Improved imaging of the Taranaki Fault reducing drilling risk

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Abstract

Accurate imaging along the Taranaki Fault has always been a challenge. The overthrust of basement and sediment cause large seismic velocity variations both laterally and horizontally which cannot be imaged accurately using conventional processing techniques.

Pre-stack depth migration (PreSDM) is an internationally proven methodology designed to accurately image features within areas containing large velocity contrasts. It can also significantly improve the resolution and accuracy of dip of near-vertical structures.

Conventional reprocessing and PreSDM were performed on two seismic lines crossing the Taranaki Fault. A combination of velocity analysis of well log data, high density velocity analysis of seismic data and geological structural interpretations were used to update and constrain the velocity models. The images after PreSDM have clearer fault plane definition through the main velocity boundaries, fine-scale structures within the overthrust and 'new' sedimentary layers which were previously interpreted to be basement.

Introduction

Pre-stack depth migration is a proven technology in mature provinces such as the North Sea or Gulf of Mexico, where it is routinely and efficiently applied to both 2D and 3D seismic surveys. The principal advantage it offers is the imaging of target events beneath or adjacent to zones where the seismic velocity varies rapidly both laterally and vertically. It also ensures that the seismic horizons are correctly positioned laterally, which can significantly alter the resolution and dip of near-vertical structures (i.e. dips > 80º) such as fault planes.

New Zealand's complex geological structure has given rise to many zones that have rapidly varying seismic velocities, including near-surface channel systems, active and ancient volcanoes, and complex fault systems. In order to image beneath these using PreSDM, however, the velocity variation that is causing the CMP imaging methodology to fail must be modelled.

PreSDM modelling usually combines velocity and structural data from a variety of sources. In a mature and extensively explored province, a single PreSDM project can be based upon part of a well defined and mapped 3D survey with six or more well ties within the prospect (Jones et al., 1996; Cabrera et al., 1992).

By contrast, the large-scale regional tectonics, lack of borehole control and sparse 2D seismic grids common to New Zealand introduce a large degree of uncertainty into any interpretation, with some events mapped over considerable distances simply not being tied to wells or outcrops. This uncertainty makes the velocity modelling process far more challenging than in more mature areas.

Where suitable velocity contrasts exist, such as between the overthrust basement and sediments in the Taranaki Basin, PreSDM offers a method for not only improving the imaging of the sediment-basement contrast, but also for validating the structural interpretation.

This paper describes the results of applying PreSDM to two 2D seismic lines in the Taranaki Basin, and the methods employed to develop and validate the structural interpretations as part of this model building process.

The Taranaki Fault

The Taranaki Fault is an easterly-dipping reverse fault of Miocene age (21-22 Ma) and defines the eastern boundary of the Taranaki Basin. Sedimentary strata has been overthrusted by as much as 10 km horizontally with up to 6 km vertical offset of basement. The dip of the fault is approximately 45 º (Holt and Stern, 1994) and appears to lessen with depth (Stern and Davey, 1990).

The objective of the PreSDM imaging was not only to attempt to image through the overthrust, but also to improve the imaging resolution and lateral positioning of all the faults in the surrounding sediments.

Regional geological analysis

We employed a layer-based modelling system, where each layer was assigned a constant vertical velocity gradient. This gradient may be purely compactional in the upper layers, but can also represent lithological or diagnenetic variations within a formation.

The layers used were typically between 100 and 750 metres thick. Thinner layers are difficult to update directly in seismic data, and, where possible they are included in the layer above or below with the appropriate modification to the layer gradient. In thicker layers, the single gradient approximation breaks down making it difficult to control the velocity contrasts at the top and base of the layer.

To constrain the velocities and gradients within the model, sonic data from several well logs in the region were analysed in detail. Velocity layer boundaries were determined on the basis of changes in vertical gradients and absolute velocities values observed in the calibrated velocity logs. In some formations, the gradients determined from this analysis were higher than expected. When these values were used in the velocity model, the migration improved significantly.

Preparation of seismic data

Velocity model building for pre-stack depth migration is primarily based upon horizon consistent velocity analysis (HCVA). This velocity analysis may be conducted on conventional CMP-gathers as part of the initial model estimate, or on depth imaged CRP gathers as part of a velocity model updating scheme. In either case, the measurement of the curvature of a reflected event as it varies with offset within the gather is used as the basis for deriving a new interval velocity for the velocity macro-layer. If the layer is modelled with a velocity gradient or function, it is calculated as a secondary step.

Whether the interval velocity is derived from a simple Dix Inversion of stacking velocities, or through a complex pre-stack tomographic inversion and ray-tracing system, it is still essentially derived from the interpretation of the single fold data within a CMP or CRP gather. The accuracy to which we can determine this velocity is therefore one of the largest limiting factors on the model building phase.

Where the data contained short period multiples, a combination of FK and RADON demultiple techniques were used to remove them as completely as possible. The impact of removing these multiples on the quality of the CMP stack was minimal, and in a conventional processing sequence a single pass of FK demultiple would have been sufficient. However, the down dipping tails of the residual multiples were observed to break up the coherence of deeper events within a CMP, which in turn limited the accuracy of the HCVA process on these deeper events. A more extensive demultiple sequence was applied to the data, and the results from the HCVA for the deeper events were greatly improved.

Defining the limit of the initial model

We constructed the initial model (Fig. 1a) using image ray map migrations to transform the migrated time interpretation to depth. Dix-inverted interval velocities were used as the basis for defining the velocity function for each layer.

The model was built up a layer at a time until either the uncertainty in the time-migrated interpretation was thought to be too great, or the velocity function derived from the stacking velocities was vastly different to that obtained in the geological analysis process.

Beneath the last certain structural event, a “flood” velocity function was then used, to complete the model down to the nominal maximum depth.

Model updating strategies

Layer stripping updates

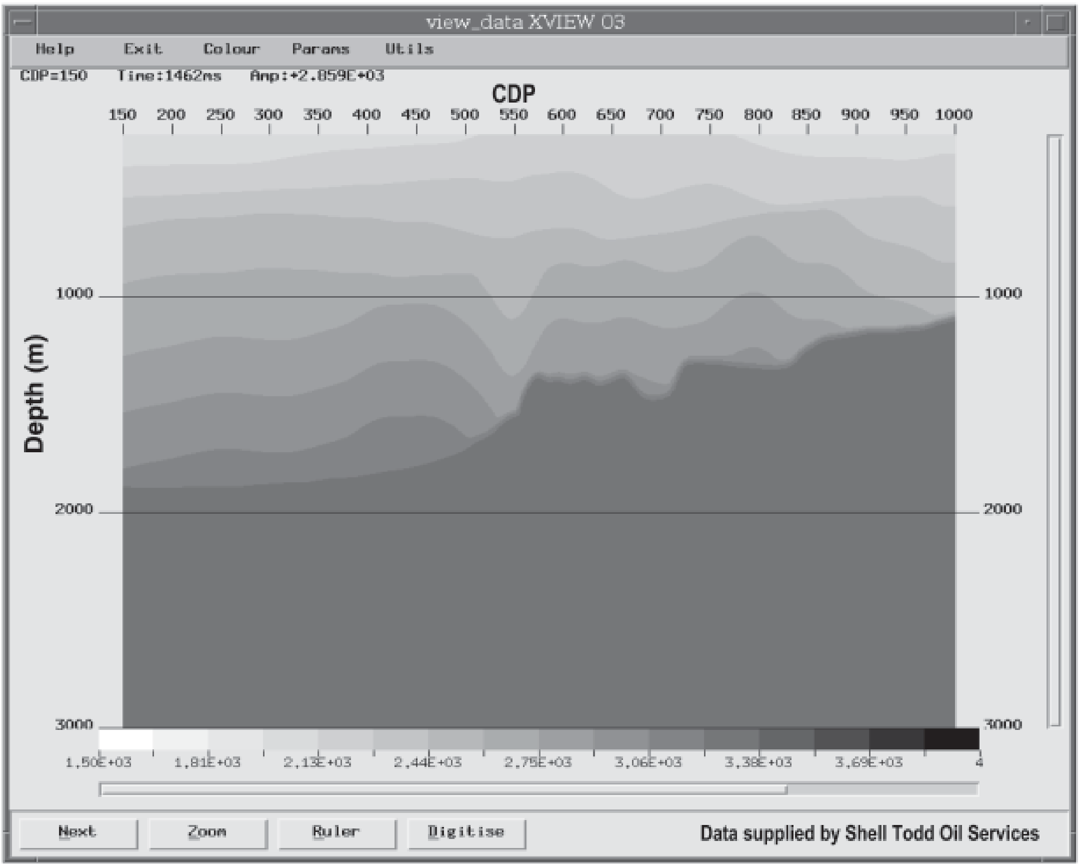
The standard model update methodology we used was to build a model with a “flood” velocity beneath the last certain event, and run a PreSDM. The next event would then be map-migrated from the migrated time interpretation and used as a guide for picking the depth structure. The residual far-offset moveout (RMO) on CRP gathers along this structural event was then analysed, and used as the basis for a tomographic inversion to modify both the velocity and structure in the model.

In practice, it was found that several velocity layers could be updated at once, as long as the changes in either velocity or structure were relatively minor. Where multiple layers were updated, the model structure was updated by re-picking on a time-converted image, which could then be stretched to depth with the new model.

High density velocity analysis

The velocity model in the upper part of the section was based primarily on tracking strong events, as there was no real well control or clear indication of optimum layer boundaries. After several iterations of model building on one of the lines, it became clear that the model being used was incorrect, and would not converge to an internally consistent solution. On some CRPs, although the near offsets were flattened, the far offsets still retained a strong degree of dip. This difference in the near and far offset raypaths indicates an under-complexity in the velocity model.

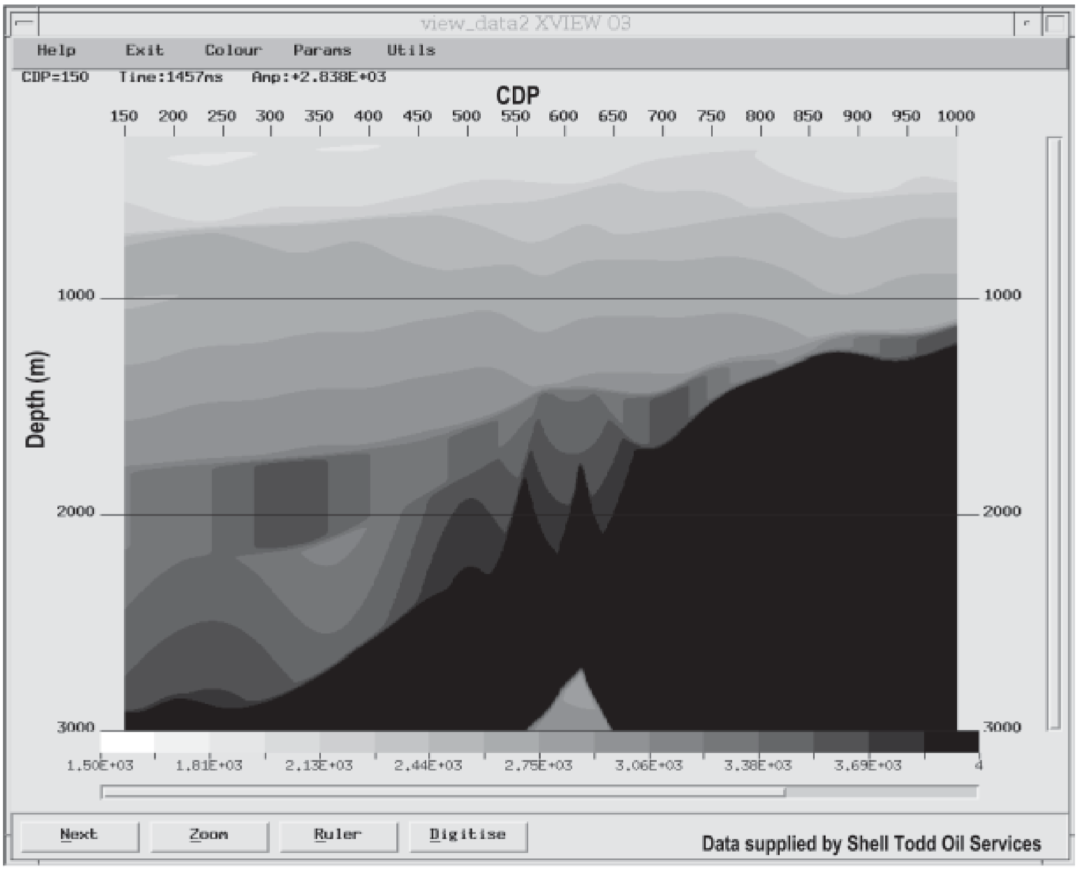
In order to examine the first 1500 ms of data, a conventional stacking velocity analysis was performed, with Time-Velocity picks being generated on every tenth CMP and at a far higher vertical density that would normally be required for stacking. The resulting stacking velocity field, when Dix inverted, smoothed and edited was used to indicate the approximate locations of the velocity boundaries. As a result, several of



CDP=150 Time:1462ms Amp:+2.859E+03

Data supplied by Shell Todd Oil Services

Figure 1a: Interval velocity model derived from the stacking velocities used in the initial conventional processing.



CDP=150 Time:1457ms Amp:+2.838E+03

Data supplied by Shell Todd Oil Services

Figure 1b: Interval velocity model derived after several iterations of PreSDM. The lighter shades of grey represent sediment layers. The dark grey to black represent basement.

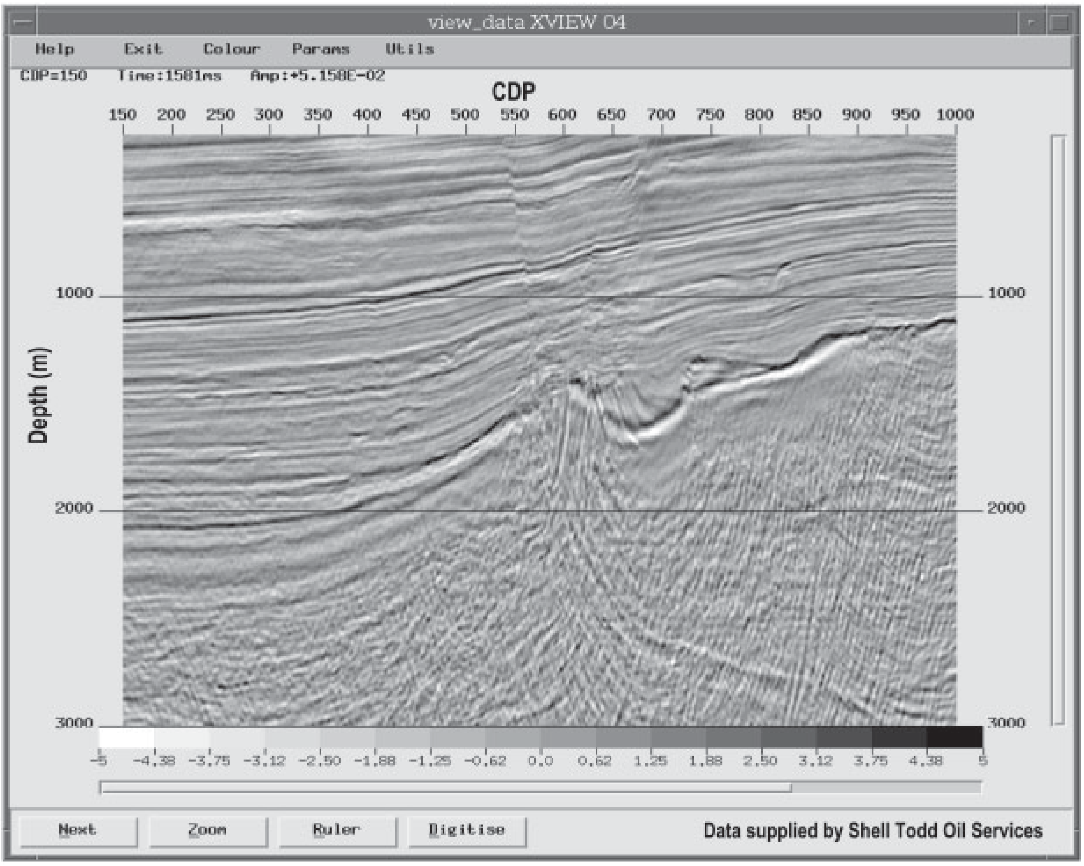


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Figure 2a: Stack created using the interval velocity model of Figure 1a.

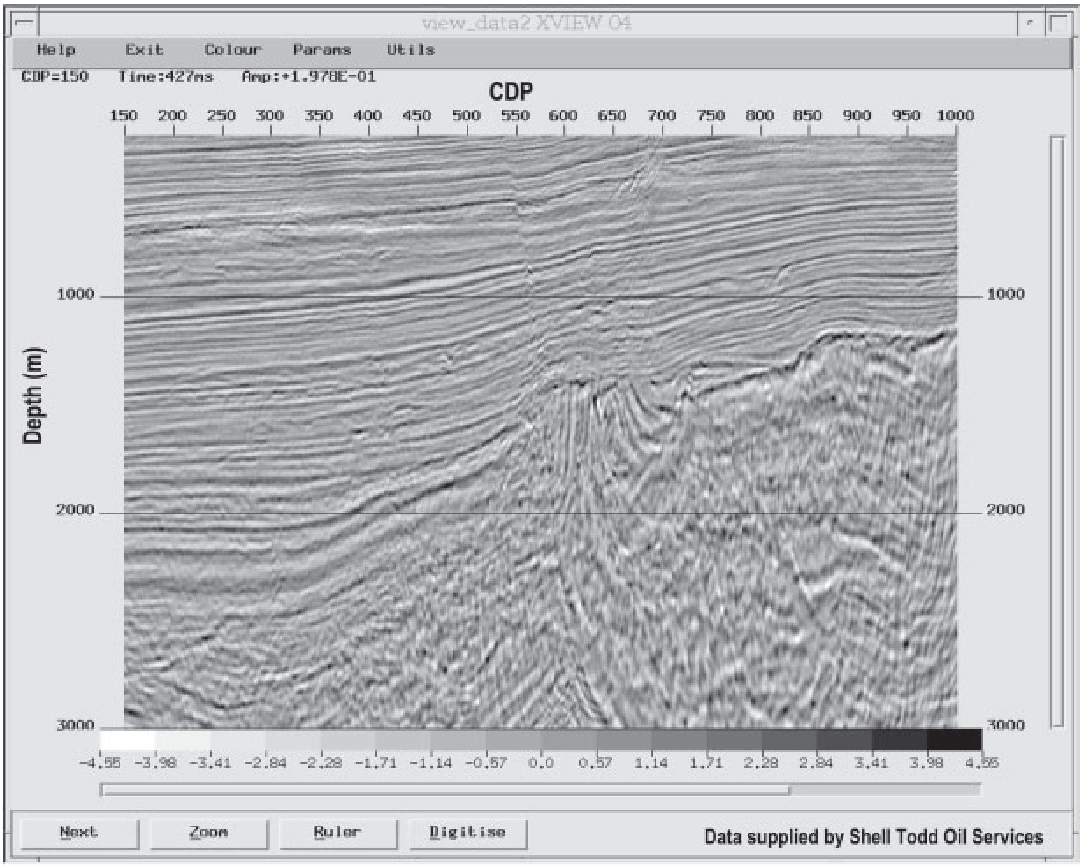

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Figure 2b: PreSDM stack created using interval velocity model of Figure 1b.

the shallow events were re-positioned by up to 100ms, and, a new, relatively high velocity event that pinched out against the sea-bed in the centre of the line was added. This greatly improved the stability of the model.

Cascaded iterations

Where the wedge-shaped high velocity overthrust terminates, the simple layer stripping methodology described above was found to be unsuitable for updating the model. Using a high-velocity flood to position the base of the overthrust layer leaves an area of uncertainty towards the tip of the wedge, where the over-migrated sediments alongside and beneath the basement disrupt and distort the image. Using a low velocity to position the sediments has a similar effect, with the poorly migrated basement distorting the nature of the basement sediment interface.

To resolve this, a wider iterative scheme was adopted. Firstly, the model was constructed in a layer-stripping fashion down to the deepest basement target horizon. The structural uncertainty at the edge of the basement wedge, and the distortions this introduced in the image, were largely ignored. This first pass through the model constrained the velocities, and allowed for the introduction of additional layers in the basement to help the stability of the solution.

A large number of possible structural interpretations could then be tested, each being run as a full PreSDM and generating both CRP gathers and a final image section. The composition and nature of the sediment-basement contact could be widely varied between the possible extremes, and incorrect interpretations rejected.

Once a stable structural solution was found, a third pass of iterations were run to fine-tune the velocity estimates within the areas where the structure had been unclear.

Limits on the final model

On both lines, the total acquisition spread was less than 3500 metres in length. In practice this limit defined the level to which the model could be updated. On the sedimentary section, although clear reflectors were visible, the lack of long offsets meant that below around 5000 metres it became difficult to increase the accuracy of the layer velocity through the application of RMO.

In addition, forward modelling and ray-tracing were used to examine how the deeper layers – particularly those beneath the overthrust – would be imaged by the small acquisition footprint.

Results

The PreSDM images generated show a good improvement in the image quality in the sedimentary section, with clear fault-plane definition through the main velocity boundaries. The throw of the main faults can be much more clearly identified, aiding greatly in the reconstruction of the history of the fault belt.

Within the overthrust, fine-scale structure has become clearer as the imaging improves revealing a degree of complexity not observed on the conventionally imaged section.

On both lines, the iteration process has led to layers that were previously considered to be part of the overthrust basement having far lower velocities than had been previously anticipated. These velocities – of around 3000 ms^{-1} - suggest that these layers are in fact sedimentary in nature.

An example of a seismic image with and without PreSDM is shown in Figures 2a and 2b.

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