Integration of seismic velocity measurements in the context of the CO_2 Storage project in the Bonaparte Basin, offshore NW Australia

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SUMMARY

An accurate seismic velocity model is essential for depth conversion and rock property determination in the context of fluid flow modelling for secure storage of carbon dioxide in the study area. Three types of seismic velocity measurements are available within the study area: velocities derived from stacking of multi-channel reflection seismic data; velocities determined in the process of ray tracing modelling of large offset refraction data acquired by ocean bottom seismographs (OBSs) along the coincident reflection/refraction transect, and velocities from well log measurements. Generally, the OBS derived velocities are faster than the stacking derived velocities in the shallow section down to 2 km depth, with particularly large (exceeding 15 %) discrepancies in the NE part of the study area. High velocities in the OBS model are consistent with well log measurements in the Newby 1 and Flat Top 1 exploration wells. Integration of OBS refraction velocities with stacking velocities through the calibration of both of them against well logs is the best way to construct a reliable velocity model for the whole section. Refraction seismic data coverage offshore Australia is expected to significantly improve as in 2013 Australia will obtain a National Pool of OBSs suitable for multi-scale experiments.

Key words: seismic velocity, depth conversion, refraction, CO_2 storage, Bonaparte Basin.

INTRODUCTION

The Bonaparte CO_2 Storage project will assess the geological storage potential of two CO_2 acreage release areas in the Petrel Sub-basin on the Australian NW Margin. An accurate seismic velocity model is essential for depth conversion and rock property determination in the context of fluid flow modelling for secure storage of CO_2 in the study area. Multiple velocity data sets are available in the study area, and we aim to define which of them, or combination thereof, will provide the most accurate depth conversion, ideally better than ±5 % for all interpreted seismic horizons in the upper 3 to 4 km of the section. We did not quite achieve that goal yet, but we defined what needs to be done to achieve it in the future.

BACKGROUND

Geology of the Petrel Sub-basin

The Petrel Sub-basin is a Paleozoic rift within the southern Bonaparte Basin. The geological reservoirs of interest include the Jurassic Plover Formation and the Early Cretaceous

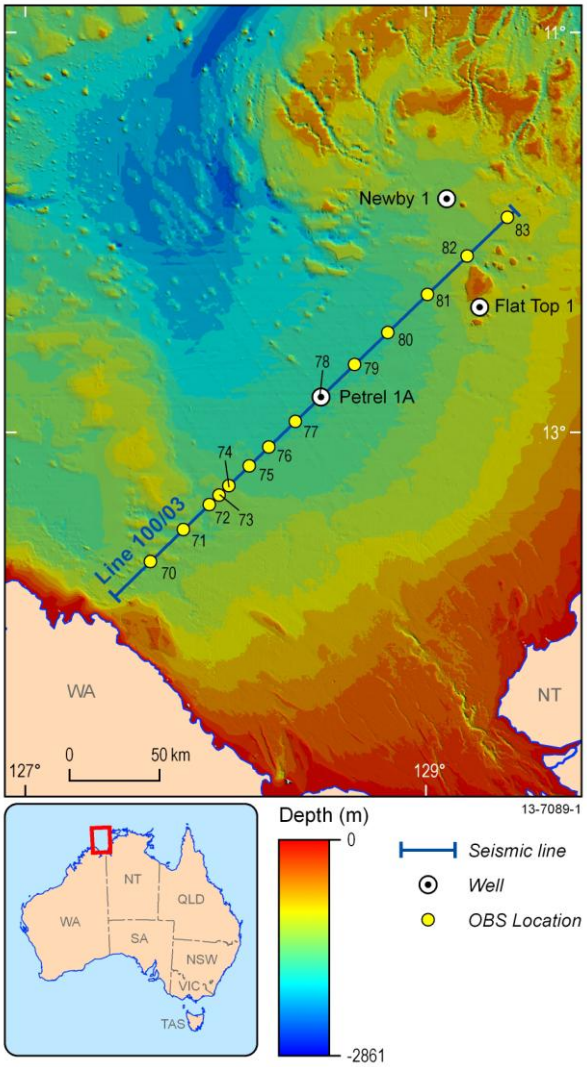

Figure 1. Location of coincident reflection/refraction line 100/03 and exploration wells in the Petrel Sub-basin.

Sandpiper Sandstone. Primary and secondary seals of interest include the Late Jurassic Frigate Formation and the Cretaceous Bathurst Island Group (regional seal). Trapping mechanisms for injected CO_2 may include faulted anticlines, stratigraphic traps, salt diapirs and/or migration dissolution and residual trapping. Water depths are generally less than 100m and depths to reservoir/seal pairs range between 800-2500m below the sea surface.

Data available

Three types of seismic velocity measurements are available within the study area: velocities derived from conventional stacking of multi-channel reflection seismic data; velocities determined in the process of ray tracing modelling of large offset refraction data acquired by OBSs along the coincident reflection/refraction line 100/03 (Goncharov et al., 2000), and velocities from well log measurements in adjacent exploration wells. The streamer length during the multi-channel reflection survey was 4 km; the offsets in the OBS experiment were from zero (shooting over each OBS) to maximum offsets exceeding 200 km for the OBSs on the flanks of the line. Average OBS spacing was ~ 15 km: the experiment was targeting deeper part of the section, down to basement and the Moho boundary.

SEISMIC VELOCITIES FROM REFLECTION STACKING AND REFRACTION DATA

Velocity models in offshore seismic work are often based exclusively on velocities derived from stacking of marine multi-channel reflection data. However, stacking velocities are only quantitatively equivalent to the true velocities under assumed ideal conditions that do not exist in the real-world (Al-Chalabi, 1994). Further, the goal of stacking is to achieve optimum focussing and imaging of the reflection data and this goal can diverge from that of calculating velocities which most closely match the true propagation velocity. Refraction and wide-angle reflection seismic data recorded in the OBS experiments are interpreted by forward modelling or inversion techniques with a key target to match velocity model response to recorded travel times as close as possible. Hence, the OBS derived velocities are closer to true propagation velocities by their nature, although they can deviate from them for a number of reasons.

Comparison of reflection stacking and refraction velocities

Average seismic velocities calculated from the original OBS velocity model of Goncharov et al. (2000), can be compared directly to the final stacking RMS velocities, and to average velocities calculated from the latter ones using the inverse Dix equation (Dix, 1955), (Fig. 2,a-c). As the analysis of corresponding residual values shows, final stacking RMS velocities are up to 10 % (~ 0.4 km/s) slower than the OBS average velocities in the shallow section, and reach more than 25 % (~ 1.0 km/s) faster values in the deeper section (Fig. 2e, g). The boundary between shallow and deeper sections is at ~ 1 km depth in the centre of the line (white colour corresponds to zero residual in Fig. 2e, g).

Average velocities calculated from final stacking RMS velocities show significantly better correlation with the OBS average velocities. The systematic overestimation of velocity at depth appears to be largely eliminated by the application of the Dix (1955) equation (white colour corresponding to zero residual dominates in Fig. 2d, f). However, OBS velocities appear to be generally higher than stacking derived velocities in the shallow section (grey colours in Fig. 2d,f prevail down to ~ 1 km depth in the centre of the line). The largest discrepancies are observed on the flanks of the section, particularly in the NE, where the OBS velocities are faster than the stacking derived, and also around the prominent high velocity feature at location 320km where the OBS velocities are slower than the stacking derived ones (Fig. 2d, f). Discrepancy between the two types of velocity models can be due to geological reasons or to differences in methodology of velocity determination in reflection and refraction technologies. For example, the flanks of the section feature steeply dipping structures so the assumption of horizontal layers used by the Dix equation may not be valid. Calibration of both types of velocity models against well log measurements allows one to judge which velocity model is better.

CALIBRATION AGAINST WELL LOG MEASUREMENTS

There are a number of exploration wells in the area of our study (Fig. 1) that have check shot and sonic log data recorded in them. Well log velocity measurements in the Petrel 1A well (Fig. 3) are representative of the whole group of wells within 10 km distance from it in the centre of the Petrel Sub-basin. Deviations of the time-depth (TD) functions between these wells and the Petrel 1A TD function do not exceed ± 50 m all

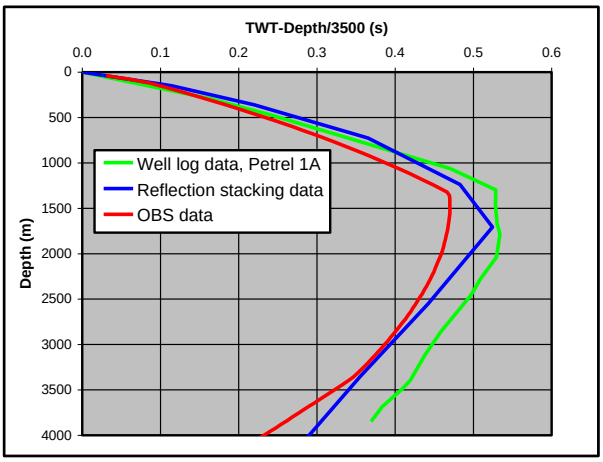

Figure 3. Depth as function of reduced TWT calculated at well log velocities in Petrel 1A well, velocities from stacking of reflection data, and from OBS refraction data at intersection of seismic line 100/03 and this well. Reduction velocity is 3500 m/s.

the way down to 4600 m at the bottom of the deepest well, Petrel 2. These wells define a relatively slow velocity domain in the centre of the Sub-basin: seismic velocities from the well log measurements in the Flat Top 1 and Newby 1 wells in the NE of the Sub-basin are substantially faster (Fig. 4). Spatial boundaries between 'slow' and 'fast' domains are hard to define due to limited data coverage. Petrel 1A well, located within the 'slow' domain is intersected by line 100/03 and its well log data can be used to calibrate stacking derived and OBS refraction seismic velocities. Flat Top 1 and Newby 1 well log data can only be used for the same purpose to a limited extent because neither of these wells is intersected by the line 100/03. However, given that TD functions in these two wells are almost identical for the larger part of the sections that they were drilled through (Fig. 4), some speculative assessment of fitness of the stacking derived and OBS refraction velocities for depth conversion in the 'fast' domain can still be made. These wells are located to the north and to the south of the line 100/03 (Fig. 1), their TD functions

are almost identical, and some significant velocity change along the line drawn from the Flat Top 1 to Newby 1 seems unlikely, although cannot be completely ruled out. Assuming that there is no such velocity change, we use stacking derived and OBS refraction velocities at intersection of seismic line 100/03 and straight line connecting the two wells for calibration against well log data in these two wells.

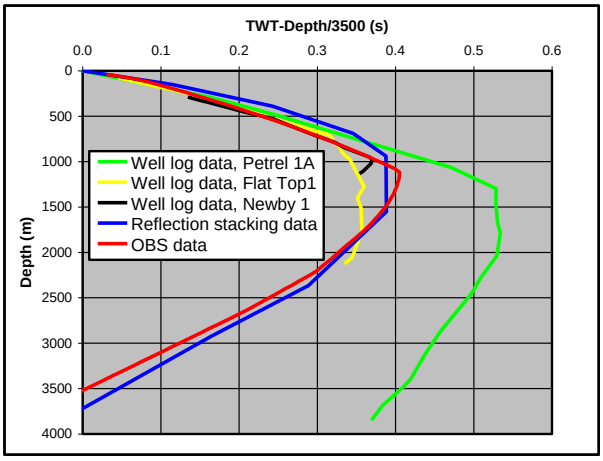

Figure 4. Depth as function of reduced TWT calculated at well log velocities in Petrel 1A, Flat Top 1 and Newby 1 wells, velocities from stacking of reflection data, and from OBS refraction data at intersection of seismic line 100/03 and straight line connecting Flat Top 1 and Newby 1 wells. Reduction velocity is 3500 m/s. Note substantially earlier travel times (hence, higher velocities) in the Newby 1 and Flat Top 1 data compared to the Petrel 1A data.

Calibration of stacking derived and OBS refraction seismic velocities against the Petrel 1A well log data shows (Fig. 3) that: (1) down to ~750 m depth OBS velocities are systematically faster than stacking derived with the well log TD function sandwiched between the OBS and stacking derived TD functions; (2) below ~ 1000 m depth both OBS and stacking derived velocities are faster than well log velocities, and OBS TD function overestimates depth more that the stacking derived one reaching 300 m (8 %) overestimate at the well bottom, while the stacking derived overestimate is 200 m (5 %). However, importantly, the OBS and well log TD functions, unlike the stacking derived one, are essentially conformant below the ~ 1300 m depth. This means that the OBS velocities in the deeper section are a closer match to well log velocities and that the larger absolute overestimate of depth by the OBS model is a side effect of accumulated discrepancies in the shallower section.

Calibration of stacking derived and OBS refraction seismic velocities against the Flat Top 1 and Newby 1 well log data shows (Fig. 4) that: (1) down to ~1000 m OBS velocities are a closer match to well log velocities, with stacking derived velocities considerably lower; (2) below ~1000 m depth OBS and stacking derived velocities are very close and (3) both are faster than well log velocities below 1000 – 1500 m. The resulting overestimate of depth by both velocity models at well bottom is only 50 m (2 %).

The main conclusion from these comparisons is that there is no simple answer as to which velocity model, the stacking, or OBS derived, is better. In the 'slow' domain OBS refraction velocities match well log velocities better than the stacking derived velocities in the deeper section. In the shallow section OBS refraction velocities are faster than the well log velocities and need to be scaled back to improve the accuracy of depth conversion. The mismatch in the shallow section may be due to the large separation of the OBSs resulting in insufficient ray coverage in the shallow section. Stacking derived velocities in the shallow section are slower than the well log velocities. In a situation like this combining stacking derived velocities in the shallow section with OBS refraction velocities in the deeper section is needed to construct a velocity model suitable for accurate depth conversion of the whole section. Opposite to what is observed in the 'slow' domain, in the 'fast' domain OBS refraction velocities match well log velocities better than the stacking derived velocities in the shallow section. Stacking derived velocities here are slower than well log velocities. In the deeper section both OBS and stacking derived velocities match well log velocities equally well. Overall, 'fast' domain velocities are better constrained from the OBS refraction data than from stacking of the reflection data. We re-iterate that conclusions about the 'fast' domain are speculative because the wells used for calibration of seismic velocities here are not intersected by the seismic line 100/03. However, integration of OBS refraction velocities with stacking velocities through the calibration of both of them against well logs emerges as the most sensible way to construct a reliable velocity model for the whole section.

TIME-DEPTH CONVERSION

OBS refraction velocities were used to calculate horizon consistent TD functions for a number of horizons interpreted to constrain fluid flow modelling in the area, from the top of the Cretaceous Bathurst Island Group down to the top of the Jurassic Malita Formation. Maximum depth to the deepest interpreted horizon from the well data is ~3100 m. These TD functions were different for 'slow' and 'fast' velocity domains. The resulting depth conversion was calibrated against wells. An average mismatch between depths to seismic horizons and their intersections by wells, for all wells and all horizons, was only 25 m. The majority of mismatches were within ± 10 %, although at a few well locations mismatches for some horizons exceeded ±20 %. Those anomalous mismatches are attributed to insufficient refraction velocity data coverage of the area: only one line, 100/03, had refraction velocities interpreted from the OBS data, and some wells are as far as 70 km away from that line. Accuracy of depth conversion is expected to improve in the future as velocities from the stacking of the reflection data recorded during the 2012 Geoscience Australia's survey 336 are integrated into the study.

Refraction seismic data coverage of offshore Australia is expected to significantly improve as Australia in 2013, for the first time, will obtain a National Pool of OBSs suitable for multi-scale experiments at sea and for onshore-offshore combined observations. Twenty broadband OBSs were purchased that are capable of short and long term deployment (up to 12 months) to a maximum water depth of 6 km. The Australian National Pool of OBSs, accessible to Australian researchers via a merit or consensus-based system, will greatly enhance the research capabilities in Earth imaging, offshore exploration and natural hazard assessment. The instruments will be made available via Australian National Seismic Imaging Resource (ANSIR), with only the costs of mobilization and deployment to be met by the users of the

equipment. In the exploration oriented research, refraction and wide-angle reflection seismic data recording by 3-components plus hydrophone OBSs will greatly enhance our knowledge of seismic velocities needed for accurate depth conversion and depth migration of seismic data.

CONCLUSIONS

Integration of OBS refraction velocities with stacking velocities through the calibration of both of them against well logs is the best way to construct a reliable velocity model for the whole section.

Time-depth functions constructed for individual horizons interpreted in the reflection seismic data on the basis of the OBS derived velocity models are acceptable for a first pass depth conversion in the study area, and would improve with denser refraction data coverage.

Refraction seismic data coverage offshore Australia is expected to significantly improve as in 2013 Australia will obtain a National Pool of OBSs suitable for multi-scale experiments at sea and for onshore-offshore combined observations.

ACKNOWLEDGMENTS

Leonie Jones identified the problem with under-sampling of the original OBS model from the ray-tracing software for the purposes of comparing it with the stacking derived velocities, and using it for depth conversion. The problem was addressed by the authors. Karen Higgins and Chris Consoli implemented our depth conversion approach to their seismic interpretation in the study area. We thank Clive Collins and Ron Hackney for review of this abstract. Daniel McIlroy generated final figures. The Geoscience Australia Catalogue reference number for this paper is 75592.

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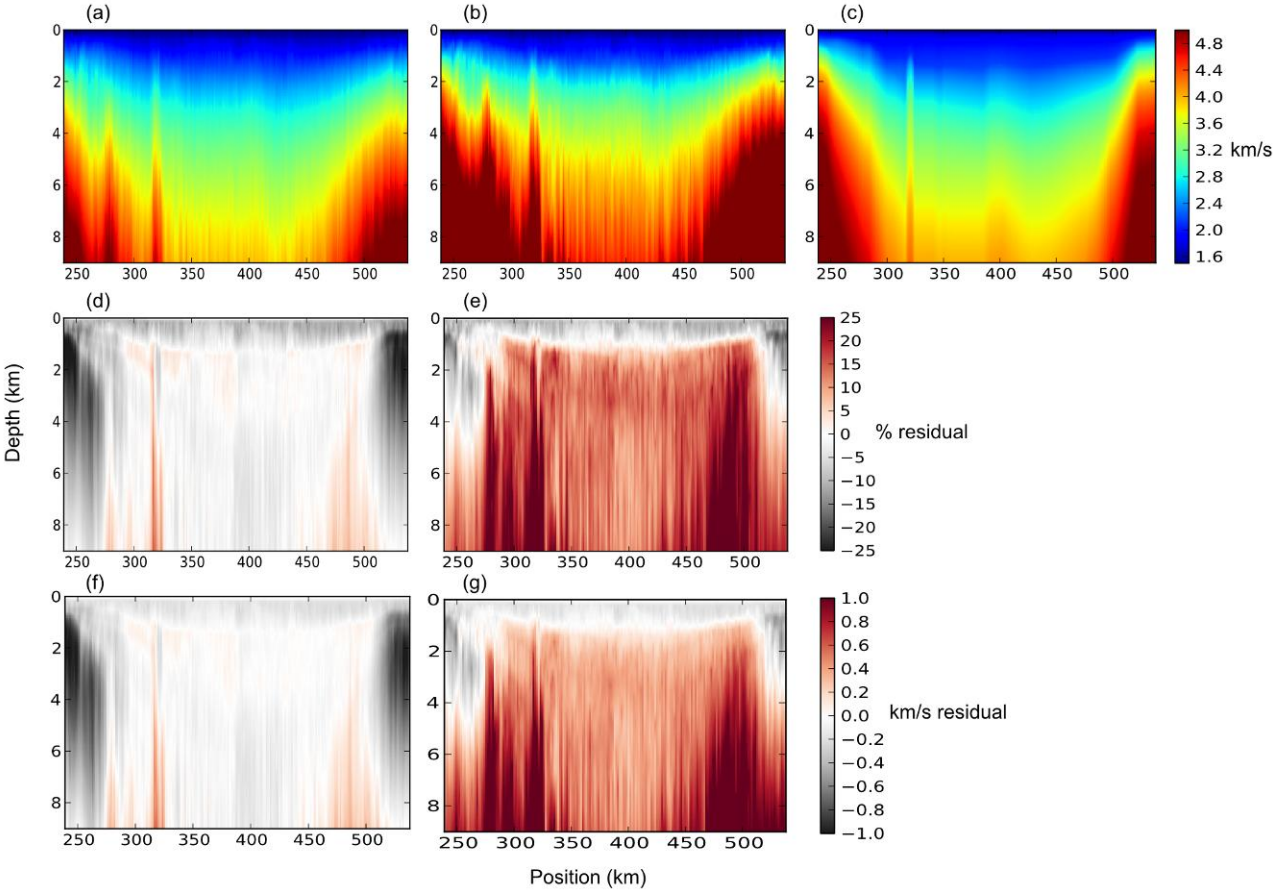

Figure 2. Comparison of average seismic velocities derived from final stacking RMS velocities using the inverse Dix equation (a), final stacking RMS velocities (b), and average seismic velocities from the OBS refraction data (c) along coincident reflection/refraction line 100/03; percentage velocity residuals: (d) - between (a) and (c), (e) - between (b) and (c); velocity value residuals: (f) - between (a) and (c), (g) - between (b) and (c).