Introduction

The Taranaki Basin was formed in response to continental rifting that saw the New Zealand landmass break away from Australia and Antarctica in the Cretaceous. This rifting was characterized by rapid subsidence and the formation of numerous deep half-grabens that were subsequently filled by terrestrial and coastal environment siliciclastics. Miocene uplift resulted in an increase of sediment supply and the progradation of the shelf edge through the survey area. Pliocene extension and the onset of back-arc rifting in the Pleistocene resulted in reactivating faults, as seen in the Maui sub-basin to the east of the survey area.

The Western Platform 3D seismic survey was designed to position over the multiple oil and gas fields with the aim to deliver a broadband 3D seismic survey for the purpose of new insights into and to allow better analysis of proven and unproven plays in the Taranaki Basin.

Deriving an accurate and geologically consistent earth model is always challenging in the Taranaki Basin due to the shallow gas clouds distributed widely in the areas. The unresolved velocity contrast and the absorption effects of the complex overburden result in distortions to the phase and amplitude attenuation at the deeper targets. The conventional ray-based common image point (CIP) tomography method has limitations in this shallow-water environment due to lack of the usable reflection information in the shallow zone for the purpose of picking residual moveout (Menzel-Jones, 2015). Full-waveform inversion conversely, uses the entire wavefield and can take advantage of the transmitted and refracted energy, providing the ability to achieve more-accurate and higher-resolution velocity models in the shallow-water environment. Some of the gas clouds in this basin are very shallow. For example, the gas clouds over the Maari field are just 100 m below the seabed, while, in the Maui field, the gas is approximately 200 m below the seabed. Water depths in the survey area are less than 100 m, which make deriving an accurate Q model with reflection-based Q-tomography challenging due to limited near-offset content of the data.

If the absorption effect of the shallow gas is not addressed properly, the amplitude and phase distortion could significantly impact the accuracy of the velocity updates and obscure and dim the imaging under the gas cloud. A model building workflow that consists of FWI and CIP tomography (Woodward et al., 2008) was applied to this data set to create tilted transversely isotropic (TTI) model. A new approach through visco-acoustic full-waveform inversion (Q-FWI), driven by diving waves, is used to estimate a 3D spatially variable Q-field to compensate for the amplitude and phase distortions associated with the shallow gas clouds.

Method and theory

The TTI earth model building workflow consists of the following steps: First, an initial TTI model was build using all information from a legacy imaging exercise. Then, a detailed overburden velocity was obtained using a combination of adjustive FWI (Jiao et al., 2015) and least-squares (LS) FWI, followed by four CIP tomography updates. After the shallow low-velocity bodies were identified, Q-FWI (Cheng et al., 2015) was applied to update the Q model. This was followed by an LS FWI update using reflection energy to add high-resolution features to the velocity field. Lastly, a joint velocity and epsilon update was performed using CIP tomography.

The conventional FWI algorithm is based on iteratively updating the model by minimizing the LS misfit function (Jiao et al., 2015), as shown in equation 1, which measures the difference-based objective function using the acquired data and the simulated data:

$$\min_{m \in M} J = \frac{1}{2} \sum_{s=1}^{S} || F[m](x_p, t) - d_0(x_p, t; s) ||^2$$  (1)
where \( J \) denotes the misfit function, \( m \) represents the models, \( d_0 \) defines the observed data, and \( F[m] \) is the forward map, which simulates predicted data.

To avoid or mitigate the cycle skipping of the conventional FWI, Jiao et al. (2015) introduced a robust traveltime-shift-based objective function. For a single frequency, the traveltime shift, \( \Delta T \), between two signals is proportional to the phase difference \( \Delta \phi \). FWI can directly minimize the traveltime shift objective function as shown in equation 2 and use the instantaneous phase gradient formulation to back-project the local traveltime shift into model error.

\[
\min_{\Delta T} J_f := \frac{1}{2} \sum_{s=1}^{N_s} \| \Delta T \|^2 - \frac{1}{2} \sum_{s=1}^{N_s} \| \Delta T(\Delta \phi) \|^2. \quad (2)
\]

The distribution of the shallow gas clouds varied vertically and spatially in the subsurface. Two bands of FWI using early arrivals successfully delineated the velocity contrast in the overburden, resulting in a model where the gas clouds are clearly identified by their low-velocity features. Once the complexity of the shallow model was resolved, the migrated image at the deeper target shows significant improvement with enhanced signal to noise ratio (SNR) and continuity of the reflections. This enables higher-quality residual moveout picking and, so, faster and more stable convergence during the CIP tomography model updates. Due to the complexity of the geological setting in this basin that exhibits significant velocity contrast across the fault blocks with various scale lengths, it is important to ensure that the tomography solutions are conformant to the geological structure. The CIP tomography with explicit and implicit geological constraints (Zdraveva et al., 2013) was implemented to deliver a geologically conformant velocity model.

The Q-FWI is enabled by a new set of second-order visco-acoustic wave equations in the time domain to explicitly separate Q-induced phase dispersion from amplitude attenuation so that, during the wavefield back propagation process, we are able to compensate for the phase dispersion effects without altering the wavefield amplitude. The Q estimation is driven by a phase mismatch between the observed and simulated seismic waveforms that are the dominant effects of Q at low frequencies. It is recommended to do the Q estimation when the velocity inversion is close to convergence (Cheng et al., 2015). To capture the shallow gas bodies with various sizes, the Q-FWI was implemented at a frequency band centred at 6 Hz with a constant Q, (150) as the starting model. The Q model obtained by Q-FWI accurately delineated the gas bodies throughout the survey (Figure 1c).

LS FWI using reflection data was performed after the fourth CIP tomography and Q-FWI updates, once a kinematically accurate model had been obtained. LS reflections FWI further enhanced the velocity model resolution, which delineates the spatial and vertical extents of the velocity contrast throughout the survey, an example of which is show in Figures 1. Detailed variation in velocity and Q within the larger Maari and Maui gas fields around the Cape Egmont Fault zone were well resolved, improving the structure and amplitude continuity of the target event close to faults.

A joint Vp and epsilon tomography update was applied at the last stage in the model building workflow to correct for the residual moveout on the CIP gathers. The aim is to extend the usable angle range for quantitative inversion by improving gather flatness at farther angle range.

Results

The processed broadband seismic data were imaged with the updated earth model using Q-Kirchhoff prestack depth migration. The phase and amplitude compensation were applied within the migration process. The sub-gas cloud imaging was enhanced, resulting in better event continuity at the reservoir interval beneath the gas clouds and more-accurate structural positioning. The improved focusing of the faults, fractures, and channels and the reliable amplitude and phase representation across the reservoir interval enabled precise interpretation and understanding of proven and unproven plays and prospect identification in this basin.
The data examples presented demonstrated that the tailored model building workflow successfully resolved fine details in both Q and velocity models representing the gas bodies, as shown in Figure 2. Additionally, the small-scale lateral velocity contrasts across the Cape Egmont Fault Zone were enhanced in a key region where tomography had been unable to achieve sufficient velocity resolution to impact the zone of interest imaging.

Conclusions

We presented a comprehensive model building approach using a combination of different FWI methods and CIP tomography to achieve high-resolution velocity and Q models in the complex geologic environment of the Taranaki Basin.

With a kinematically accurate velocity model in place, applying Q-FWI, followed by high-resolution CIP tomography and LS FWI with reflection energy, enabled us to obtain detailed high-resolution models for both Q and velocity. Performing the imaging with Q-Kirchhoff prestack depth migration successfully compensated for the kinematic and absorptive effects of the shallow gas anomalies. By mitigating the complex overburden effects, reservoir-level images in this historically challenging basin were significantly improved.

Acknowledgements

We thank WesternGeco Multiclient for their collaboration on this work and permission to present the results.

References


**Figure 1** Model extracted at 500 m at Maari and Maui gas fields around the Cape Egmont Fault zone; (a) initial model, (b) final model, (c) updated Q model.

**Figure 2** Image overlay with, (a) final velocity model, (b) updated Q model.