Reaching the Pantheon: A Multidisciplinary Approach to Data Reprocessing and Depth Imaging in the Vulcan Sub-basin.

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SUMMARY

This study presents the results of reprocessing a 580 km^2 subset of the narrow-azimuth Pantheon 3D survey, which was acquired in 2005 in the Vulcan Sub-basin, Timor Sea. The primary objective of the reprocessing was to improve data quality around the Vesta structure, where prospectivity depends on understanding the extent of potential reservoir sands associated with the adjacent Oxfordian delta system. Previous attempts at the processing of this dataset were made in 2007 and later in 2011, as part of a MAZ reprocessing effort. This project was initiated to address persistent issues with image degradation and to provide a clearer characterisation of the Oxfordian reservoir sand, and other potential exploration targets.

During the reprocessing, significant improvements in image quality were realised, using only the narrow-azimuth data, through the cumulative and careful application of many modern processing methods. Of note, the impactful steps included de-multiple, de-noise, de-ghosting, velocity model building, constrained FWI and high-resolution tomography. Depth imaging using Q tomography also assisted in reducing data degradation beneath hydrocarbon-related diagenetic zones (HRDZ) and minor traps containing escaped gas from the underlying petroleum system. The reprocessing project benefitted from a multidisciplinary collaboration between diverse skillsets including signal processing, velocity model building, rock physics, potential field modelling and imaging.

Key words: Vulcan Sub-Basin, Depth Imaging, Velocity Model Building, Multidisciplinary approach

INTRODUCTION

Seismic data processing has proven challenging for many explorers in the Vulcan sub-basin and in the wider Timor Sea region. A common processing challenge encountered in the region is the shallow and hard sea floor, which generates strong multiples and guided waves. This is compounded by velocity inversions in the Tertiary and Cretaceous overburden, which generate interbed multiples and often contribute to a lack of velocity moveout discrimination between coincident deeper primaries and the shallow-generated multiples (*Dunne et al, 2013*). Imaging can also be locally challenged by the presence of carbonate reefs at or near the sea floor. The net impact of these challenges results in uncertainty in the velocity estimation, generating imaging artefacts (e.g. fault shadowing) and depth conversion errors, as revealed by drilling activity in the basin.

Further processing challenges exist in the Swan Graben area (***Figure 1(a)-1***) covered partly by the 580 km^2 Pantheon 3D survey, which was acquired in 2005. These include sea floor channelling (***Figure 1(b)***), shallow gas (leaking along fault planes and trapped in small structural closures), hydrocarbon-related diagenetic zones (HRDZ), and interpreted salt diapirism (*Smith and Sutherland, 1991*). The impact of these known, suspected and potential latent imaging challenges was manifested in the severe image degradation noted in previous processing attempts, particularly within the targeted Lower Vulcan formation, where oil sands were discovered by the Vesta-1 and Vesta-2 wells.

As a distinct geological feature of the Vulcan sub-basin, the Swan graben is primarily oriented in a northeast-southwest direction. The bounding faults have considerable displacement with large vertical movements, creating significant differences in elevation on either side of the blocks and influencing the thickness of sedimentary layers within the graben. Looking ahead at the reprocessed data, ***Figure 1(c)*** shows a depth slice through the late Jurassic faulted zone and ***Figure 1(d)*** shows a corresponding amplitude map to illustrate the complexity of the fault system of the graben. The large displacement and associated rock property changes along and across the bounding faults cause fault shadow distortions. Slow velocity within the graben reduces discrimination by moveout between multiple and primary events. Similar issues may arise from anisotropy differences near fault locations.

The Swan Graben is also known for its Palaeozoic salt diapirism. However, the interpretation of salt diapirs remains uncertain due to limitations in existing datasets. Salt diapirism and withdrawal influence tectonic movements, potentially reactivating faults and inducing geomechanical stress. These factors can cause further variations in velocity, affecting the signal-to-noise ratio of the seismic data and distorting the image beneath. More importantly, salt tectonics can play a crucial role in forming hydrocarbon traps and seals.

HRDZs are relatively widespread in the region and are characterised by varied diagenetic processes, such as cementation, dissolution, compaction, mineral alteration, and hydrocarbon migration (*O'Brien, et al, 1995*). These processes significantly impact rock properties, creating localised seismic velocity anomalies, strong multiples and inelastic attenuation. Whilst localised absorption anomalies occur within and below an HRDZ, they are not widespread throughout the Pantheon 3D and thus present as localised imaging challenges.

Additionally, the survey area suffers from pronounced shallow velocity anomalies, characterised by high-velocity reefs and, conversely, shallow paleochannels filled with lower-velocity sediments. These anomalies significantly distort the imaging across the entire depth range, deteriorating data quality and complicating accurate depth velocity modelling, subsequent inversion, and interpretation. ***Figure 1(b)*** highlights a depth slice through the shallow section, displaying a paleo-channel filled with anomalously slow-velocity material. This velocity anomaly causes image "push-down" beneath it. Conversely, ***Figure 1(c)*** shows a slice through deeper section of the graben zone, an area with fast lateral velocity variations due to large displacements along fault planes. Note that the dominant orientation of velocity anomalies differs between shallow and deep sections. The challenge is very much one of 3D velocity estimation that is well suited to modern Full Waveform Inversion (FWI) processing technology.

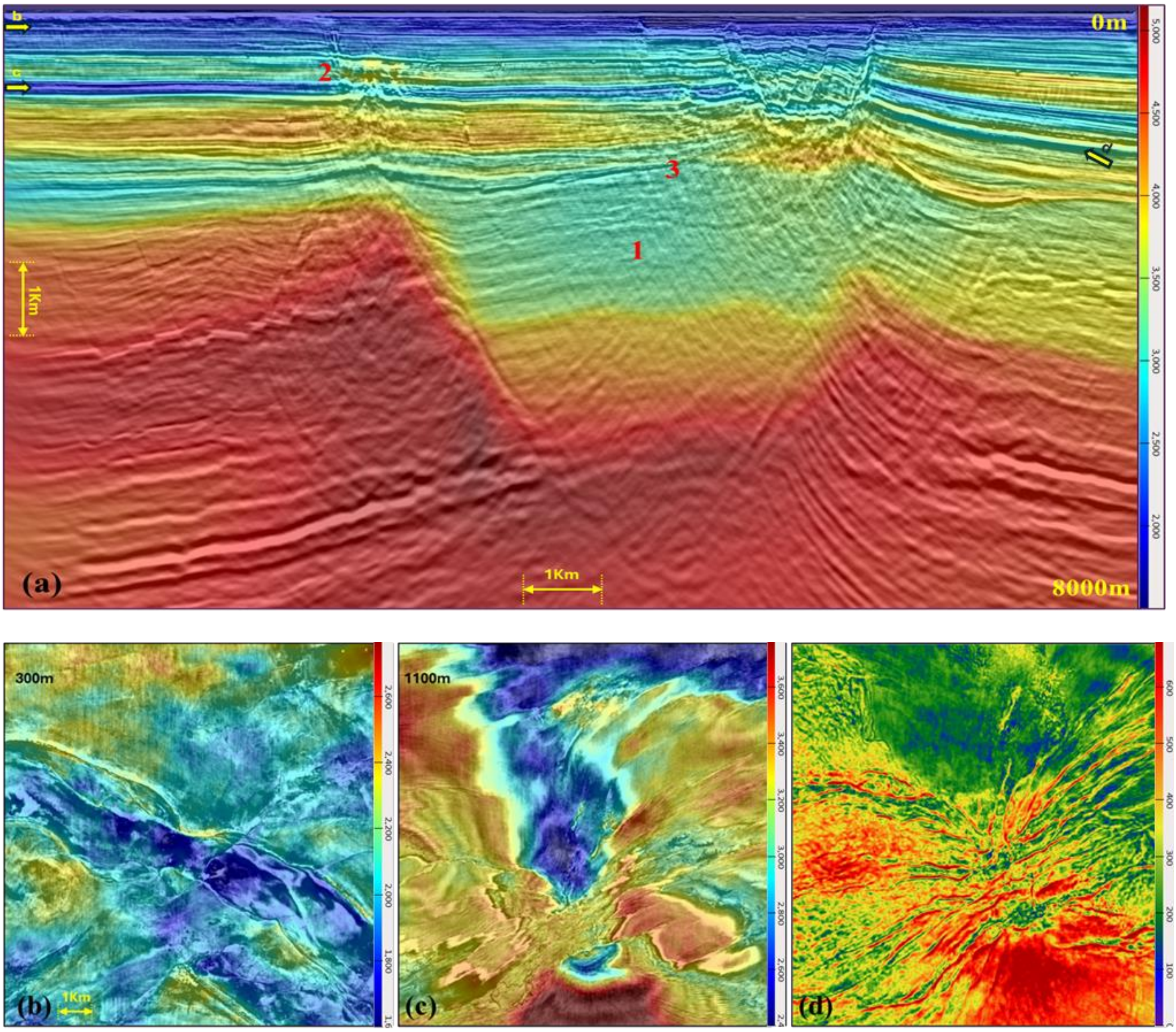

Figure 1. Example of data demonstrating geological complexity; (a) reprocessed PSDM section overlaid with corresponding velocity model: a-1) Swan Graben, a-2) HRDZ, a-3) Base Cretaceous; (b) depth slice through shallow section (300m) with channel filled with slow velocity material which are causing "push-down" effects on image; (c) depth slice through deeper section (1100m) cutting through the faulted zone of the graben (note orientation of the graben is different to the orientation of shallow channels); (d) amplitude map in a 100m window down from the Valanginian unconformity showing complexity of the late Jurassic fault system.

IMPACT OF MODERN REPROCESSING

An integrated approach proved essential to address the imaging challenges laid out. This combined the insights across disciplines, beginning with advanced time processing techniques and high-resolution velocity model building. Key methodologies include advanced de-ghosting, cutting-edge techniques for multiple attenuation with the generation of multiple models and a joint adaptive subtraction (***Figure 2***), high-resolution seismic tomography enhanced by FWI to invert for VP, visco-acoustic Q tomography and Q imaging coupled with Tilted Transverse Isotropic (TTI) anisotropy. Additionally, integrating non-seismic constraint data was critical, incorporating geological inputs; well log data from both the reprocessing area; and a broader VSP database which covered the entire sub-basin. Complementary data from diverse disciplines, such as rock physics modelling and gravimetry, also helped to obtain a deeper understanding of the data and the geological environment.

Multiple iterations of seismic tomography were performed during velocity model building, starting from an initial model. This commenced with an update of the shallow interval before progressively updating to greater depths. Each iteration was accompanied by a grid PSDM of the entire volume, residual moveout (RMO) picking, tomographic updating, comparison of the resultant interval velocities with available well sonic logs and VSP data, geological sense checks, analysis of mis-ties with depth markers and migration QC. Each iteration of the model update had the objective to globally reduce RMO, obtain an improved image quality, decrease velocity-related distortions (such as pull-ups or push-downs) and reduce well marker depth mis-ties. The updated velocity profile should also behave consistently with available sonic log well data. Whenever these conditions were not met, the results were analysed to ensure a clear understanding of the causes of such discrepancies. The model was further refined to ensure there were no adverse changes after each model update.

FWI was used as part of the combined approach for the model building alongside seismic tomography. The first two iterations were initially conducted with seismic tomography, followed by a 12 Hz FWI sweep. This process was repeated, incorporating an additional iteration of seismic tomography before proceeding with an FWI sweep to a maximum frequency of 15Hz. This interleaved approach leveraged the strengths of both methods. Seismic tomography was utilised to refine the low-frequency model updates, ensuring more accurate travel times, flat image gathers and reduced depth mis-ties. Meanwhile, FWI significantly enhanced the model resolution, bringing short-scale detail and improving the velocity model.

The survey area is affected by anomalies of numerous types and sizes with high absorption and attenuative effects, most commonly related to faulted zones, shallow low-velocity anomalies, and HRDZs. These correspond to low-saturation gas entrapment and wave scattering caused by sub-surface heterogeneity, such as fractures or different rock types. Contrary to initial expectations, the absorption anomalies within the HRDZs are not widespread across all stratigraphic zones. Instead, they are confined to limited areas. This localisation can likely be explained by a high level of heterogeneity within these zones.

Seismic amplitudes are distorted at such anomalies, leading to diminished signal at high frequency, often accompanied by a sagging depth distortion. Tomographic inversion is employed to build a detailed 3D visco-acoustic model alongside the VP and TTI model components. This is followed by pre-stack depth migration (QPSDM) to apply the appropriate corrections. The tomographically inverted 3D Q model was used for subsequent interpretation and AVO analysis, serving as a supportive source of information.

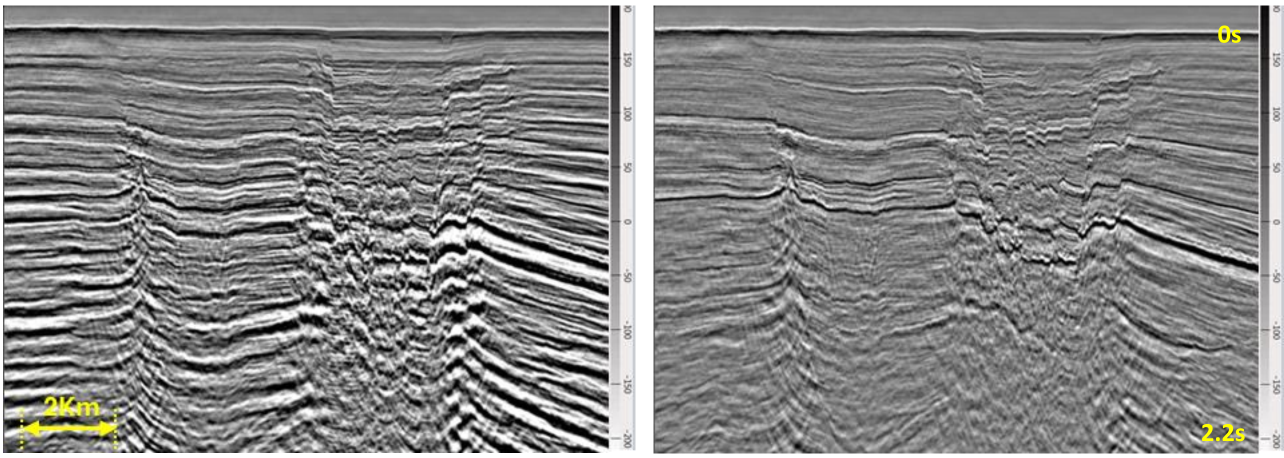

Figure 2. Example of data demonstrating the de-multiple: PSTM QC near stack input (left) and PSTM QC near stack after main pass of de-multiple (right).

IMPACT OF MULTIDISCIPLINARY TECHNIQUES

The data quality beneath the Valanginian unconformity is compromised by noise, and the quality deteriorates further beneath areas with extensive faulting. Additionally, interval velocities estimated from NMO scanning of seismic gathers were significantly slower in the graben area. In this part of the survey, only two wells had sonic data, which indicated anomalously slow velocity, as low as 3300 m/s at 3 to 4 km depth. This observation posed questions whether the velocities were truly slow or whether the well data was compromised.

Further constraint data was explored to validate the slow velocity trend. Given the limited well data within the specific project area, a wider VSP database from the entire Vulcan Sub-basin was reviewed. With access to significantly more statistical data, it was confirmed that velocity data from the few available wells penetrating deeply buried parts of the Vulcan Formation supported the slow velocity trend. This helped define the extent of the low-velocity area and constrained the range of interval velocity values retained.

Based on interim grid PSDM imaging, confirming the observation of slow velocities within the Swan Graben became particularly important. Apart from enhancing the model for depth conversion and imaging, anomalously slow velocities significantly reduced the discrimination between primary and multiple events in the pre-stack data. It is essential to ensure that the events we optimally stack are primaries and not multiples. This challenge, combined with lower data quality and a reduced signal-to-noise ratio within the faulted zone, rendered the de-multiple process as critical for this dataset. Furthermore, the slow velocity area is restricted by a bounding fault, creating strong lateral velocity contrasts. Accurately defining this boundary in the model is crucial for imaging within the footwall fault blocks. It should also be noted that an accurate definition of geological boundaries and velocities is essential for building an accurate TTI anisotropy model.

Rock physics modelling of a key test line was conducted as a further QC of the seismic velocities, enabling lateral and vertical extrapolation of well-based velocities (***Figure 3***). This was achieved by using interim grid PSDM results to map horizons away from well control while using regional rock physics trends to predict burial-dependent velocities within each of the identified stratigraphic intervals. Attention was focused on the velocity inversion below the Valanginian unconformity, where over-pressured shale rock physics trends for the Lower Vulcan formation matched much of the estimated seismic velocities within the same stratigraphic interval. Salt was inserted into the model as a trial to search for signs of salt diapirism within the seismic interval velocities (from FWI, tomography and velocity scanning).

In contrast to the interpretation presented by *Smith and Sutherland (1991)*, as also reflected in (internet-hosted) summaries on the Vulcan Basin by Geoscience Australia, the velocity modelling and velocity data shown in ***Figure 3*** do not support an interpretation of salt within the Swan Graben in the Late Jurassic Vulcan Formation, and, as a result, salt diapirism does not explain the poor data quality noted within that interval during legacy processing studies. Interpretation of the final PSDM volumes remains ongoing and further supports the interpretation of Silurian-aged salt, deeper in the section and without large diapiric structures juxtaposing against much younger rocks. This is a significant study finding and encourages a revision of publicly available briefing materials on the Vulcan sub-basin.

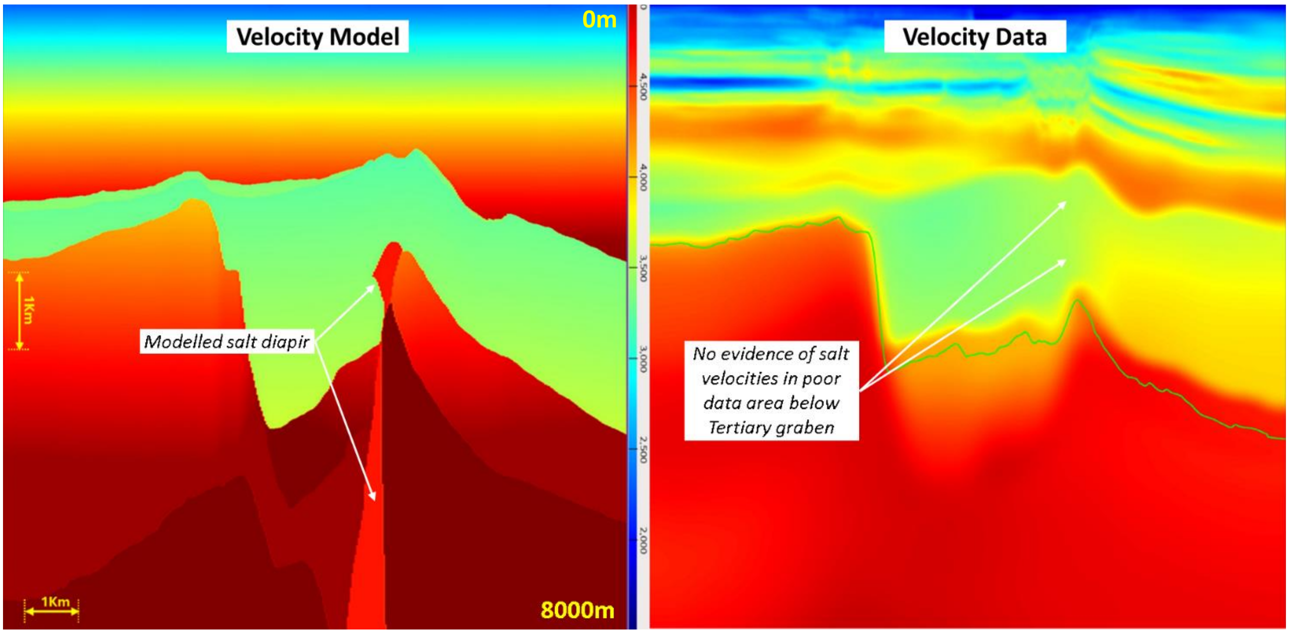

Figure 3. Interval velocity is derived from rock physics modelling (left), and the result of velocity model building is based on seismic tomography, FWI, and anisotropy (right). The colour scale is the same for both. Note, the rock physics modelling is focused below the Valanginian unconformity. Excluding the insertion of salt into the model, there is a significant level of similarity in overall velocity behaviour, suggesting that there are no major discrepancies between the two models despite being built based on entirely different data.

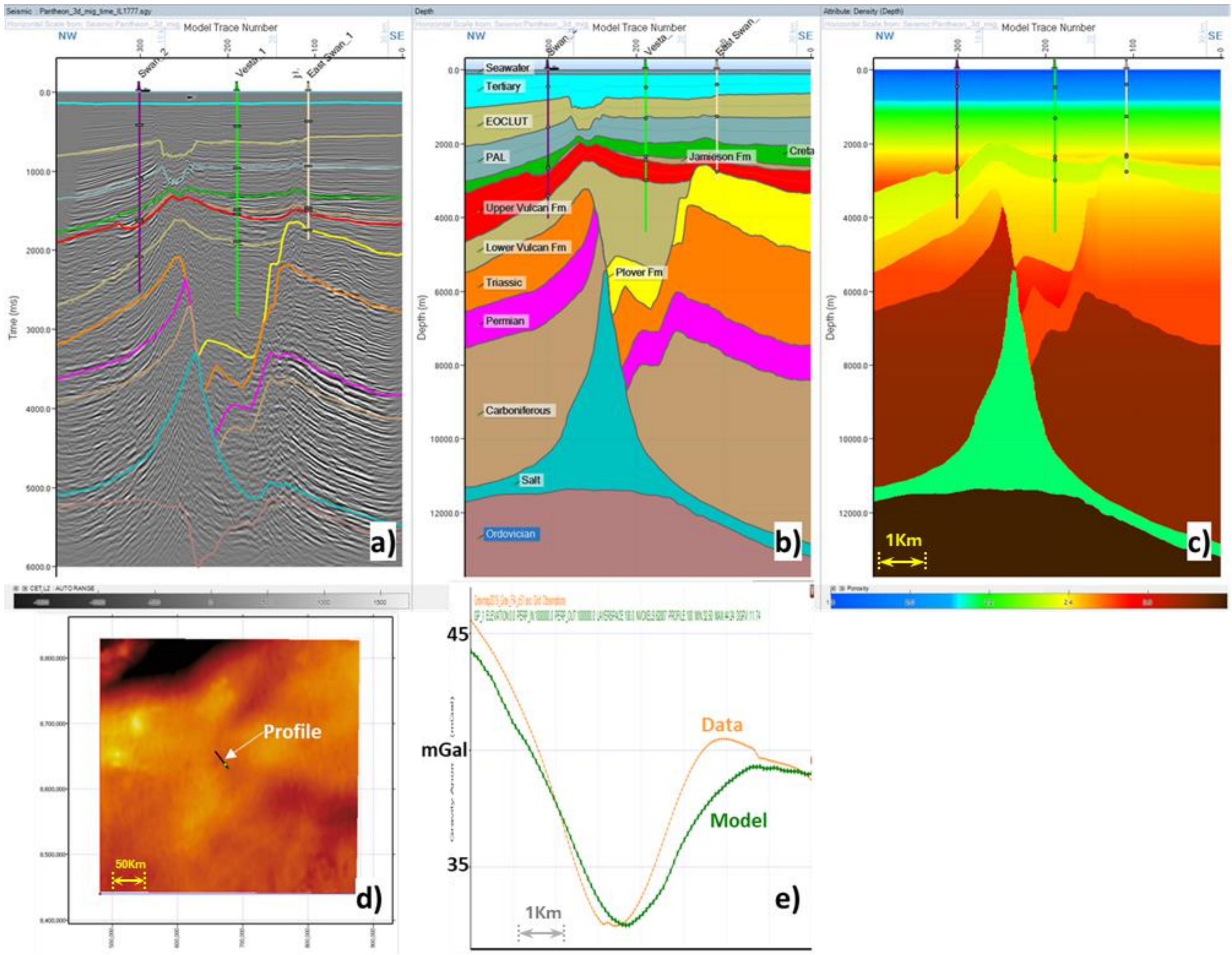

Figure 4. Modelling of gravity data as a further QC on the modelled and estimated seismic velocities, as well as validating interpretation of the salt within the deeper section. The interpreted seismic profile (a) is converted to the depth domain using its rock physics model velocities (b), with the same rock physics model used to produce a density profile (c). Satellite gravity data are extracted over the modelled line (d), then the gravity data is modelled (e), with iterative refinement of the model until a good match is achieved.

A novel feature of modelling velocities using rock physics trends is the ability to simultaneously model gravity data over the same profile, with the rock physics model forming the necessary link between velocity and density (***Figure 4***). After extracting gravity measurements from published satellite gravity data, the seismic interpretation is depth converted and interactively adjusted to improve the match with the gravity model. The final (integrated) model shown is consistent with the seismic reflection and gravity data. The best match was achieved with the salt constrained within the western footwall of the Swan Graben. A minor component of the observed low gravity anomaly originates from the thick over-pressured shale interval within the Swan Graben. Salt withdrawal away from the major listric fault contributes strongly to the observed gravity response.

Well data was utilised throughout the velocity model building to ensure quality control. This included VSP and sonic log data, which helped make decisions by distinguishing between primary and noise trends for moveout picking. Well markers played a key role in estimating anisotropy. During the velocity model building at depths where RMO was observed to be relatively insensitive to velocity, there were consistent depth mis-ties between well markers and the seismic. These mis-ties were analysed, calibrated with specific geological layers, and used to estimate anisotropy parameters in a structurally consistent manner. The final QPSDM was performed using a non-elliptical TTI mode.

It should be noted that this area is known for significant azimuthal anisotropy. Combined with high lateral velocity contrasts and complex fault patterns with a dominant orientation, multi-azimuth processing might be worth revisiting using the insights gained during this reprocessing. In any case, the cumulative improvements of processing using only the narrow-azimuth Pantheon 3D are expected to advance the evaluation of known accumulations and prospects in the surveyed area (***Figure 5***).

Interpretation of the final QPSDM products has commenced, with seismic interpreters noting improvements in the entire section, but most notably in the Swan Graben itself, where more coherent structural dips can now be interpreted. Permo-Triassic horst blocks are imaged with significantly greater clarity, as evidenced by their internal fault patterns, and a major listric fault was revealed that controlled the development of the Swan Graben. Fault shadowing effects have been significantly reduced throughout.

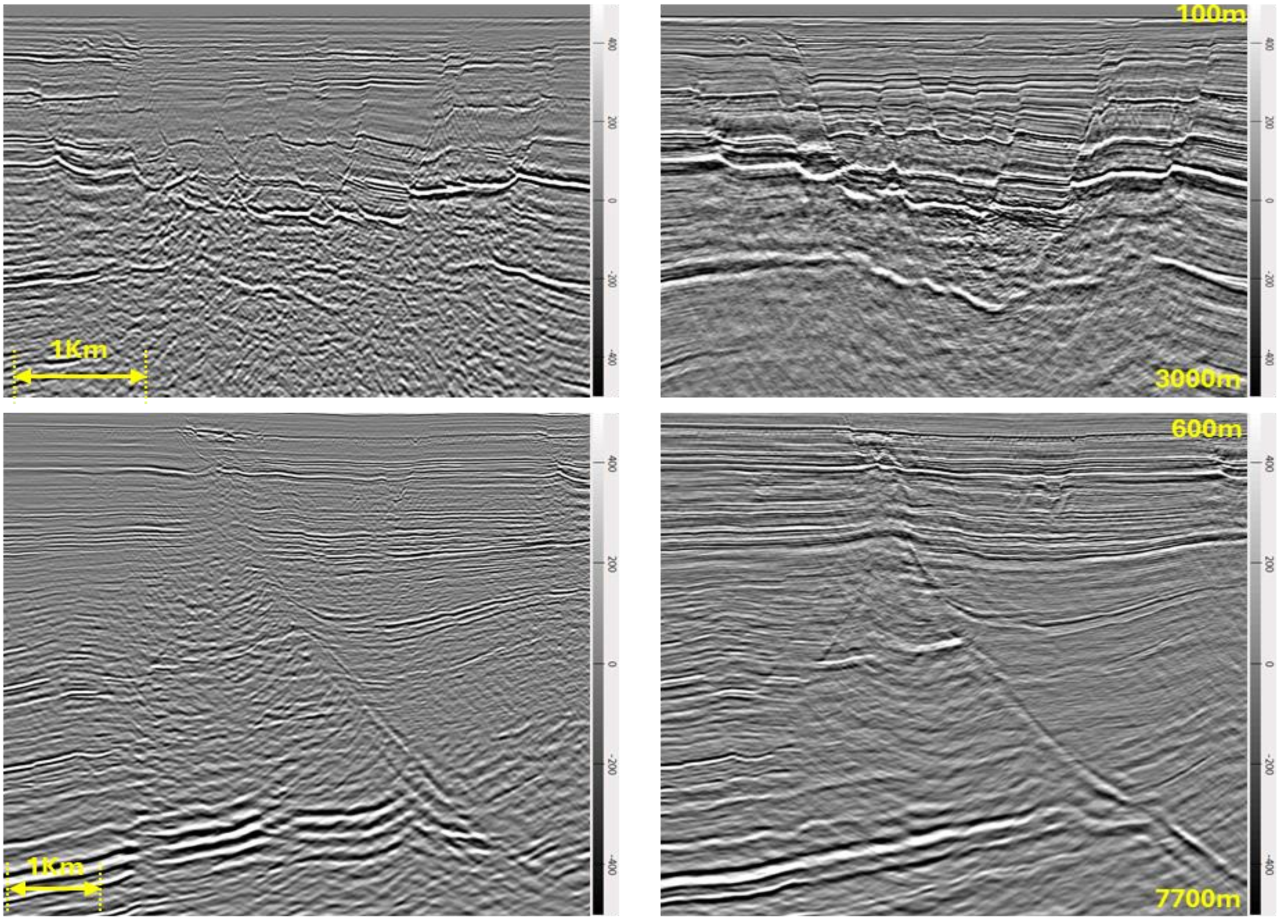

Figure 5. Comparison between Legacy processing (left) and Current reprocessing (right). The upper pictures show the shallow Tertiary graben area, while the lower pictures cover from surface to the top of Permian near major fault with an HRDZ anomaly above. Images are in the depth domain.

CONCLUSIONS

The reprocessing of the Pantheon 3D, located in the Vulcan sub-basin, Timor Sea, achieved significant improvements in data quality by integrating advanced processing techniques such as modern de-ghosting, de-multiple, high-resolution tomography, and FWI. This was supported by non-seismic sub-surface constraint data, including VSP and well logs from the entire sub-basin, rock physics modelling, and simultaneous modelling of gravity data. The collaboration across various disciplines was regarded as crucial in identifying and resolving issues, enhancing the overall quality and understanding of the data, and presenting alternative geophysical interpretations regarding salt diapirism in the Swan Graben.

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