary reflection synthetics from depth models that are averaged and resampled to intervals of 16 m or greater.
The disadvantages of the reflectivity method are related to the artefacts produced when the $t$-$x$ domain synthetic is constructed using what is essentially an inverse point source $\tau$-$p$ transform. Several methods for suppressing these artefacts are discussed in Chapter 5 but these are not appropriate for the construction of an elastic synthetic where the entire wavefield must be preserved. Aliasing effects can often be prevented by reducing the size of $\Delta p$ to satisfy the aliasing condition (see Equation 5-18). For some depth models, $\Delta p$ may need to be further reduced to give an accurate integration over a rapidly varying reflectivity. FFT wraparound can also be avoided by increasing the seismogram length to more than double the maximum time of interest. These measures typically increase the computation time by a factor of 10, so that it takes 24 hours to compute an elastic synthetic from a 3000 layer depth model using an IBM RISC System/6000 520.

\[ \text{Figure 2-6. Synthetic S-wave events are located near the large } p \text{ edge of } \tau$-$p \text{ synthetics a) and often extend further than expected towards zero offset in the } t$-$x \text{ synthetic b).} \]

Troublesome artefacts are sometimes generated from large amplitude S-wave reflections and refractions that are located near the large $p$ edge of the synthetic when viewed in the $\tau$-$p$ domain (Figure 2-6a). These produce strong edge effects in the $t$-$x$ domain synthetic due to the $p$ weighting term in the inverse point source $\tau$-$p$ transform. This often gives S-wave refractions the appearance of extending closer to zero offset than expected (Figure 2-6b). Fortunately, these artefacts can be easily allowed for in an interpretation or removed by FK filtering. It may also be possible to reduce these artefacts using an appropriate interpolation procedure to obtain $R_0(\omega,k)$ and then applying a 2D inverse FFT to obtain the $t$-$x$ domain synthetic (White, 1996).
2.4  A DETAILED ELASTIC SYNTHETIC FOR THE GIPPSLAND BASIN

In this section, I use the reflectivity method to construct an accurate and detailed elastic synthetic for the Gippsland Basin. The major challenge was to prepare a detailed elastic depth model from little more than a sonic log. A simplistic matching procedure was then applied to correct the elastic synthetic for differences between the synthetic and field data wavelets.

2.4.1  Building a depth model for Well 3

Initially, my best opportunity for obtaining a synthetic tie was Well 3, in which a reliable sonic log had been acquired from 288-3000 m. Well 3 is located within 100 m of Line A and passes through the Miocene carbonates (MC) and the Latrobe Group coal sequence (CS) before terminating beneath the target zone at a two-way time of 2.2 s. Figure 2-7 indicates the elastic depth model constructed from this well and I now discuss the preparation of each component.

I obtained a detailed model of the P-wave velocity (beneath 288 m) by applying an automated blocking algorithm to the checkshot corrected sonic log according to a minimum layer thickness of 1 m. Subsequent testing using stacked elastic synthetics revealed this depth sampling restriction to be ideal in the trade-off between accuracy and synthetic computation time (see Chapter 4). The development and testing of the blocking algorithm is discussed in Appendix B.

Excellent correlation between the sonic and density log enabled the latter to be averaged over the layers defined during the sonic log blocking. I applied Gardner's empirical law (Equation 2-5) to fill a region (288-850 m) not covered by the density log (Gardner, et al., 1974).
\[ \rho = 0.31 V_p^{0.25} \]  

(2-5)

I used a theoretical compaction trend, based on the packing of elastic spheres, to account for the shallow region that was not logged (Gassman, 1951). After dividing the compaction zone into 37 layers of gradually increasing thickness, I parameterised Equation 2-6 using the velocity of the first-break refraction and the average velocity deduced from checkshot information. I again applied Gardner's equation to assign a density to each layer. The compaction trend provided a smooth transition into the early part of the blocked velocity model thereby avoiding false reflections at that level.

\[ V_p \propto z^{1/2} \]  

(2-6)

![Graphical representation of depth model](image)

*Figure 2-7. The depth model used to construct the elastic synthetic seismogram for Well 3.*
During an earlier feasibility study, I found that an S-wave velocity log is not essential to ensure an accurate match to mode converted events. These results are presented in Chapter 4, where I show the close comparison between the synthetic computed from an S-wave velocity log and the approximate Poisson ratio (\(\sigma\)) trend for Well 1. For Well 3, I used estimates of the Poisson ratio for each geological formation to derive an "artificial \(V_S\) log". The Poisson ratio estimates were based on laboratory measurements of core samples from the main formations.

The quality factors \(Q_P\) and \(Q_S\) define the amount of inelastic attenuation during P- and S-wave propagation. I initially set \(Q_P = Q_S = 85\) for the entire depth model as suggested during a meeting with the project sponsors. I later realised that increased values were required in the water layer and compaction zone to better match the direct wave's amplitude variation with offset. I used \(Q_S = Q_P\) based on an assessment of the measured values for a variety of rock types (Bourbié, et al., 1987). Subsequent tests using \(Q_S = 2Q_P\) and \(Q_S = 0.5Q_P\) indicated that my initial choice provided the best match to deep S-wave reflections (see Chapter 4).

### 2.4.2 Prestack field data matching

The elastic synthetics shown in this thesis were constructed using a 35 Hz zero phase Ricker wavelet (Figure 2-8) and the modelling parameters listed in Table 2-1. If the source wavelet were known, it would have been necessary to compensate for the frequency reduction associated with the inverse \(\tau-p\) transform (see Chapter 5). The other parameter selections were based on my initial tests using the reflectivity method and according to the acquisition parameters of the 1992 regional seismic survey (Appendix A). An air/water reflection coefficient of approximately 0.90 seemed likely given the rough sea conditions that often occur in Bass Strait.
Figure 2-8. Waveform a) and amplitude spectrum b) of a 35 Hz zero phase Ricker wavelet.

<table>
<thead>
<tr>
<th>No. ray parameters</th>
<th>668</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{\text{init}} ) (s/km)</td>
<td>0.001</td>
</tr>
<tr>
<td>( p_{\text{max}} ) (s/km)</td>
<td>0.669</td>
</tr>
<tr>
<td>Record length (ms)</td>
<td>4000</td>
</tr>
<tr>
<td>( \Delta T ) (ms)</td>
<td>4</td>
</tr>
<tr>
<td>No. of time points used in computation</td>
<td>2048</td>
</tr>
<tr>
<td>No. channels</td>
<td>300</td>
</tr>
<tr>
<td>( x_{\text{min}} ) (km)</td>
<td>0.1</td>
</tr>
<tr>
<td>( x_{\text{max}} ) (km)</td>
<td>3.8375</td>
</tr>
<tr>
<td>Source depth (km)</td>
<td>0.005</td>
</tr>
<tr>
<td>Receiver depth (km)</td>
<td>0.006</td>
</tr>
<tr>
<td>Air/water reflection coefficient at the source</td>
<td>0.90</td>
</tr>
<tr>
<td>Air/water reflection coefficient at the receiver</td>
<td>0.90</td>
</tr>
<tr>
<td>No. hydrophones per group</td>
<td>32</td>
</tr>
<tr>
<td>Distance between each hydrophone (km)</td>
<td>0.00390625</td>
</tr>
</tbody>
</table>

Table 2-1. Modelling parameters used to construct the elastic synthetics in this thesis.

I applied a simplistic matching procedure to correct the \( t-x \) domain synthetics for the main wavelet differences using the coal sequence reflections as a reference point (Figure 2-9). In applying a single static shift, scalar multiplication, phase rotation and recording filter, I did not attempt to account for source array effects or other differences in frequency content. The simplicity of this matching procedure meant that I have not forced the elastic synthetic to match the field data. Amplitude scaling and bandpass filtering were then applied to enhance deep reflections.
Figure 2-9. The synthetic/data matching procedure corrected the synthetic for the main wavelet differences and included amplitude scaling and bandpass filtering to enhance deeper reflections.

Supergathers, consisting of four interleaved CMP gathers, were used to allow the full range of offsets in the field data to be compared to the elastic synthetic. The CMP ordering ensured that events in the supergather were reflected from near the well, even under conditions of moderate dip. Supergather 842 (Figure 2-10a) was located nearest to Well 3 and contained strong refraction and guided-wave events. The elastic synthetic (Figure 2-10b) provided an excellent overall match to the timing and amplitude of key events in the supergather. It was particularly successful in matching the coal sequence amplitude response and the coal sequence surface multiple.
Figure 2-10. The noise contributions to a supergather (four interleaved CMP gathers) from the Gippsland Basin a) were well matched by the elastic synthetic seismogram computed for Well 3 b).

The greater amplitudes and slopes of refraction events and guided waves in the supergather are probably due to moderate anisotropy. The directivity of the source array might also account for the inaccuracies at the far offsets. In identifying the noise contributions to stacked data, absolute accuracy at the far offset events was not crucial because these events were muted prior to stacking. As discussed in the next chapter, the high quality of the match allowed several zones of strong noise to be identified (Table 2-2).
<table>
<thead>
<tr>
<th>D</th>
<th>Direct wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>Miocene carbonates</td>
</tr>
<tr>
<td>CS</td>
<td>Coal sequence</td>
</tr>
<tr>
<td>CS SM1</td>
<td>First-bounce coal sequence surface multiple</td>
</tr>
<tr>
<td>NZ1</td>
<td>Mode converted interbed multiples</td>
</tr>
<tr>
<td>NZ2a</td>
<td>MC/CS interbed multiples</td>
</tr>
<tr>
<td>NZ2b</td>
<td>MC/CS PPSP/PSPP reflections</td>
</tr>
<tr>
<td>NZ2c</td>
<td>MC/CS PSSP reflections</td>
</tr>
<tr>
<td>NZ3</td>
<td>Surface-related long period multiples</td>
</tr>
</tbody>
</table>

Table 2-2 Key to the annotation used to locate noise events in the elastic synthetics. Where possible, the labels are positioned to the upper right of an event.

2.4.3 Stacked field data matching

Minimal processing was applied to the matched synthetic and its neighbouring supergathers, using a single mute and NMO correction according to the RMS velocity calculated from the depth model. The stacked synthetic was spliced into the supergather section without the need for further matching adjustments. The field data comparison (Figure 2-11) was again exceptional, particularly within the coal sequence, the target zone and at the coal sequence surface multiple. This result shows that it is possible to obtain synthetic ties without resorting to phase matching or heavy duty processing.

Discrepancies in the compaction zone were expected but appear to have little effect upon the deeper response as demonstrated by the accurate modelling of the surface-related multiples. The Miocene carbonate reflections appeared to arrive about 35 ms earlier in the synthetics than in the supergather stacks and with larger amplitudes. Close examination of these reflections revealed greater guided wave interference in the supergather that reduced the stack amplitude of events above 1.0 s. I suspected that the timing discrepancy was related to the use of checkshot corrected velocities in modelling method in which Q attenuation effects are included (see Section 4.2.4). The stacked elastic synthetic did not provide a perfect match to the field data but the ability to follow the effects of the processing helped to explain the main discrepancies.
Figure 2-11. The spliced stack display contains the elastic synthetic (centre traces) and the adjacent supergathers after minimal processing through to stack. The high quality of this synthetic tie resulted in the identification of three zones of persistent noise in stacked data from this region.

2.5 CONCLUSIONS

In this chapter I showed that detailed and accurate field data matching is possible using the reflectivity method. This approach can produce stable synthetics for realistic depth models without generating artefacts that limit subsequent applications. In effect, the accuracy of the field data comparison is only limited by the original assumptions of isotropy and horizontal layering, and the ability to build a representative elastic depth model from little more than a sonic log. In the next chapter, I exploit the high quality of the synthetic tie to identify three zones of persistent noise in stacked data from this region.
Chapter 3

Identifying noise in seismic data

3.1 INTRODUCTION

Modelling studies are often performed in order to gain an understanding of the noise contributions to a seismic dataset. Some studies have predicted that specific noise trains, such as the mode converted reflections below a coal sequence, are strong enough to persist after CMP stacking (Fertig and Müller, 1978). However, without an adequate synthetic tie it is difficult to prove a noise hypothesis. For shallow, high amplitude noise events (i.e., supercritical reflections) it has been possible to confirm noise hypotheses using simplistic modelling and field data analyses (Winterstein and Hanten, 1985). However, it becomes increasingly difficult to determine the noise events that influence the deeper stack response. Furthermore, modelling alone can not predict all of the noise events associated with marine seismic acquisition. In some cases, cable motion and side-scattering can produce coherent noise events that dominate the deep stack response (Larner, et al., 1983).

In this chapter, I use several techniques to interpret the noise contributions to the elastic synthetic computed from Well 3. By virtue of the excellent synthetic tie, I am able to determine those that are most likely to persist in stacked sections from the Gippsland Basin. These include: 1) mode converted interbed multiples (generated within the Latrobe Group coal sequence); 2) S-wave reflections and long period multiples (generated at the coal sequence and Miocene carbonates), and 3) surface-related multiples. This noise interpretation later plays a central role in the development and testing of processing methods appropriate for this region.
3.2 IDENTIFYING MODELLED NOISE EVENTS

3.2.1 Modelling selected parts of the wavefield

Several noise contributions were identified by computing additional synthetics that contained components of the full reflection response. For example, the full extent of S-wave contributions was realised by allowing only P-wave contributions to propagate through the layer-to-layer recursion. The synthetic computed "without mode conversions" indicated the importance of S-wave events at offsets greater than 800 m and reaffirmed the need for elastic modelling (Figure 3-1). Its direct comparison to the elastic synthetic revealed: 1) the importance of mode converted short period multiples to the coal sequence response (NZ1); 2) S-wave refractions from the high velocity carbonates, and 3) S-wave reflections below the coal sequence (NZ2c).

![Figure 3-1. The synthetic computed without mode conversions revealed the importance of S-wave contributions at offsets greater than 800 m.](image)

Semblance analyses and zoom displays of the near offsets in the target zone indicated the possibility of S-wave reflections with only slightly lower stacking velocities than the primary reflections (NZ2b). Stacking the "without mode conversions" synthetic revealed
that S-wave reflections account for much of the coal sequence and target zone stack response (1.3-2.2 s), but very little elsewhere (Figure 3-2). This suggested that: 1) mode conversions within the coal sequence comprise a major part of the coal sequence response; 2) S-wave reflections (NZ2b) are likely to interfere with primary reflections in the target zone, and 3) that P-wave multiples dominate the deep stack response.

![Figure 3-2](image)

Figure 3-2. Stacking the synthetic computed without mode conversions suggested that S-wave reflections comprise much of the coal sequence and target zone stack response (1.3-2.2 s).

The coal sequence surface multiple (CS sm1), long period interbed multiples (NZ2a) and other surface-related multiples (NZ3) were identified by controlling reverberations on a layer-to-layer basis. However, I was forced to average-resample the depth model to a 16 m interval in order to avoid the problems associated with the modelling of primary reflections for a large number of highly reflective layers (see Chapter 1). Fortunately, the
full synthetic appeared quite similar to the original elastic synthetic, so that its noise interpretation should also be representative of the field data (Figure 3-3a).

By excluding multiples from the air/water interface I identified the guided waves (supercritical surface multiples) and realised the extent to which ghost and water bottom multiples distort the waveform of deeper reflections (Figure 3-3b). This was accompanied by a significant reduction in the coal sequence surface multiple (2.5 s) and in the reflections below this (NZ9), which are therefore likely to be surface-related multiples. It is worth noting that the S-wave refractions extend closer to the near offsets than expected due to the edge effect problem discussed in the previous chapter.

Figure 3-3. The 16 m averaged-resampled depth model was used to compute the full reflection response a), a synthetic lacking surface multiples b), a synthetic lacking all multiples c), and a synthetic containing only P-wave primaries d).
I then excluded all multiples, firstly retaining both P- and S-wave primaries (Figure 3-3c) and then retaining only the P-wave primaries (Figure 3-3d). Primaries are only generated down to 2.2 s so it appears likely that interformation interbed multiples account for much of the deep stack response. These are most likely generated between the coal sequence and the sea floor (NZ3) or the Miocene carbonates (NZ2a). From the primary synthetics, it is again clear that the S-wave reflections (NZ2b) interfere with the target zone primaries. Their relation to the deeper S-wave reflections (NZ2c) suggests that these are the PPSP/PSSP and PSSP reflections associated with the coal sequence.

These additional synthetics indicate the type of each significant noise train present in the elastic synthetic and suggest that: 1) mode converted short period multiples play a major role in extending the coal sequence response into the early part of the target zone (1.2-1.6 s); 2) P-wave surface-related multiples dominate the deep stack response (below 2.4 s), and 3) P-wave interbed multiples and PPSP/PSSP S-wave reflections interfere in the central target zone (1.5-2.4 s). However, these results do not indicate where the latter category of noise is generated nor whether it accounts for the lateral variation of the target zone noise.

3.2.2 Depth model variation

A simple technique for locating the origin of noise events is to vary the depth model in the region from which they are expected to originate. A logical place to start is the shallow S-wave velocity model, which determines the amount of mode conversion that occurs near the sea floor (Spudich and Helmberger, 1979; White and Stephen, 1980). I varied the Poisson ratio trend over the first 300 m to define S-wave velocity models representative of harder and softer sea floors. The hard compaction zone depth model produced an elastic synthetic that contained significantly stronger S-wave refractions while the soft compaction zone depth model produced an elastic synthetic that did not appear to contain S-wave refractions at all (Figure 3-4).
Figure 3-4. Only the S-wave refractions were significantly altered in the elastic synthetics computed from depth models that were representative of harder and softer sea floors.
The insensitivity of the S-wave reflections (NZ2b, NZ2c) to the sea floor model suggested that significant mode conversion must also occur away from the sea floor. In the previous chapter I found that significant mode conversion occurs at thin low velocity layers. Therefore efficient mode conversion might also occur at the Miocene carbonates where moderate velocity sediments form thin layers between the high velocity carbonates. The Miocene carbonates might also act as the upper multiple-generating layer for the interformation interbed multiples found below the coal sequence (NZ2a).

![Graph showing depth model with different types of changes](image)

**Figure 3-5.** The complex structure of the Miocene carbonates was simulated by reordering layers in the depth model (P-wave velocity shown) from 600-1100 m.

To confirm this hypothesis, I simulated the complex channelling structure of the carbonates by reordering layers in the depth model between 600 m and 1100 m. I computed synthetics for three reordered depth models containing different amounts of structural variation (Figure 3-5). Zoom displays of the target zone response confirmed the Miocene carbonates' influence upon both the S-wave reflections and long period interbed multiples (Figure 3-6). The stacked synthetics showed enough variation in the
target zone to account for the lateral noise variation observed in the field data, while remaining consistent with the structural variation expected in the carbonates (Figure 3-7).

**Figure 3-6.** Zoom displays of the target zone response confirmed the Miocene carbonates' influence upon both the S-wave reflections and long period interbed multiples. Panel a) is the original elastic synthetic from 1.2-2.2 s and between 100-1330 m. Panel’s b), c) and d) are the elastic synthetics respectively computed from the "subtle", "moderate" and "large" change depth models.

**Figure 3-7.** Panel's a), b), c) and d) are the stacks for each of the synthetics shown in Figure 3-6. They show enough variation in the target zone to account for the lateral noise variation observed in the field data.
Having identified the target zone noise contributions, I then attempted to pinpoint key target reflections using a synthetic computed from only the first 2200 m of the depth model. Only a few subtle differences were observed in the target zone stack response suggesting that considerable processing is required to improve the deep seismic image near Well 3.

3.2.3 Analysis techniques

Noise identification is easier when performed in a seismic data domain where different event types are well separated from each other. The $\tau$-$p$ domain achieves an excellent separation between most event types and has the advantage of exact periodicity (along $p$ traces) for multiples. Elastic synthetics can be easily computed in the $\tau$-$p$ domain by applying an inverse FFT to the reflection response $R_\theta(\omega, p)$. However, a $\tau$-$p$ domain version of an elastic synthetic will appear as if it were acquired using an infinite length cable.

Several interpretational advantages can be seen in the $\tau$-$p$ domain version of the elastic synthetic computed from Well 3 (Figure 3-8). The guided waves and direct wave are confined to the large $p$ values and the S-wave reflections, although appearing somewhat incoherent, are separated by angle from the P-wave events in the target zone. Using this analysis I was able to identify a supercritical section of the reflections from the Miocene carbonates, which I later used to improve velocity analyses.

Semblance analyses are particularly useful for determining which noise reflections are most likely to remain after stacking. As shown in Chapter 7, RMS velocity functions for signal and noise can be computed from the depth model and used to identify events in the semblance analysis. For the elastic synthetic, this revealed that the NZ2a events lie within 5-15% of the primary velocity function, while the NZ2b events lie within 10-20%.
Finally, the display method can also assist the interpretation of elastic synthetics. For example, I found that the traditional "variable area wiggle" was useful for identifying S-wave reflections in the $t$-$x$ domain. Red/Blue displays help to reveal amplitude variations with offset and can be used to identify multiples on this basis. In the $\tau$-$p$ domain, dB colour displays help to boost weak events so that the amplitude differences between all events can be judged without time gain applied. Perhaps the most important aid to a noise interpretation is the ability to perform fast screen swapping between several analyses.
3.3 IDENTIFYING COHERENT NON-MODELLED NOISE EVENTS

In the previous section, I showed that it is possible to interpret the main noise contributions to an elastic synthetic. However, the noise interpretation of field data is complicated by the need to identify noise events associated with the acquisition. Scattered energy appears to pose the greatest problem, particularly in areas where the sea floor is shallow and hard, as it can be boosted by CMP stacking to produce coherent noise trains with a linear moveout across a stacked section (Larner, et al., 1983).

Non-modelled noise contributions can be identified during an inspection of several shot records across a seismic line. To deduce the origin of specific noise events, I recommend use of Larner's paper as it provides several examples of the main types of acquisition noise. I found that acquisition noise is most visible at large travel times and at the near offsets where seismic events are weakest. Noise types that are independent of the source explosion can also be found prior to the first-break refractions. Some noise types have a strong frequency dependence so it may be useful to inspect the data over several short bandwidths.

Some types of acquisition noise are difficult to identify in CMP gathers, even when they are easily seen in nearby shot records (Larner, et al., 1983). For example, in a supergather from Line A, I was able to identify strong noise bursts (Figure 3-9a), while in a nearby shot record I found several indications of forward and backscattered energy (Figure 3-9b). Looking back at the supergather, the scattered energy can be seen but is much weaker and therefore difficult to identify. After applying a low pass filter to the same shot record, I found two low velocity events (~ 300 m/s) that are probably caused by the mechanical motion of the cable (Figure 3-9c).
Figure 3-9. I found strong noise bursts in a supergather from Line A a) but overlooked the forward and backscattered energy indicated in a nearby shot record b). I then found low velocity noise after low pass filtering the same shot record c).
For seismic data from the Gippsland Basin, the low velocity cable noise is quite weak and does not appear to affect the stacked sections. Data spikes and noise bursts are quite common and persist through to stack unless suppressed using an automated editing algorithm included with ProMAX™. The scattered noise dominates the stacked section below 2.0 s and is generated by irregularities at the sea floor or in the shallow geology. During the processing of Line B, I was able to trace a particularly strong scattered noise train to an oil pipeline that crossed the line at right angles. These noise events are partially suppressed by the dip filtering action of migration. Further improvements in the deep stack response might result from the use of a wide source array, which would help to direct more energy into the in-line plane.

3.4 CONCLUSIONS

Prestack seismic data from this region contain a wide range of noise events and this allowed me to develop some general guidelines for noise identification using elastic synthetic seismograms. My approach involves comparisons across several seismic data domains using additional synthetics that are computed from variations upon the original depth model and with some parts of the response removed (Table 3-1). Acquisition noise that can not be modelled must be identified from an inspection of shot records, which should prove relatively straightforward after using the elastic synthetics to identify the main noise events.

In identifying the noise contributions to seismic data from the Gippsland Basin, I confirmed my suspicion that S-wave reflections play a prominent role in the subcoal imaging problem. However, I was surprised to discover the role of the Miocene carbonates in generating the S-wave reflections and long period multiples with the coal sequence. I had originally thought that greater mode conversion would occur at the sea floor. Hard sea floors and carbonate platforms exist in most of the Australian offshore exploration permits, so that S-wave noise problems might be quite common.
Table 3-1. Elastic modelling strategies for noise identification.

Improved seismic imaging in the Gippsland Basin might be achieved if the interference effects of each of the noise contributions can be reduced during the processing. Strong motivation for a $\tau$-$p$ domain approach results from the wide variety of troublesome noise events. In Table 3-2, I restate the noise contributions, their influence upon the stacked section and the properties that could be exploited to achieve suppression.

Table 3-2. The noise contributions to seismic data from the Gippsland Basin and the properties that could be exploited to achieve suppression.
Chapter 4

Building a detailed elastic depth model with limited information

4.1 INTRODUCTION

Seismic wave propagation in a solid, isotropic medium is controlled by the P-wave velocity \( V_p \), the density \( \rho \), the S-wave velocity \( V_s \) and the inelastic attenuation of P- and S-waves \( Q_p \) and \( Q_s \). I refer to the variation of these parameters in the subsurface as the "elastic depth model". For most seismic reflection experiments only the P-wave velocity is likely to be known for parts of the depth model. Fortunately, a coarse description of the P-wave velocity is often sufficient to interpret the main features of a seismic dataset. However, in the Gippsland Basin and many other exploration permits, signal and noise events depend strongly on other parameters in the elastic depth model. In this situation, the construction of an accurate synthetic tie requires knowledge of how the poorly constrained parts of the depth model affect the reflection response.

Accurate modelling and sensitivity analyses are also important to prestack inversion studies (McAulay, 1986), especially when the seismic data contain strong multiples and mode converted events. In building an elastic depth model, one must first select an appropriate depth sampling interval as thin layers, of significant lateral extent, will affect seismic data in a similar manner to thicker, anisotropic layers (Folstad and Schoenberg, 1992).

Extra care must be taken near the sea floor where strong surface multiples are generated and the efficiency of mode conversion is highly sensitive to the S-wave velocity (White and Stephen, 1980). Despite this, mode converted reflections are often neglected in marine seismic studies because the presence of unconsolidated sediments at the sea floor
results in only weak PSSP reflections (Kim and Seriff, 1992) which are then further suppressed by conventional processing. However, mode converted reflections can be quite strong for a hard sea floor, along with other noise events such as guided waves and surface multiples, and these may not be fully suppressed by processing. When the S-wave velocity approaches and then exceeds the P-wave velocity in water, abrupt changes in the appearance of the guided waves could have serious ramifications for the field data processing (Kennett, 1996).

The influence of the S-wave velocity on a thin layer reflection response is of considerable importance to AVO studies involving oil and gas bearing sands. Some studies suggest a high level of sensitivity (Payne, 1991), despite the (often unspecified) requirement of weak P-wave velocity contrasts across the thin layer. Currently S-wave velocity logs are often not acquired. As used in Chapter 2, the S-wave velocity of the deeper sediments can be approximated using Poisson ratio estimates and the P-wave velocity log, in order to obtain a synthetic tie.

Density affects reflection amplitudes only and can be estimated from the P-wave velocity using Gardner's equation (Gardner, et al., 1974). Another important influence upon seismic waves is inelastic attenuation, which is well approximated by a frequency independent quality factor (Kennett, 1975) for the bandwidth of the reflection signal. Finally, it must be remembered that horizontal variability in structure will limit the accuracy of a synthetic tie, although the extent to which the match will be affected is not easily predicted.

Previous studies into the sensitivity of the seismic reflection experiment usually involve some form of synthetic modelling and tend to focus on the influence of a single part of the depth model or a single noise type. In most cases, the lack of detail in the depth model or the limitations of the modelling method are such that the results are not representative of field data. The sensitivity analyses must also be carried through to
stack so that the remaining dependencies are limited to the acquisition parameters, dip and the character of the geology.

In Chapter 3, I interpreted the noise contributions to marine seismic data from the Gippsland Basin using elastic synthetic seismograms computed from a detailed elastic depth model. The depth model was built solely from P-wave velocity and density measurements obtained from part of a nearby well. Despite this, the full synthetic seismogram computed using the reflectivity method gave an accurate description of prestack and stacked seismic data. I now use this example to discuss the general construction of an elastic depth model. My separate investigations of depth sampling, S-wave velocity, density, Q attenuation and lateral structure therefore constitute a sensitivity analysis of seismic data to the poorly constrained parameters in an elastic depth model.

4.2 P-WAVE VELOCITY MODEL

In each of the experiments in this chapter, the depth model from Chapter 2 was used as a reference from which alternative depth models were investigated and linked to field data observations. Changes to the signal and noise events in the elastic synthetic were used to assess the sensitivity to variations in the depth model.

4.2.1 Depth sampling

How much detail is required in an elastic depth model to obtain an accurate synthetic tie to field data? I found a depth sampling interval (Δz) of 1 m to be sufficient for a typical seismic bandwidth (0-70 Hz) using the reference depth model. Naturally, more detail is required when highly reflective layers are present and when higher frequencies are used. To reach this conclusion I average-resampled the raw well-logs to coarser depth sampling intervals, then computed and stacked the elastic synthetics for each. The same
compaction zone was used in each model to avoid surface related effects that might confuse the results.

![Figure 4-1](image_url)

Figure 4-1. A spliced stack comparison indicating the dependence of stacked elastic synthetics (centre) on the depth sampling interval and the extent to which thin layering can influence seismic data from this region.

Splicing these synthetics within an adjacent stacked section (Figure 4-1) revealed the extent to which depth sampling can influence a synthetic tie. For $\Delta z = 0.25$-1 m, the stacked synthetics are nearly identical and provide an excellent match to both signal and noise. For $\Delta z = 2$-8 m, timing errors appear to increase in a linear fashion and noise interpretation becomes far more difficult (e.g., the coal sequence surface multiple near 2.5 s). For $\Delta z = 16$-32 m, key primary events are drastically altered to the extent that these synthetics barely match the stacked data.
I selected four important events in the elastic synthetic and measured their travel times and peak amplitudes as $\Delta z$ was varied, which upon graphing suggested that the synthetic had stabilised for $\Delta z \leq 1$ m (Figure 4-2). These graphs also helped to place limits on the timing and amplitude errors for other events in the stacked synthetic. Seismic data from this region appear quite insensitive to layering on a scale below 1 m, therefore I do not expect finer depth sampling to account for the remaining discrepancies in the field data comparison.

![Graphs](image)

**Figure 4-2.** A graphical analysis of the timing a) and amplitude b) of four key events suggested that the elastic synthetic had stabilised for depth sampling intervals below 1 m. The two-way times (TWT) and amplitudes were normalised for each event using the synthetic computed from the 0.25 m model.

### 4.2.2 Replacing missing sonic log sections

Missing segments of the sonic log used to build an elastic depth model can strongly affect the quality of a synthetic tie and result in a false noise interpretation. I investigated the deterioration of the synthetic tie (Figure 4-3a) and noise interpretation by removing large sections of the sonic log and remodelling. Only a few of the high velocity
carbonates were lost when replacing the first 500 m of the sonic log with a linear, checkshot corrected trend. The synthetic tie (Figure 4-3b) remained quite accurate because the main noise contributions were represented. However, the reduced transmission loss gave the coal sequence interbed multiples (NZ1) a significantly higher frequency content.

![Graph](image)

**Figure 4-3.** The absence of the early part of the sonic log can dramatically alter the appearance of the stacked elastic synthetic a). With a shallow 500 m section missing, the coal sequence and its short period interbed multiples (NZ1) suffered only minor changes b). However, the noise events (NZ2) generated in the missing region were significantly altered when a 1000 m section was removed c).

The remainder of the Miocene carbonate sequence was omitted when replacing the first 1000 m of the sonic log with a linear trend. The long period interbed multiples and S-wave reflections (NZ2) generated in the missing region are clearly absent from the stacked synthetic in the target zone (Figure 4-3c). The coal sequence response now has
a much higher frequency content due to the reduced transmission loss and this also affects the appearance of the coal sequence surface multiple (CS sm).

From these simple tests it appears that over 75% of the well must be logged to maintain enough accuracy to warrant a detailed elastic modelling study. It is possible that the transmission effects through a missing section could be simulated by a statistical replacement of the missing part of the depth model. However, isolated noise events will remain difficult to identify if the missing section includes a noise generating formation.

4.2.3 The sea floor model

Seismic data are highly sensitive to the P-wave velocity model at the sea floor through the strong surface-related multiples that are generated there. However, shallow sonic logs are rarely acquired or can not be trusted near the sea floor. Sea floor sediments are likely to possess highly variable acoustic properties, although an overall character (e.g., hard, soft) can usually be assigned to the sea floor from a particular region. My experiences in modelling seismic data from the Gippsland Basin have indicated the sea floor model to be the main difficulty in building an elastic depth model.

I found that simple curves can be used to approximate the P-wave velocity trend near the sea floor. Although a linear trend \((V_p \propto z)\) can be adequate in some regions, the P-wave velocity of sea floor sediments might often conform better to a theoretical model based on the compaction of elastic spheres (Gassman, 1951). Both the theoretical compaction trend \((V_p \propto z^{1/6})\) and the linear trend are defined using only two parameters and these can be estimated from checkshot information or the first-break refractions, provided that velocity anisotropy is negligible near the sea floor. For the reference model, I used the checkshot time at the start of the sonic log and the slope of the first-break refraction at the near offsets and found that the compaction model gave a better tie.
The sea floor model is a strong influence upon the P-wave refractions and guided waves that often dominate an elastic synthetic. Perhaps the sea floor model should be selected, and perhaps adjusted, based upon the synthetic tie to these events. The use of simple trends can sometimes result in poor matches when there is distinct layering in the shallow subsurface, such as a thick, low velocity mud layer at the sea floor. If this occurs, interval velocity estimates obtained from a velocity analysis of nearby field records might help to introduce further detail into the sea floor model. Finally, the RMS velocity of the proposed sea floor velocity model should be compared to field data semblance analyses as a useful check prior to remodelling.

4.2.4 Checkshot corrections

Although checkshot corrections can help to replace missing sections of a sonic log, it appears that they should not be used to drift correct the sonic log when constructing an elastic depth model. For "borehole compensated" logging tools, the majority of sonic log drift appears to be positive and can be explained by the frequency dependency of the P-wave velocity (Goetz, et al., 1979). In other words, the difference between the checkshot time and the integrated sonic log time is mostly due to the greater Q attenuation suffered by the seismic pulse used to record the checkshot survey.

If the Q attenuation of the logging pulse is negligible, then the drift correction should not be applied as the Q attenuation of the seismic pulse will be simulated by the modified reflectivity method. In fact the drift correction should not be applied, even if the Q attenuation of the logging pulse is significant because a better match will be achieved by adjusting the Q values to represent a relative (rather than absolute) inelastic attenuation.

The sonic log for Well 3 had been drift corrected and this explains the early arrival of the Miocene carbonate reflections relative to the coal sequence reflections that were used as the tie point. In contrast, the elastic synthetics for Wells 4 and 5 (see Chapter 9) were
constructed without applying a drift correction and did not indicate any significant timing discrepancies between these formations. With further work, it may be possible to use the checkshot survey to refine Q estimates in some sections of the depth model, allowing for the possibility of other sources of drift.

4.3 S-WAVE VELOCITY MODEL

4.3.1 The sea floor model

For a typical sea floor transition zone, an increase in the S-wave velocity gradient results in more efficient mode conversion (White and Stephen, 1980). I studied this effect in the previous chapter by varying the Poisson ratio trend over the first 300 m to define elastic depth models representative of harder and softer sea floors (Figure 3-4). I found that the hard sea floor synthetic contained significantly stronger S-wave refractions while the soft compaction zone synthetic did not appear to contain S-wave refractions at all. This sensitivity was also observed in field records from the Gippsland Basin, suggesting that an analysis of the S-wave refractions in field data might help to constrain the S-wave velocity model near the sea floor.

In regions where there are carbonates or volcanics at the sea floor, it is possible that the shallow S-wave velocities will be greater than the P-wave velocity of water \( (V_p = 1.5 \text{ km/s}) \). When this occurs, the guided wave events are highly sensitive to S-wave velocity model via the positioning of the critical reflection points for the S-wave reflections (Kennett, 1996). A better understanding of this phenomenon may have important ramifications for noise suppression in regions where the shallow S-wave velocity fluctuates around 1.5 km/s.
4.3.2 Replacing a missing S-wave velocity log

When an S-wave velocity log is unavailable, laboratory estimates of the Poisson ratio for each significant geological formation can be used to construct an "artificial" S-wave velocity model. I developed and tested this approach using a "real" S-wave velocity log from another well in the Gippsland Basin. The experiments below suggest that P-wave processed seismic data are quite insensitive to the S-wave velocity model provided that it contains as much detail as the P-wave velocity model.

I observed a strong connection between the sonic log and the Poisson ratio measured over a 300 m interval for Well 1. Ignoring fluctuations of limited depth extent, an obvious formation change in the sonic log was reflected by a change in the Poisson ratio (Figure 4-4a). Furthermore, the sonic log trend was mirrored by the Poisson ratio. The $V_S-V_P$ distribution for each formation suggested that large geological formations might be well approximated by a single Poisson ratio (Figure 4-4b). This meant that the average Poisson ratio for each formation could be used to construct a representative S-wave velocity model. Using a single Poisson ratio for each formation ($\sigma_A = 0.37$, $\sigma_B = 0.25$), the S-wave velocity model compared extremely well to the "real" S-wave velocity log (Figure 4-4c). Errors in applying the formation Poisson ratios caused an overall mismatch between the "artificial" and "real" S-wave velocities but tended to preserve the S-wave impedance contrasts.

I added a water layer and shallow compaction zone to form a depth model to determine the sensitivity of elastic synthetics to the S-wave velocity model. In particular, I studied the PPSP/PSPP events as these were well isolated from other events in the elastic synthetic (Figure 4-5). Zoom comparisons revealed that the synthetic computed from the "real" S-wave velocity log (Figure 4-6a) was almost identical to that computed from the "artificial" S-wave velocity model (Figure 4-6b). The match remained quite accurate when $\sigma_B$ was reduced to 0.20 (Figure 4-6c) and increased to 0.30 (Figure 4-6d). These
small differences are likely to be rendered unimportant in situations where primary P-wave reflections interfere with the S-wave events and thus dominate the stack response.

Figure 4-4. An S-wave velocity log from Well 1 suggested that formation changes are often accompanied by a change in the locally averaged Poisson ratio a). The $V_S-V_P$ distribution suggested that each formation could be assigned a single Poisson ratio b) to produce an "artificial" S-wave velocity log that closely resembles the measured log c).
Figure 4-5. I incorporated the "artificial" S-wave velocity log into a simplistic depth model to study the sensitivity of elastic synthetics to the S-wave velocity model using the strong and isolated PPSP/PSP events.

Figure 4-6. The PPSP/PSP events computed from the measured log a) compared well to those computed from the "artificial" S-wave velocity log b). The match remained accurate when the Poisson ratio of the lower formation was reduced to 0.20 c) and was increased to 0.30 d).

The insensitivity of the Gippsland Basin synthetics to the S-wave velocity profile does not imply that S-waves can be excluded from the synthetic computation. The example in the previous chapter (Figure 3-2) where S-waves were excluded from the recursion is a strong reminder of their relevance to marine seismic exploration. The experiments above
merely suggest that a coarse model of the Poisson ratio is often sufficient to produce an accurate synthetic tie. This implies that a composite reflection response is insensitive to the S-wave velocity, which may explain why AVO analyses are not always reliable. AVO techniques are not likely to indicate changes in the Poisson ratio when applied to highly reflective, thin layered sequences. Instead, AVO methods work best when the P-wave impedance contrasts are small so that the S-wave impedance contrasts play a greater role in forming the composite reflection response.

The S-wave events that persist in seismic data from the Gippsland Basin originate from a large number of strong S-wave impedance contrasts and thus require detail in the elastic depth model. For instance, I observed significant changes in the timing of the mode converted interbed multiples (NZ1) when the S-wave velocity model was averaged over 10 m and 100 m intervals. My approach for building an S-wave velocity model proved useful because any errors in applying the formation Poisson ratios tended to preserve the S-wave impedance contrasts, which in turn preserved the composite reflection response. The long traveltine S-wave events, whose timing might have been affected by inaccuracies in the S-wave velocity model, were well suppressed by CMP stacking. This interesting distinction between detail and accuracy suggests that a smooth Poisson ratio trend is well suited to the task of building an elastic depth model.

### 4.4 DENSITY

Density solely affects the amplitude of both primary and noise reflections. When a density log is unavailable, Gardner's equation can be used to estimate the density model from the P-wave velocity. For the reference depth model, Gardner's equation provided an excellent match to the "real" density log, except at the coal sequence where it was consistently in error by up to 1 g/cc. This was not surprising as Gardner's equation is based on measurements from a large number of typical sedimentary rocks and the Latrobe Group coal seams have exceptionally low densities.