The Kupe Velocity Model - 4D Taranaki Project

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BIBLIOGRAPHIC REFERENCE

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ABSTRACT

The Kupe mapping area (KUP) is the first of seven offshore regions within the Taranaki Basin to be seismically mapped as part of the GNS Science 4D-Taranaki (4DT) Project. Seventeen horizons were interpreted throughout the region.

Here we present the velocity model used to depth convert the 4DT seismic interpretation within the KUP area. Constant velocities are used for five layers including the water column and basement. All other layers, six in total, used a \( V_0 / k \) method, where \( V_0 \) represents velocity at the top of a layer, and \( k \) represents the velocity gradient within a layer. Layer velocities were clipped at a maximum of either 4000 or 5000 metres per second (m/s) so that thick layers did not have unrealistically high velocities.

The velocity model is represented as a voxet (3D cellular cube) with 1 km x 1 km x 100 millisecond (ms) cells that contain an average velocity attribute that is used for time-depth conversion. A comparison between the depths of horizons calculated by the model and depths derived from the local well model (calibrated two-way time (TWT) / Depth curve) in the Kupe region indicates mean differences of between 10 and 20 m with the minimum value of 1.85 m (seabed) and maximum value of 57.5 m (K90 at Tahi-1).

The 4DT model predicts a thicker sedimentary sequence than that previously modelled by Thrasher et al (1995) for the Kupe Region. The Top Cretaceous surface is up to 2.5 km deeper on the western side of the Manaia Fault, and up to 1.7 km deeper on the eastern side.

The velocity model is provided by GNS Science in Fohrmann et al. (2012a), in both ASCII and SEGY formats, for both time and depth domains.

KEYWORDS

Taranaki Basin, 4DT, Kupe mapping area, depth conversion, velocity model, average velocity, interval velocity, stacking velocity, GOCAD, voxet
1.0 INTRODUCTION

The Kupe mapping area (KUP) is one of seven regions within the Taranaki Basin (Figure 1) that are being mapped by GNS Science as part of the 4D Taranaki (4DT) project (Arnot et al., 2008; Leitner et al., 2008; Leitner et al., 2006) using publically available seismic reflection data. The overall objective of this multi-year project is to produce a digital atlas of the seismic stratigraphy and structure within the Taranaki Basin, and associated derivative products such as petroleum generation models, migration models, and structural restorations. The primary mapping and interpretation reports for the KUP study are provided in Fohrmann et al. (2012a, 2012b).

This report provides a detailed overview of the velocity model used to depth convert the 4DT seismic interpretation within the KUP area, and provides summary depth statistics, including the error in the depth-conversion at well locations. Finally this velocity model is compared to the previous model of Thrasher et al. (1995).

The time-depth conversion methods presented in this report are based on the ‘$V_0 / k$’ methods described by Marsden (1992) and Etris et al.,(2001) using functions given by Al-Chalabi (1997). The KUP area has been divided into layers where the vertical component of velocity within a layer is modelled with linear functions. $V_0$ represents velocity at the top of a layer, and $k$ represents the velocity gradient within a layer.

Figure 2 illustrates the general modelling workflow. Firstly, modelling constraints were identified, filtered and processed. Then layer boundaries were chosen based on velocity discontinuities, and a series of vertical velocity functions were derived from well data. These functions were integrated with seismic stacking velocities to generate $V_0$ grids across the whole of the KUP area. Velocity / depth functions derived from regional well data were used for deeper layers that were not sampled sufficiently by local wells or stacking velocity data. Finally a voxet model (3D cellular model) was built using Paradigm GOCAD software. Each cell within the voxet model contains an average velocity attribute. This voxet model is provided by GNS Science in Fohrmann et al. (2012a), in both ASCII and SEGY formats, for both time and depth domains.

Further details about each step in the modelling workflow are presented in the following sections.
Figure 1   Location of the Kupe Mapping area (yellow box, KUP). Petroleum wells are shown as circles. Other mapping areas of the 4D Taranaki Project are: NGR, Northern Graben; NWP, Northern Western Platform; WPL, Western Platform; CEN, Central; SIV, Southern Inversion Zone; ONS, Onshore; WAN, Whanganui Basin.
2.0 MODEL CONSTRAINTS AND PRE-PROCESSING

The velocities used for time-depth conversion were constrained using local well data within the KUP area, regional well data from the greater southern Taranaki Basin (see listing in Appendix A), and seismic stacking velocity data. The choices for possible layer boundaries were limited to the existing collection of seventeen TWT surfaces that have been mapped across the region. For details about the seismic interpretation within the KUP area, including also the depth-structure and isopach maps that were created using this velocity model, refer to Fohrmann et al. (2012a, 2012b).

Previous velocity studies within the Taranaki Basin such as Stagpoole (1998), Thrasher and Cahill (1990) or Thrasher (1988) were useful in terms of methodology, and as a point of reference to indicate the velocity ranges for rock layers of certain age and depth.

The following sections describe the data used for time-depth conversion in more detail and explain the pre-processing steps undertaken prior to the use of these data as model input. Figure 3 shows the locations of well and stacking velocity data within the KUP area.

2.1 LOCAL WELL VELOCITY DATA

The time-depth relationships from seven wells in the KUP area were used in this analysis. These data are derived from high-resolution sonic logs that have been calibrated with lower-resolution check-shot data (Zhu et al., 2010). Table 1 lists the wells in the KUP area and the depth range of their sonic log data. Kupe-South-3 data were not used because sonic data were only acquired over 8% of the well path, between 3030 and 3312 m.

Velocity analysis of the well data has been carried out on the interval velocity log \(V_{int \ log}\) which is the first order derivative of the time-depth curve. The calibrated two-way time (TWT) depth logs for these wells have a sample interval of 2 m.
Table 1 Coverage of sonic log data within the KUP area. KS = ‘Kupe South’. Depths are relative to the drilling platform.

<table>
<thead>
<tr>
<th>Wells</th>
<th>Sonic range (m)</th>
<th>TD (m)</th>
<th>Min Z</th>
<th>Max Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kupe-1</td>
<td>3682</td>
<td>100</td>
<td>3682</td>
<td></td>
</tr>
<tr>
<td>KS-1</td>
<td>3503</td>
<td>35</td>
<td>3503</td>
<td></td>
</tr>
<tr>
<td>KS-2</td>
<td>3250</td>
<td>640</td>
<td>3250</td>
<td></td>
</tr>
<tr>
<td>KS-3</td>
<td>3438</td>
<td>3030</td>
<td>3438</td>
<td></td>
</tr>
<tr>
<td>KS-4</td>
<td>3795</td>
<td>570</td>
<td>3780</td>
<td></td>
</tr>
<tr>
<td>KS-5</td>
<td>3200</td>
<td>460</td>
<td>3220</td>
<td></td>
</tr>
<tr>
<td>Tahi-1</td>
<td>1776</td>
<td>490</td>
<td>1770</td>
<td></td>
</tr>
<tr>
<td>Toru-1</td>
<td>4158</td>
<td>500</td>
<td>4140</td>
<td></td>
</tr>
</tbody>
</table>

2.2 STACKING VELOCITY DATA

Stacking velocity data within the KUP area were sourced from one 3D seismic survey (Kerry 3D, (Western-Mining-Corporation, 1996)) and 171 2D seismic lines (see lines used for interpretation in Fohrmann et al. (2012a). The region of 3D coverage encompasses all wells except Tahi-1 and stacking velocity data are spaced every 200 m. Outside the 3D survey region, data coverage is generally consistent with 1-2 stacking velocity data points every 2 km. The data are sparser south of the Tahi-1 well, and there are gaps around the edge of the Kerry 3D survey (see Figure 3).
Figure 3  Position of well data (cross hairs) and stacking velocity data (dots) within the KUP area. Major reverse faults (at P50 level - from Fohrmann et al (2012a)) are indicated by the solid black lines. All wells are located on top of the Manaia Anticline, on the eastern side of the Manaia Fault. The grey polygon marks the area of stacking velocity data derived from the Kerry 3D survey. See Figure 1 for location.
2.2.1 Conversion to Interval Velocities and Filtering

A generalised form of the Dix Equation (Nowroozi, 1989) shown below, was used to calculate interval velocities from stacking velocity data (hereby called ‘Dix interval velocities’). The essential assumptions for this conversion are that stacking velocities are assumed to be equivalent to root-mean-square velocities and layers are horizontal and isotropic.

\[ V_{\text{int}} = \left( \frac{t_2 v_{\text{stack}2}^2 - t_1 v_{\text{stack}1}^2}{t_2 - t_1} \right)^{\frac{1}{2}} \]  

(Eq. 1)

where,

- \( V_{\text{int}} \) = interval velocity
- \( t_1 \) = travel time of first reflector
- \( t_2 \) = travel time of second reflector
- \( v_{\text{stack}1} \) = stacking velocity of first reflector
- \( v_{\text{stack}2} \) = stacking velocity of second reflector

The estimation of stacking velocity, in general, carries many uncertainties, which tend to increase with depth as both the signal to noise ratio, and dominant wavelet frequency within seismic data, decrease with depth. Uncertainty in stacking velocity estimation also varies between seismic lines and between seismic surveys because of different acquisition parameters, different processing methods and different geology.

When Dix interval velocities are calculated from stacking velocities, the error with depth becomes amplified (Hajnal and Sereda, 1981). Also, the Dix equation has an uncertainty that is inversely proportional to the TWT thickness of the interval (Hajnal and Sereda, 1981).

A filter comprising maximum cut off values for TWT and velocity, and a minimum cut off value for TWT interval thickness, was used because of the uncertainties described above. Maximum values for TWT and velocity were derived by comparing well velocities to Dix interval velocities. Figure 4 shows all Dix interval velocities within 500 m of the Kupe-1, and Kupe-South wells plotted with the well \( V_{\text{int}} \) velocity logs against TWT. Dix interval velocities are generally lower than well velocities to about two seconds TWT, where they become similar. At TWTs greater than three seconds, beyond the depth range of well data, Dix interval velocities climb steeply up to 7000 m/s. This last trend is unconstrained, and seems highly unlikely in the Kupe region where no large thicknesses of high velocity volcanic / igneous / salt assemblages have been interpreted and seismic data have indicated only sedimentary layering (Fohrmann et al., 2012a). No Dix interval velocities below three seconds TWT were used and all Dix interval velocities greater than 5000 m/s were also eliminated. This value is considered a reasonable upper threshold for the velocity of strata penetrated by the Kupe wells.

Finally, because of errors that are accentuated with thin layers, all Dix interval velocities calculated for intervals with thickness less than 200 ms TWT were not used.
2.3 **Regional Well Data**

Well velocity data outside the KUP area, were used to provide constraints on the velocity for deeper layers that are only partially, or not penetrated by the Kupe wells. All the wells from which velocity data were assessed are listed in Appendix A; and their velocity data are derived from the calibrated time-depth curves found in Arnot *et al.* (2010), Juniper *et al.* (2010) and Zhu *et al.* (2010).

Well velocity data were filtered based on an analysis of uplift history. A significantly different uplift history between locations suggests that the corresponding velocity / depth relationships would also be different because of differing compaction histories. Generally, the velocity / depth profile for uplifted rocks reflects the maximum depth of burial, rather than the present depth because the rocks remain compacted (Armstrong et al., 1998; Sheriff, 1978).
Burial histories for all regional wells were examined using Late Miocene erosion values from Wood et al. (1998), as an indication of uplift; and Pleistocene-Pliocene sediment thickness values from Thrasher et al. (1995), as an indication of subsidence. It was found that wells in regions that had experienced a large amount of uplift since the Late Miocene (Uplift – Subsidence > 1000 m), typically had higher velocities over the same depth range (see Figure 5). These wells were excluded from the analysis.

2.4 TWT HORIZON MERGING, SMOOTHING AND CALIBRATION

The TWT horizons that define the boundaries of layers in the velocity model are represented by grids with cell size 500 x 500 m. All grids are continuous throughout the KUP area. The seismic horizons have been merged with any horizons that they on-lap, or are truncated by. Reverse faults are represented by vertical steps with the up-thrown side preserved.

Abrupt changes in the shape of a horizon (such as across reverse faults) will lead to abrupt lateral changes in velocity and therefore produce undesirable depth changes. To create smooth transitions across surfaces all TWT grids have been smoothed everywhere using three passes of a 10 x 10 km sized window. After smoothing the grids were re-calibrated at well locations and to ensure stratigraphic consistency, any surface-crossings that resulted from smoothing were removed. Figure 11 illustrates the difference between processed and unprocessed TWT horizons.

The Manaia and Taranaki Faults are two significant thrust faults which are likely to have vertical velocity inversions. Over-thrust regions are difficult to model when using grids to define the model geometry because only one z-value can be stored in each grid cell. These regions are therefore not perfectly represented in this model.

Figure 5 Average velocity / Depth profile coloured by Post-Miocene Burial History

Figure 5 Average velocity / Depth profiles for regional Taranaki Basin wells (see list of wells in Appendix A) coloured by burial history. The burial history value is the summation of total uplift minus total subsidence since the Late Miocene. All Kupe wells apart from Tahi-1 are in the grey group. The Tahi-1 well is in the blue group. All wells in the red group are from regions that have undergone significant uplift, and consequently show higher velocity trends. These wells are not considered suitable for use in the Kupe velocity model.
3.0 WELL VELOCITY MODELLING

3.1 MODELLING APPROACH

The Kupe velocity model comprises eleven velocity layers. Layer boundaries and velocity functions are based on changes in long-wavelength (~500 – 1000 m) velocity trends identified from well data. The layer boundaries and type of velocity function used for each layer are presented in Table 2. The velocity model layers between mean sea level (top) and basement (bottom), the method to derive velocity for each layer and the values for \( V_0 \) and \( k \) where singular values were used.

Velocity within a layer has been either made constant \( (V = V_0) \) or calculated with the function (Al-Chalabi, 1997):

\[
V = V_0 + k(Z - Z_0)
\]  
(Eq. 2)

where:

\( k \) is the velocity gradient within each layer.

\( V_0 \) is the velocity at the top of the layer.

\( Z \) is calculated depth.

\( Z_0 \) is the depth to the top of the layer.

The following equation is the corresponding time-depth relationship derived as the integral of the equation above (Al-Chalabi, 1997):

\[
Z = Z_0 + \left( \frac{V_0}{k} \right) \left( e^{k(T - T_0)} - 1 \right)
\]  
(Eq. 3)

\( V_0 \) is either given as an array of values (surface input) or as a singular value for each velocity interval.

\( k \) and \( V_0 \) values were derived from well velocity data by finding the time-depth profile that gives the minimum depth-error across all wells for each interval, according to the methods proposed by Legge and Rupnik (1943).

The spatial distribution of the well data, indicated in Figure 3 is not ideal when trying to extrapolate their velocity / depth relationships across the KUP area. Like most exploration wells they were drilled on a structural anomaly, the top of the Manaia Anticline, where stratigraphic formations are either relatively thin and/or shallow. All the wells are located along the eastern side of the Manaia Fault, however west of the fault many formations are significantly thicker, particularly within the Miocene interval. These wells are also spatially clustered. With the exception of Toru-1 and Tahi-1, they all sit within a 5 km radius of Kupe South-1. All these factors contribute to uncertainty in the derived velocity / depth relationships and affect the reliability of the velocity model.

The modelling strategy for dealing with poor well coverage has been to simplify the velocity functions. Examples of simplified velocity functions are:

- The velocity gradient \( (k) \) is kept constant across the KUP area for each layer even though we recognise that this is not a geologically realistic scenario.
• Constant velocity profiles were used in situations when either, a positive velocity trend with depth could not be justified from the data and a negative trend did not seem appropriate, or where there was not enough information to provide further detail. Where possible, constant velocity values were derived by plotting TWT interval-thickness against layer thickness in metres and finding a best fit line, the slope of which gives a constant velocity (see Appendix B). This method has been adapted from Thrasher and Cahill (1990). The use of constant velocity profiles does create unlikely velocity inversions at depth in some situations.

• Velocity clips are used to limit the velocity to the range of well data.

3.2 Layer Velocity Character

The velocity character of each layer is described in the following section. Refer to Figure 6 to compare well velocity logs with the modelled velocity profiles. The logs show that layer velocities vary considerably, and over short depth intervals (50 - 100 m). This variation is assumed to largely reflect local changes in lithology (interbedding).

Table 2 The velocity model layers between mean sea level (top) and basement (bottom), the method to derive velocity for each layer and the values for $V_0$ and $k$ where singular values were used.

<table>
<thead>
<tr>
<th>ID</th>
<th>Layer</th>
<th>Method</th>
<th>$V_0$ (m/s)</th>
<th>$k$ (m/s per m)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Seabed-Datum</td>
<td>$V=\text{Constant}$</td>
<td>1480</td>
<td>0</td>
<td>Water Column</td>
</tr>
<tr>
<td>2</td>
<td>N70-Seabed</td>
<td>$V=V_0+k(Z-Z_0)$</td>
<td>surface</td>
<td>0.47</td>
<td>$V_0$ derived from Dix interval velocities, $k$ derived from local wells</td>
</tr>
<tr>
<td>3</td>
<td>N52-N70</td>
<td>$V=V_0+k(Z-Z_0)$</td>
<td>surface</td>
<td>0.87</td>
<td>$V_0$ derived from Dix interval velocities, $k$ derived from local wells</td>
</tr>
<tr>
<td>4</td>
<td>N50-N52</td>
<td>$V=\text{Constant}$</td>
<td>3450</td>
<td>0</td>
<td>Calculated from local well data</td>
</tr>
<tr>
<td>5</td>
<td>N45-N50</td>
<td>$V=V_0+k(Z-Z_0)$</td>
<td>surface</td>
<td>0.58</td>
<td>$V_0$ derived from Dix interval velocities, $k$ derived from local wells, $V \leq 4000$ m/s</td>
</tr>
<tr>
<td>6</td>
<td>P60-N45</td>
<td>$V=V_0+k(Z-Z_0)$</td>
<td>surface</td>
<td>0.38</td>
<td>$V_0$ derived from Dix interval velocities, $k$ derived from local wells, $V \leq 4000$ m/s</td>
</tr>
<tr>
<td>7</td>
<td>P50-P60</td>
<td>$V=\text{Constant}$</td>
<td>3250</td>
<td>0</td>
<td>Calculated from local well data</td>
</tr>
<tr>
<td>8</td>
<td>P20-P50</td>
<td>$V=\text{Constant}$</td>
<td>3490</td>
<td>0</td>
<td>Calculated from local and regional well data</td>
</tr>
<tr>
<td>9</td>
<td>P10-P20</td>
<td>$V=V_0+k(Z-Z_0)$</td>
<td>surface</td>
<td>0.75, 0.27</td>
<td>$V_0/k$ calculated from regional well $V/Z$ relationship. Two functions used (see section 3.2.9). $V \leq 5000$</td>
</tr>
<tr>
<td>10</td>
<td>K90-P10</td>
<td>$V=V_0+k(Z-Z_0)$</td>
<td>surface</td>
<td>0.97, 0.47</td>
<td>$V_0/k$ calculated from regional well $V/Z$ relationship. Two functions used (see section 3.2.10). $V \leq 5000$</td>
</tr>
<tr>
<td>11</td>
<td>Basement-K90</td>
<td>$V=\text{Constant}$</td>
<td>4500</td>
<td>0</td>
<td>$V$ is derived from regional wells</td>
</tr>
</tbody>
</table>
3.2.1 Seabed to Datum (Water Column)

The water column has been modelled with a standard constant velocity of 1480 m/s (Yilmaz, 1987).

3.2.2 N70 to Seabed (Late Pliocene and Pleistocene)

In general the well data show a gradual velocity increase from ~1800 to ~2300 m/s (over depths between ~30 and ~800 m) due to an increase in sediment compaction. The velocity gradient applied to the whole interval is 0.47 m/s per m. Shorter wavelength variation (50-100 m) is ~ ±500 m/s. The reliability of the velocity logs for this interval is poor and velocity is mostly constrained by check-shot data. Apart from Kupe-1 and Kupe South-1 sonic logs have not been recorded above 500-750 m (refer to Table 1).

3.2.3 N52 to N70 (Early to Late Pliocene)

Well data show a gradual velocity increase from ~2300 m/s to ~3000 m/s (over depths between ~800 and ~1600 m) due to an increase in the sediment compaction. The modelled velocity gradient is 0.87 m/s per m, which is higher than the previous interval, indicating an increasing rate of compaction with depth. The lower two thirds of this unit have frequent high amplitude spikes in velocity (~750 - 1000 m/s) above and below baseline.

3.2.4 N50 to N52 (Early Pliocene)

This layer is thinly exposed in the Kupe wells (maximum well-penetrated thickness is 220 m at Toru-1) but encompasses a high range in velocity over depths between ~1500 and ~2000 m. Typically the unit can be divided into an upper high velocity layer (~4000 m/s) and an underlying lower velocity layer (~2500 - 3000 m/s). The upper high velocity layer probably reflects the presence of cemented sandstones and/or shell beds within the stratigraphy. The two layers could be better discriminated if there was a mapped horizon between them, instead, a constant velocity of 3450 m/s is used here rather than invoking a negative velocity gradient over the combined interval.

3.2.5 N45 to N50 (Late Miocene)

The well data show a gradual velocity increase related to sediment compaction. The long wavelength trend in well log data suggests a velocity between 3000 and 4000 m/s for depths between ~1600 and ~2800 m. The velocity gradient is 0.58 m/s per m, which is significantly lower than that used for the N52-N70. This is probably due to these strata being closer to compaction equilibrium than the younger intervals above. The shorter wavelength velocity variation in wells is reasonably high (~750 m/s), although there are fewer spikes than at higher stratigraphic levels.

Where Late Miocene intervals were relatively thick, their velocity maxima were clipped at 4000 m/s. This value was taken from the Pukeko-1 well, west of the KUP area, which has sampled a very thick section of Miocene and records maximum velocities of around 4000 m/s.
3.2.6 P60 to N45 (Early to Mid Miocene)

The well data show a gradual velocity increase over the whole interval. The long wave length velocity trend is between 3000 and 4000 m/s, over depths between ~1700 and ~3500 m. Spikes in velocity relative to the baseline trend range from ± 300 to 500 m/s. The best-fit velocity gradient is 0.38 m/s per m. The well data indicate a velocity inversion near the base of the interval.

Velocities in the thicker Early Miocene intervals were clipped at 4000 m/s.

3.2.7 P50 to P60 (Oligocene and earliest Miocene)

The velocity range for this interval is relatively large (~ 2500 – 5200 m/s over depths of ~2600 – 3600 m). Well data indicate that velocities are typically higher at the top of the interval. A constant velocity of 3250 m/s was used for this interval.

3.2.8 P20 to P50 (Eocene)

This interval is only sampled within the KUP area by the Toru-1 and Kupe-1 wells, so regional well data were included in the analysis. Figure 7 shows the velocity / depth distribution for all data in this interval. The velocity ranges between 3000 and 4000 m/s with spikes on the order of 1000 m/s. The depth range of samples is between 2500 and 4000 m. A constant value of 3490 m/s was used for this interval.

3.2.9 P10 to P20 (Paleocene)

Kupe South-4 is the only well that samples a complete Paleocene section within the KUP area (see Figure 6), so regional well data were also included in the velocity analysis. Figure 8 shows the velocity / depth distribution of regional well data including Kupe South-4. Velocity data within this layer range between 2000 and 5000 m/s, with short wavelength variation on the order of 1000 m/s. The depth range of samples is between 3000 and 5500 m. The data has been grouped into two main trends, which have been modelled by two separate functions. The boundary between the two functions occurs at 4400 m depth where the two functions intersect. Velocities were clipped at 5000 m/s.

3.2.10 K90 to P10 (Upper Late Cretaceous)

Within the KUP area only the Tahi-1 well samples this interval, and these data have been combined with regional well data for the velocity analysis. Figure 9 indicates the velocity distribution with depth. Velocity ranges between 2000 and 5000 m/s, over depths between 1000 and 3500 m. Two trends have been recognised. The relatively slower trend (Trend A in Figure 9) is derived only from Tahi-1 data. The boundary between the two functions occurs at ~3000 m depth where Trend A has been extrapolated to intersect the higher-velocity trend (B). Velocities were clipped at 5000 m/s.

3.2.11 Basement to K90 (Lower Late Cretaceous)

Only the upper part of this layer has been sampled in the KUP area by Tahi-1 and these velocity data have been combined with regional well data (Figure 10). The velocity data are highly variable with velocities ranging from 2000 to 6000 m/s and contain many short-wavelength (50 m) velocity spikes (up to ~1000 m/s amplitude). As there is no coherent pattern in the velocity data, a constant interval velocity of 4500 m/s was used. This value was chosen as an approximate average between the shallow samples at Tahi-1 (~3000 m/s to 4500 m/s range) and higher values in deeper parts of the basin (~4000 to 5000 m/s).
range). A consequence of simplifying the model for this layer is that in some of the deeper parts of the KUP area a velocity inversion is created, where the immediately overlying K90-P10 layer (clipped at 5000 m/s) has a higher velocity. This inversion is unlikely and it is accepted that the model probably underestimates the depth to basement in these regions.
Figure 6 Velocity intervals bounded by mapped seismic horizons, well velocity logs (grey, 1st order derivative of time / depth log) and the modelled velocity profile (red) for all wells in the Kupe region except Kupe South-3. Wells are shown from south (left) to north (right).
Figure 7  Depth / velocity distribution of regional well data for the P20-P50 layer. A constant velocity of 3490 m/s was used for this layer (see Appendix B).

Figure 8  Depth / velocity distribution of regional well data for the P10-P20 layer. Two velocity functions were used (indicated in red, and annotated). The functions describe best-fit trends for groups A and B. Function boundaries are indicated by dashed lines and occur where functions intersect so that a smooth velocity transition occurs. Velocities were clipped at 5000 m/s.
Figure 9  Depth / velocity distribution of regional well data for the K90-P10, layer. Two velocity functions were used (indicated in red, and annotated). The functions describe best-fit trends for groups A and B. Function boundaries are indicated by dashed lines and occur where functions intersect so that a smooth velocity transition occurs. Velocities were clipped at 5000 m/s.

Figure 10  Depth / velocity distribution of regional well data for the Basement to K90 layer. The pattern of velocities is very variable and a constant value for this layer (4500 m/s) is used.
4.0 \( V_0 \) MAPS

A geo-statistical approach was taken to produce maps of \( V_0 \) for each layer across the KUP area. First, velocity values at the top of a layer were calculated from Dix interval velocities (see section 2.2). Variogram maps were then generated from these data and preliminary velocity grids (1 km cell size) were created using kriging to produce a surface describing the trend of \( V_0 \) across the KUP area along a TWT horizon. This ‘\( V_0 \) trend’ was then calibrated to well-derived \( V_0 \) values using the ‘kriging with external drift’ method as described by Druble (2003).

Figures D-1 to D-4 (Appendix C) are maps of \( V_0 \) across the KUP area for levels above the P60 horizon. These maps show how the velocity changes across the basin at this level, and the velocity range used in the modelling. The dominant control on velocity is the shape of the seismic horizon that defines the top of the velocity layer i.e. velocity increases as the top of the layer becomes deeper. Deeper seismic horizons are more complex and cover a greater depth range and therefore an increasingly greater range in \( V_0 \).

The filtered Dix interval velocities (section 2.2) constrain \( V_0 \) trends across the KUP area for the shallow intervals (N70-Seabed, N52-N70, N45-N50, P60-N45). For the deeper intervals (P10-P20, K90-P10), the sparse Dix interval velocity data is not sufficient to krig \( V_0 \) trends and a linear velocity / depth relationship, derived from regional well data, is used instead.

Figures D-5 and D-6 (Appendix C) illustrate the velocity values calculated at the P20 and P10 levels. Both these horizons are at a TWT that is mostly below the range of filtered stacking velocities and \( V_0 \) grids have been calculated using the \( V/Z \) functions presented in Figure 8 and Figure 9. To calculate these values it is necessary to depth convert the overlying layer. Both maps show the areas where the velocity was clipped at 5000 m/s. At the P20 level the \( V_0 \) values in the NW are clipped, and at the P10 level all \( V_0 \) values on the western side of the Manaia Fault and in most of the northern part of the KUP area are clipped.

5.0 VOXET REPRESENTATION, SMOOTHING AND WELL CALIBRATION

A voxet (3D cellular cube) was used to represent the velocity model within the GOCAD software environment. The cell size within the voxet is 1 km x 1 km x 100 ms, and contains an average velocity attribute (VAVG) that is used for time-depth conversion. This value was calculated from smoothed interval velocity values (VINT) and then calibrated to well average velocity values. The procedure to derive the final calibrated VAVG value is outlined below.

- A depth attribute (\( Z \)) was calculated using equation 3 (section 3.0).
- An interval velocity (VINT) attribute was then calculated using equation 2 (section 3.0).
- VINT voxet values were smoothed with an averaging filter using a window of size 2 x 2 x 2 cells.
- VAVG values were then calculated from all VINT values and stored as a separate attribute. \( VAVG = Z / TWT \).
- Well-average-velocity (WELL_VAVG) values were resampled to voxet cells (using arithmetic average ) and stored as a separate attribute.
- For cells which overlap with well-paths a correction factor (CF) was calculated such that \( CF = WELL\_VAVG / VAVG \).
- To prevent abrupt changes in velocity at the well location CF was interpolated away from the well locations using a kriging function, such that within 3 cells CF would equal one.
- The final well-calibrated-average-velocity values (FINAL_VAVG) were then calculated: FINAL VAVG = CF x VAVG

Figure 11 shows VINT and VAVG attributes along an example section through the velocity model and illustrates the level of smoothing across faults on the TWT horizons and also the smoothing applied to velocity values.
Figure 11  Example section through the GOCAD voxet velocity model in two-way time, running west (left side) to east and showing:  A: initial unprocessed layer boundaries (black lines) and faults (red-lines);  B: the initial VINT values loaded into voxet, and the velocity-layer boundaries (black lines) which have been smoothed across faults and merged with layers above and below;  C: the smoothed VINT profile;  D: the final average velocity values calculated from C, and calibrated to well average velocity values.
6.0 DEPTH CONVERSION RESULTS

Figure 12 illustrates the final depth converted Top Basement horizon. Basement is ~ 11.4 km deep (relative to MSL) in the northeast of the KUP area, and lies between 7 and 8 km depth in the northwest.

Summary statistics for all the depth converted 4DT horizons are presented in Appendix D. Depth-structure and isopach maps for these horizons are illustrated in Fohrmann et al. (2012a).

6.1 ERROR IN TIME-DEPTH CONVERSION AT WELL LOCATIONS

Table 3 lists both relative and ‘actual’ depth error in the time-depth conversion. Errors are listed for each 4DT seismic horizon, at each well location. The error has been calculated as the difference in the time-depth conversion between the 4DT velocity model, and each well model (calibrated time / depth curve). Relative errors are depth errors presented as a percentage of horizon depth (horizon depth calculated using individual well models).

The difference in the time-depth conversion between the 4DT velocity model and the well model occurs because the 4DT model is represented by a voxet, which has a vertical resolution that is much coarser than the well model. When well-log data were used for calibration well log samples were averaged over a 100 ms window.

The relative error is highest in the seabed conversion where it is up to 8 % (~ 4 m), and decreases to less than 1 % for most of the deeper reflectors. The largest relative error at depth is in the conversion of the K90 reflector at Tahi-1 where there is 4% error (57 m).

The high seabed error is a result of poor voxet resolution in the shallow subsurface. Voxel cells are 100 ms TWT in the vertical dimension, but the seabed surface mostly lies at less than 100 ms at the well locations. However the error is still within the vertical seismic resolution of the seabed. Vertical seismic resolution is dependent on the dominant wavelength of a reflector; a quarter of the dominant wavelength is considered an acceptable threshold to differentiate between two seismic reflections (Yilmaz, 1987). For the seabed reflector a typical dominant frequency of 50 Hz (Crampton et al., 2011) gives a wavelength of 30 m and therefore a quarter wavelength of 7.5 m (using a water column velocity of 1480 m/s).

The high relative error for K90 at Tahi-1 is caused by the difference between the resolutions of the voxet and well models combined with the fact that well velocities change significantly above and below the K90 reflector (Figure 6).
Figure 12 Depth to Top Basement horizon within the KUP area. The coordinate system is New Zealand Transverse Mercator. See Figure 1 for location.
6.2 COMPARISON WITH Taranaki Basin Petroleum Atlas

Figure 13 illustrates key differences between the depth results of this study and the Taranaki Basin Petroleum Atlas published by Thrasher et al. (1995). Depths have been calculated at the Top Cretaceous level. The 4DT surface is deeper everywhere except in the southeast, and this is because the 4DT velocity model employs faster velocities.

The greatest difference occurs on the western side of the Manaia Fault, within the Waiokura Syncline, where the 4DT depth surface is up to ~2.5km deeper. Here the local combined thickness of the Oligocene – Miocene unit (P50 – N50) is predicted to be up to ~6 km thick using the 4DT model, which is ~2.3 km greater than that previously mapped (see Figure 14). Despite the lack of data to constrain Miocene velocities on the western side of the Manaia Fault, the 4DT velocity model is considered an improvement over the earlier model. The previous model applied a very different function (see Figure 14), in which interval velocity actually decreases with increasing unit thickness, from ~3600 m/s down to 2300 m/s, the latter being well below the velocity data measured in the Kupe wells for this interval (Figure 6). Conversely, the velocities in the 4DT model are within a range constrained by the well data, steadily increase with unit thickness, and are conservatively clipped at 4000 m/s.

On the eastern side of the Manaia Fault, underneath the Manaia Anticline, the 4DT Top Cretaceous surface is up to 1.7 km deeper. The difference here is due to a combination of faster Miocene velocities and also significantly faster Paleocene velocities. Thrasher et al (1995) used an average velocity of 3400 m/s for the Paleocene interval. The 4DT model uses velocities that increase with depth up to 5000 m/s for this interval (Figure 8).
Figure 13  Difference in depth to Top Cretaceous between 4DT and Thrasher et al (1995). Where values are negative the 4DT surface is deeper. The Manaia Fault has been buffered in white to hide inconsistent discrepancies due to differences in fault interpretation. Whilst a proportion of any difference will be due to different horizon interpretations, the 4DT surface is mostly deeper throughout the Kupe region because faster velocities have been employed.
Figure 14 Comparing the present 4DT model for the combined Oligocene-Miocene interval with the velocity model used by Thrasher et al. (1995), the actual function for which was published in Thrasher and Cahill (1990). Interval velocity is calculated as unit thickness (m) / TWT unit thickness x 2000.
Table 3  Errors in the time-depth conversion - for each 4DT seismic horizon - at each well. Depth error (bottom chart) is calculated as the difference in the depth conversion between the 4DT model and each separate well model (calibrated time / depth curve). Negative errors mean the 4DT model predicts a shallower horizon than the well model. Relative errors are depth errors presented as a percentage of horizon depth (horizon depth calculated using well models).

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7.0 SUMMARY

Velocity in the subsurface within the Kupe mapping area has been modelled using a series of linear functions that lie within the range of existing well velocity data. Where appropriate, stacking velocity data were used for the velocity model away from well locations.

In the deeper parts of the basin the use of constant velocity values for the P50-P60 and Basement–K90 layers leads to unlikely velocity inversions, and we consider that the thickness of these layers, in these deeper regions, may be underestimated.

The velocity model is represented as a voxet (3D cellular cube). Although this is an efficient way of modelling the data there are some limitations. The voxet model has a coarser vertical resolution than that of well data and so there are differences in depth between horizons depth converted using the well calibrated TWT/Depth curve, and horizons depth converted using the 4DT model. The mean absolute error at the well locations is between 1.85 m (seabed) and 57.5 m (K90 at Tahi-1), but generally ranges between 10 and 20 m.

Despite using conservative velocity functions the 4DT model in general employs faster velocities and thus predicts a thicker sedimentary sequence within the Kupe region than that previously predicted by Thrasher et al. (1995). The Top Cretaceous surface is up to 2.5 km deeper on the western side of the Manaia Fault, and up to 1.7 km deeper on the eastern side.

The final voxet model used to depth convert the 4DT seismic interpretation is provided in Fohrmann et al. (2012a) in both ASCII and SEGY formats, for both time and depth domains.

8.0 ACKNOWLEDGEMENTS

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We thank Paradigm Ltd. for use of their GOCAD software for all data processing, velocity modelling and time-depth conversion.

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### APPENDIX A: REGIONAL WELL DATA

Table 4  Local and regional wells considered for velocity analysis. Wells marked by asterisks were not used for velocity analysis because they are in locations with exceptional uplift values (refer section 2.3). The well velocity data used for analysis were derived from the calibrated time-depth curves found in: Arnot et al. (2010), Juniper et al. (2010) and Zhu et al. (2010).

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Figure 15  Cross plots showing TWT- thickness vs thickness in metres for the N50-N52 (top), and P50-P60 (bottom) layers. Data are from wells within the KUP area. The straight line represents the best fit interval velocity value for each layer.
Figure 16  Cross plot showing TWT- thickness Vs thickness in metres for the P20-P50 layer. Data are from Kupe and regional wells. The straight line indicates the best fit interval velocity value for the layer.
**APPENDIX C: \( V_0 \) MAPS**

**Figure 17** \( V_0 \) map at the Seabed level (velocity at top of N70 to Seabed layer). Well locations are indicated by the cross-circle symbols. The coordinate system is New Zealand Transverse Mercator. See Figure 1 for location.
Figure 18  \( V_0 \) map at the N70 level (velocity at top of N52 to N70 layer). Well locations are indicated by the cross-circle symbols. The coordinate system is New Zealand Transverse Mercator. See Figure 1 for location.
Figure 19  $V_0$ map at the N50 level (velocity at top of N45 to N50 layer). Well locations are indicated by the cross-circle symbols. White space regions within the boundary polygon represent where the layer is mapped as being not present. The coordinate system is New Zealand Transverse Mercator. See Figure 1 for location.
Figure 20  \( V_0 \) map at the N45 level (velocity at top of P60 to N45 layer). Well locations are indicated by the cross-circle symbols. White space regions within the boundary polygon represent where the layer is mapped as being not present. The coordinate system is New Zealand Transverse Mercator. See Figure 1 for location.
Figure 21  $V_0$ map at the P20 level (velocity at top of P10 to P20 layer). Well locations are indicated by the cross-circle symbols. White space regions within the boundary polygon represent where the layer is mapped as being not present. $V_0$ has been calculated as a function of depth using the equations presented in The coordinate system is New Zealand Transverse Mercator. See Figure 1 or location.
Figure 22  $V_0$ map at the P10 level (velocity at top of K90 to P10 layer). Well locations are indicated by the cross-circle symbols. White space regions within the boundary polygon represent where the layer is mapped as being not present. $V_0$ has been calculated as a function of depth using the equations presented in Figure 8. The coordinate system is New Zealand Transverse Mercator. See Figure 1 for location.
APPENDIX D: SUMMARY OF DEPTH STATISTICS

Table 5 Summary depth statistics for 4DT horizons mapped by Fohrmann et al. (2012a) within the KUP area. Minimum depth does not always decrease when going from older to younger stratigraphic levels because of the erosion and uplift pattern within the KUP area.

<table>
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<th>Horizon</th>
<th>Min Depth</th>
<th>Max Depth (m)</th>
<th>Interval</th>
<th>Max Thickness (m)</th>
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<td>10190</td>
<td>K80 – K90</td>
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<td>8870</td>
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<td>8070</td>
<td>P20 – P30</td>
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<td>P30 – P50</td>
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</tr>
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