Integrated modelling of seismic velocities and impact on prospect evaluation

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SUMMARY

It is often assumed that velocities associated with good quality seismic images can be directly used for time-to-depth conversion, pore-pressure prediction or even as a driver for seismic amplitude interpretation. However, such applications require seismic velocities to be properly integrated with velocities derived from well-data using relevant geological insights to increase the usefulness of this type of geophysical data. Forward modelling can help to manage the different scales involved and to assess consistency between different velocity data sources.

Seismic velocities, irrespective of the method used to obtain them, should be compared, and calibrated to well-data. Well-based velocities include edited VSP data; time-depth tables derived over intervals with a quality synthetic/seismic tie; and rock physics depth trends derived from sonic and other wireline logs. Geological insight is obtained from inspection of velocity trends; use of well markers; stratigraphic mapping; and basin modelling insights. Integration software can help by converting between common velocity types and by deriving regional burial trends and depth-dependent calibrations between velocity data from different sources.

An example from the Campos Basin, Brazil, shows how well data alone can underpin time-to-depth conversion to reveal hidden structures below shelf-slope breaks and salt diapirs, while also addressing the interpretation of amplitudes for prospect derisking. In the Browse Basin, Australia, velocities derived from well-data can help to QC processing velocities. Comparing seismic and well-based velocities then helps to identify possible overpressured zones. More efficient and sustainable exploration could result from treating velocities as a valuable geophysical dataset requiring interpretation, and not just a by-product of seismic processing.

Key words: seismic velocities, AvO, quantitative interpretation, pore-pressure prediction, integration.

INTRODUCTION

Velocities are an essential component of subsurface exploration using seismic reflection data. They impact on imaging and enable conversion of the seismogram’s recording time into depth, more simply referred to as depthing, or depth conversion. They can also be used for lithology, porefill, and pressure prediction. Despite this, modern interpreters often use them carelessly or tend to avoid using them at all.

It is convenient to think that after spending millions on seismic acquisition and processing using the latest imaging methods, that your velocity data will be ready for depth conversion; ready for use in AvO studies; and can be interpreted simply by direct inspection in terms of its geological controls. This is simply not the case in almost any real-life situation. Some excellent workflows have been published to handle the depth conversion problem (Etris et al., 2001, Schultz, 1999) and for using seismic velocities as an interpretation volume (Schultz, 1999).

Throughout the oil industry, significant effort is spent interpreting seismic amplitudes (Avseth et al., 2005) often in search of an elusive DHI (direct hydrocarbon indictor) to polarize prospect risking. However, integration between seismic velocities and quantitative interpretation appears limited to calculating angle ranges for AvO analysis and some attempts at building low frequency models for seismic inversions, which often lack rigour. Seismic velocities are increasingly being used for pore-pressure prediction (Dutta 2002), yet the linkage between velocities, overpressures, rock physics and seismic amplitudes/AvO barely appears in the literature (Dutta, 2006).

In most exploration settings, greater use of velocities can be achieved through what is essentially a 3-step process. The first step is to develop trends and/or linkages between seismic and well-based velocities to achieve QC; calibration; and more accurate extrapolation. The second step is to forward model velocities in a similar manner to which seismic amplitudes are modelled, with tight integration imposed between the simultaneous modelling of both geophysical measurements. The third step (not discussed in this paper) is to appropriately adjust exploration risks and volumes based on such integrated geophysical analyses.

The central thesis of this paper is that velocities are useful and important geophysical datasets which should be integrated fully into a subsurface evaluation. We propose velocity modelling as a vital step for building confidence in applications ranging from imaging; depth conversion; interpretation; and seismic amplitudes/AvO, with cumulative benefits to prospect volumetrics; risking; and well planning.

The approach we propose contrasts with other methodologies that work well when there is sufficient data quality and quantity. These alternatives include using full-waveform inversion (FWI) velocities with abundant well calibration or brute force geostatistical approaches (Magneron, 2014) when sufficient seismic velocity and well data exists in a study area. Neither of these alternative methods cope with legacy 2D seismic acquired on a sparse regional scale, nor situations where seismic velocities are unavailable. The workflow we propose is more general and can be used to complement these other methodologies in situations where they are better suited.

Our discussion of the proposed workflow is broken into three parts; focussing first on the sources of velocities; then on building useful databases; followed by some background to our method for the simultaneous modelling of traveltimes and amplitudes. We then review an example from the Campos Basin in Brazil which highlights the workflow's impact on prospect evaluation under circumstances where alternative methods were not possible. Finally, we consider a case study from the Browse Basin in Australia with implications for processing and imaging as well as pore-pressure prediction.

VELOCITY SOURCES AND TYPES

Time-depth conversion might qualify as the simplest mathematical process in geophysics. Effectively, one only has to multiply seismic traveltime by velocity to get depth. The problem is that, away from well control, the velocity is always an estimate. Traveltime uncertainty also exists, and needs to be considered, but in some situations, it can almost be neglected (e.g., when using high quality 3D seismic with confident event mapping).

Before considering estimation and uncertainty in the velocities used for depth conversion, it is important to set a clear distinction between velocity *sources* and velocity *types*. In using the term *sources*, we refer to the geophysical method by which the velocities are acquired (Reilly 1993). The two main sources of velocities are from seismic data (with offsets) or wells (wireline logging). Table 1 lists some of the common sources of velocity information and summarizes some of the pros and cons of using them for time-depth conversion.

In using the term *types*, we refer to the mathematical definition under which the velocities have been stored or otherwise represented. Examples include interval velocities; average velocities; and RMS velocities, each of which has a specific and distinct mathematical description. Certain velocity types have properties that make them more convenient to use during time-depth conversion, thus conversions exist between different velocity types (e.g., Dix conversion).

One of the geophysicist's roles is to assess the availability and quality of velocity data for time-depth conversion in each project. It may transpire that well-based velocity data is the only data available and often, for example with legacy 2D seismic data, it may prove to be the best data to work with.

Many seismic interpreters are tempted to use seismic velocities, sometimes for reasons of convenience and especially if expensive processing methods have been applied. The current best practice in seismic velocity estimation would involve 3D coverage, very long-offsets, wide-azimuth, wide-aperture acquisition with full-waveform inversion and reverse time migration imaging, with calibration to several well synthetic time-depth relations. This level of acquisition, seismic processing and velocity manipulation is simply not possible in most projects and would still carry uncertainty that should be assessed relative to well-based velocity data.

Well-based velocities play a vital role in calibrating seismic velocities to achieve depth conversions that match well control. Calibration corrects seismic velocities for anisotropy caused by non-vertical wave propagation. The remainder of this paper focusses on further applications for well-based velocities, many of which remain relevant even for situations where high quality seismic velocities are anticipated.

VELOCITY DATABASES

A solid database of velocity information underpins successful velocity modelling applications. Dedicated software can help to QC, manage, and compare different velocity sources, as well as convert between different velocity types. It is vital to incorporate well tops and corresponding horizons into the analysis. This can aid QC, but more importantly it allows re-datuming to mudline (for offshore datasets) and grouping by lithostratigraphy which helps to reveal compaction trends.

Persistent breaks in the compaction trends usually correspond to well-known geological boundaries in the basin, for example, the bases of the Tertiary and Cretaceous sequences in the Westralian Super-Basin. By incorporating tops into the analysis, it is possible to identify any lateral variability in the compaction trends at each well, which may reflect broad lithological changes caused by climate or provenance during different geological time periods. Such insights tend to materialize out of the data analysis, especially when guided by an existing regional geological understanding, resulting in the formulation of a regional depth conversion strategy.

As an example, Figure 1 shows a velocity database from the Campos Basin, Brazil, which was built from 9 checkshot surveys acquired in a wide range of water depths within a particular study area. After editing some outlying time-depth pairs at a few wells, the data were redatumed to sea floor to reveal that the time-depth behaviour can be well-represented using a single V_0-k trend. No further stratigraphic subdivision of the data appears to be necessary, at least for the clastic post-salt interval encountered by these wells.

V_0-k trends represent compaction processes (both mechanical and chemical) and as such are related to rock physics models. In some circumstances, rock physics models could be used to augment well-based velocity databases, keeping in mind dispersion effects (Gopa et al., 1994) and end-member averaging (or scale differences/heterogeneity) that can occur over some intervals in checkshots/VSPs.

Seismic velocities should also be added to velocity databases when they overlap with wells that have some form of well-based velocity data. After QC, it is possible to derive anisotropy correction factor logs, export these and build a 3D anisotropy correction model using key horizons to guide the interpolation away from well control and then apply this model as multiplier to the seismic velocity volume. Calibrated seismic velocities can then be used directly for time-depth conversion; for pore-pressure prediction; and as a driver for AvO modelling.

SIMULTANEOUS MODELLING OF TRAVELTIMES AND AMPLITUDES

For the case studies discussed next, we use a new software approach (called *Quiacito*) that ensures a tight integration between the traveltime and amplitude/AvO components when modelling observed seismic data. The software allows the entire section to be modelled interactively and simultaneously in terms of event traveltimes (driven by P-wave velocity) and event amplitudes/AvO (driven by S-wave velocity; density; and the same P-wave velocity).

Data is used to constrain the modelling wherever it exists, such as QC'd seismic velocities; well-based V_0-k trends; or rock physics models based on well logs. Hybrid models can be built using stratigraphic controls to switch between the underlying data sources. Models can be built in both the time and depth domain using seismic to guide the layering choices and for mapping layer boundaries. Explicit trend linkages or rock physics models are used to link P-wave (interval) velocities with S-wave velocity and density, thereby enabling AvO modelling at layer boundaries. Hydrocarbon porefill can be added to porous layers using Gassmann fluid substitution to modify the elastic properties within the proposed trap.

Regarding the construction of synthetic seismic Margrave and Foltinek (1995) wrote that "*typically, no raytracing is involved, no attempt is made to model mode conversions, coherent noise, attenuation, or any other 2-D or 3-D effects. That the models often prove strikingly similar to migrated seismic sections is a testament to the effectiveness of seismic processing at eliminating unwanted effects*". Although our approach models angle-dependent amplitudes within a 2D cross-section, at this time, we do not attempt to model the effects listed above because it is nearly impossible to replicate the extent of seismic processing used to suppress them.

We therefore assume that the section we model exists, at least locally, in 2.5D. In omitting ray-tracing we effectively assume that seismic processing/imaging has achieved a plane-wave decomposition, regardless of structural dip on an interface. We also assume that seismic processing removes multiples; mode conversions; coherent noise; inelastic attenuation and anisotropic effects. For synthetic computation we use the Aki-Richards' 3-term approximation with truncation applied to reflections beyond the critical angle.

The *Pareto principle*, namely that "*20% of the effort accounts for 80% of the results*", is invoked to justify more simplistic modelling than is technically possible. This is also what is done in most commercial software packages for Quantitative Interpretation. The idea is that if you can get close to matching a synthetic to at least part of the seismic response then you can claim some confidence in the underlying interpretation and proceed to modify prospect risking accordingly.

CAMPOS BASIN (BRAZIL) CASE STUDY

In developing an exploration prospect, perhaps the most important task is to define the trap. In structurally complex settings, or for low relief structures, defining the trap can be sensitive to the interpretation and the velocities used to perform time-depth conversion. Figure 2 shows a regional 2D seismic line from the Campos Basin in Brazil. The section contains shallow targets, with possible amplitude anomalies, as well as deeper presalt targets.

Mapping in the time domain is straightforward but the steeply dipping sea floor and salt diapirs impact upon the time-depth conversion and our understanding of whether robust structural traps exist. Reliable seismic velocities were not available, but several nearby wells have checkshot surveys and show consistent time-depth relations, which are indicative of a compaction-dominated setting (Figure 1). This allows use of the V_0-k method for depth conversion, particularly for the clay-dominated overburden using V_0=1500 and k=0.485. We apply constant velocities for the water layer, salt and presalt carbonates to convert the time interpretation into depth, using a layercake approach (Figure 3).

Hydrocarbon contacts can also be added into the depth conversion model using Gassmann fluid substitution to adjust the depth conversion velocity within the trap. Figure 3 shows hypothetical oil-water contacts, which can be used to assess the range of possible spill points for both the post-salt and presalt targets. This "one-line" interpretation suggests that a sizeable presalt trap could exist here and that its position is shifted laterally from where the time data would suggest. Similarly, in the post-salt section, a new target was revealed on the depth converted section where no significant closure had existed on the time domain data.

Further work on seismic amplitudes can then be focussed on assessing structural conformity of a possible hydrocarbons within the bounds of this depth closure. Using regional knowledge of the basin or long distance well ties, whilst remaining mindful of the sequence stratigraphic interpretation, allows lithologies and fluids to be provisionally assigned to each layer in the model. These are combined with some appropriate rock physics models and seismic wavelets to generate AvO synthetics. These synthetics help to guide seismic interpretation by assessing event polarity and phase; and by noting differences in the relative strength of events as well as identifying lateral variations caused by burial.

In the shallow post-salt section, where seismic amplitude support might reasonably be expected, we observed some brighter amplitudes as well as some intriguing events that appear to cross-cut stratigraphy (Figure 4a). Prominent half-space events, such as the sea floor or top salt were used to scale the synthetic to the seismic amplitude range. Such amplitude calibration is often preferred over the traditional updip/downdip calibration method which can be sensitive to thickness changes in the targeted events.

At the target level, we sought to match one of the brighter amplitude events using a thin unconsolidated sand encased within the clay-dominated overburden. The Sun rock physics model (Sun, 2004) was applied to this sand using typical default parameters borrowed from other regional rock physics studies. The encasing clay layers were modelled using the V_0-k trend and standard industry empirical regressions for density and S-wave velocity. Regional temperature gradients, hydro-pressures and salinity were combined with expected oil properties to define fluids within the model.

The model itself covers a wide range of burial depths, which causes measurable amplitude variations even within the structural closure. Comparing the brine and oil cases reveals a distinctive polarity change in the modelled oil zone, even though the overall absolute amplitude level does not appear to vary much at the proposed contact, as is also the case on the seismic (Figure 4). The strongest evidence for oil in this example, is the match to the cross-cutting event by the modelled polarity change at the oil-water contact.

Synthetic models for alternative fluid, lithology and pressure scenarios were also built to assess the chance that the amplitude anomalies are caused by lateral variations unrelated to trapped hydrocarbons. Further rigour was added by considering the match to other angle stacks and by extracting amplitude values around mapped events on both the synthetic and seismic data. Allowing for some interference and lateral variability in sand thickness, the post-salt targets appear well explained by the modelled oil sands. This amplitude interpretation was underpinned by the simultaneous modelling of the time/depth structure and the use of *fill and spill* logic to identify structural limits of the prospective accumulation.

BROWSE BASIN (AUSTRALIA) CASE STUDY

The Browse Basin is representative of much of the Westralian super-basin both in terms of its geology and burial history but also in terms of the maturity of exploration within it. Much has been learnt from the many wells drilled, yet the area is large and outlying parts remain lightly explored. Velocities have played a role throughout its exploration history and continue to remain relevant particularly in areas with limited seismic and well control. Some examples include establishing depth control for maturity modelling; overpressure prediction in the frontier areas; and avoiding large errors (hundreds of meters) in well planning (i.e., Snarf-1).

A well velocity database was built for the Browse Basin using all the available VSP data (at the time of publication). Twenty-eight wells were included in the study and a clearer trend interpretation emerged after these were grouped into sub-basins within the greater Browse area (Figure 5a). The VSP dataset extends from near sea floor to inter-Triassic depths, so our discussion is therefore limited to this age range of sediments.

Well tops were added to the database to enable trend analysis based on stratigraphy. Throughout the Westralian super-basin, the Tertiary, Cretaceous and Jurassic/Triassic sections can be differentiated based on depositional environment and dominant lithostratigraphy. The Tertiary section contains abundant cool-water carbonates; the Cretaceous is dominated by marine shales; and the Jurassic/Triassic (with some notable exceptions) is mostly deltaic sands and shales.

Figure 5b shows our well velocity database for the Tertiary section, after redatuming to sea floor and colouring each well based on sub-basinal grouping as indicated in Figure 5a. Separate V_0-k trends emerge, and these appear highly consistent with published regional geological interpretations. A schematic cross-section through the Browse basin (Figure 17 from Geoscience Australia, 2020) suggests lateral variability in carbonate content within the Tertiary sequences, with increasing carbonate content from the inner to the outer parts of the basin, as suggested by the grouped V_0-k trends. An exception to this is the outermost Seringapatam trend (not included in the Geoscience Australia study) where seismic stratigraphy suggests a reduction in Tertiary carbonates (which downlap and thus thin out) and an increase in deep-water shales, which explains the lower velocities there.

Interpreted V_0-k trends for the Cretaceous show less lateral variability within the basin. They also show almost no compaction which is likely attributed to thermal over-pressuring. Compaction resumes, albeit relatively slowly (mostly dominated by chemical processes), in the Jurassic and Triassic whose V_0-k trends also show relatively minor lateral variability within the basin.

The Browse Basin V_0-k trends can be used selectively to perform velocity modelling for the purpose of reviewing seismic processing. Figure 6 shows an example of this using a regional 2D seismic line from the north-eastern Browse Basin that had PSDM reprocessing. Modelling was achieved by interpreting major stratigraphic events in the time domain (Figure 6a) and tying these into distant well control (linking up with other time domain seismic datasets) to confirm the age interpretation. The model was converted to depth using the V_0-k trends assigned to each layer then compared to the seismic interval velocities, which were supplied in the depth domain (Figures 6b and 6c).
The line straddles the boundary of the Outer Browse and Seringapatam sub-basins and so we trialled both sets of V_0-k trends, including hybrid combinations of both. A better match to the seismic velocities was achieved using the Seringapatam trends throughout, but this was not the objective of the modelling. Our initial goal was to see if we could get close to modelling the seismic velocities. In areas with lesser seismic data quality, such models might be used for processing QC or as accurate starting models for imaging or inversion methods.

The comparison between Figures 6b and 6c suggests that it is possible to match high quality seismic velocities using only VSP data guided by a robust interpretation. Some discrepancies exist within the prograding Tertiary carbonate section, yet many of these could be modelled by adding additional layering in areas where brighter amplitudes are observed. Other discrepancies could be caused by unexpected lateral variations in lithology or over-pressures. Further investigation using amplitude and AvO modelling might help to further differentiate between these subsurface scenarios.

The question of over-pressures was considered on another line from the same survey following the observation of some pyramidal-shaped features, with chaotic internal geometries, which were reminiscent of mud volcanoes observed in seismic from the other parts of the world. This additional seismic line was modelled in the same manner as the previous line and the seismic velocities were subtracted from the modelled velocities to derive an uncalibrated overpressure indicator attribute. The pyramidal features were in fact faster on the seismic velocities than the modelled velocities, therefore over-pressuring was ruled out (at least for those features).

CONCLUSIONS

The case studies shown here demonstrate that it is possible to build high quality well velocity databases with strong linkages to regional geological knowledge in a study area. Complex velocity models can be built using trends derived from these databases and combined with amplitude and AvO modelling to improve integration within prospect evaluation. Seismic velocities are valuable geophysical datasets and velocity modelling is the key to interpreting them and extracting full value from them.

Other applications for velocity modelling include seismic processing QC and perhaps more importantly the design of initial velocity models for CMP stacking, imaging, or inversions, including full-waveform inversion. Improved pore-pressure prediction using seismic velocities might be achieved using hydrostatic velocity models as a reference volume for detecting velocity slowdowns potentially caused by overpressures. Finally, velocity models can be combined with rock physics models to derive starting models for properties such as density and resistivity thus driving improved inversions using potential fields in sedimentary basins.

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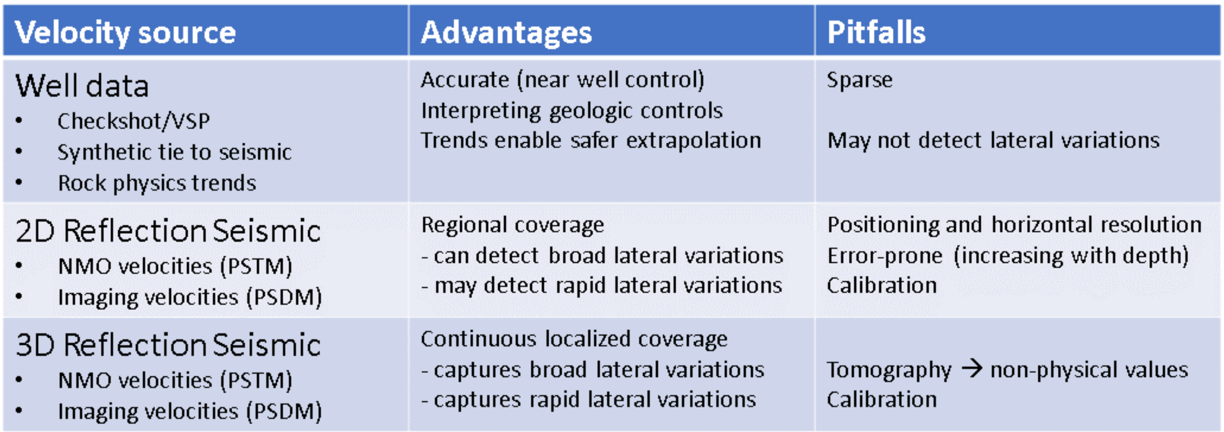

Velocity source	Advantages	Pitfalls
Well data • Checkshot/VSP • Synthetic tie to seismic • Rock physics trends	Accurate (near well control) Interpreting geologic controls Trends enable safer extrapolation	Sparse May not detect lateral variations
2D Reflection Seismic • NMO velocities (PSTM) • Imaging velocities (PSDM)	Regional coverage - can detect broad lateral variations - may detect rapid lateral variations	Positioning and horizontal resolution Error-prone (increasing with depth) Calibration
3D Reflection Seismic • NMO velocities (PSTM) • Imaging velocities (PSDM)	Continuous localized coverage - captures broad lateral variations - captures rapid lateral variations	Tomography → non-physical values Calibration

Table 1. Velocity sources with pros and cons.

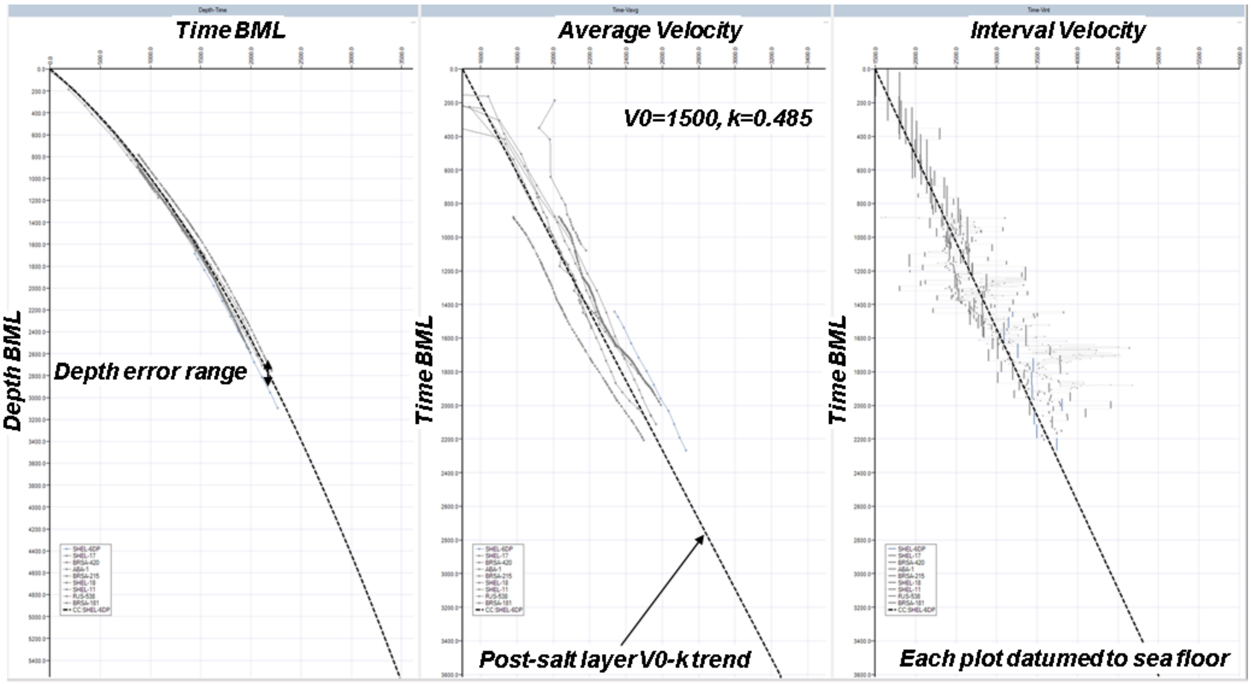

Figure 1. Velocity database and V_0-k trend, after redatuming to sea floor, for 9 wells in the Campos Basin, Brazil.

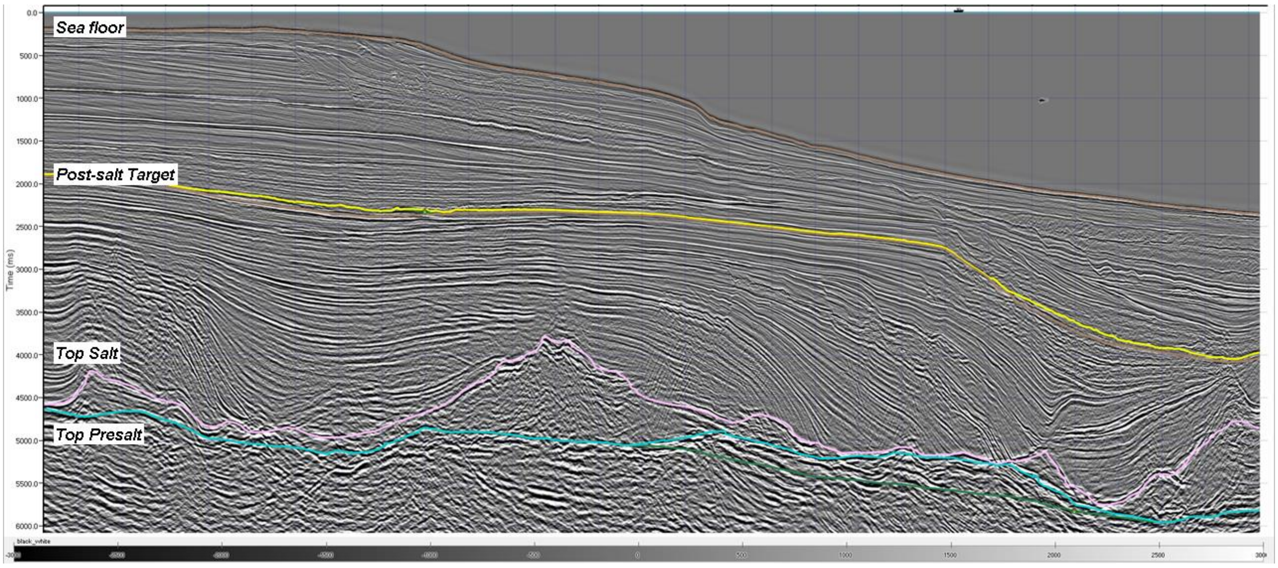

Figure 2. 2D time-domain seismic line from the Campos Basin, Brazil, with interpreted depth conversion horizons.

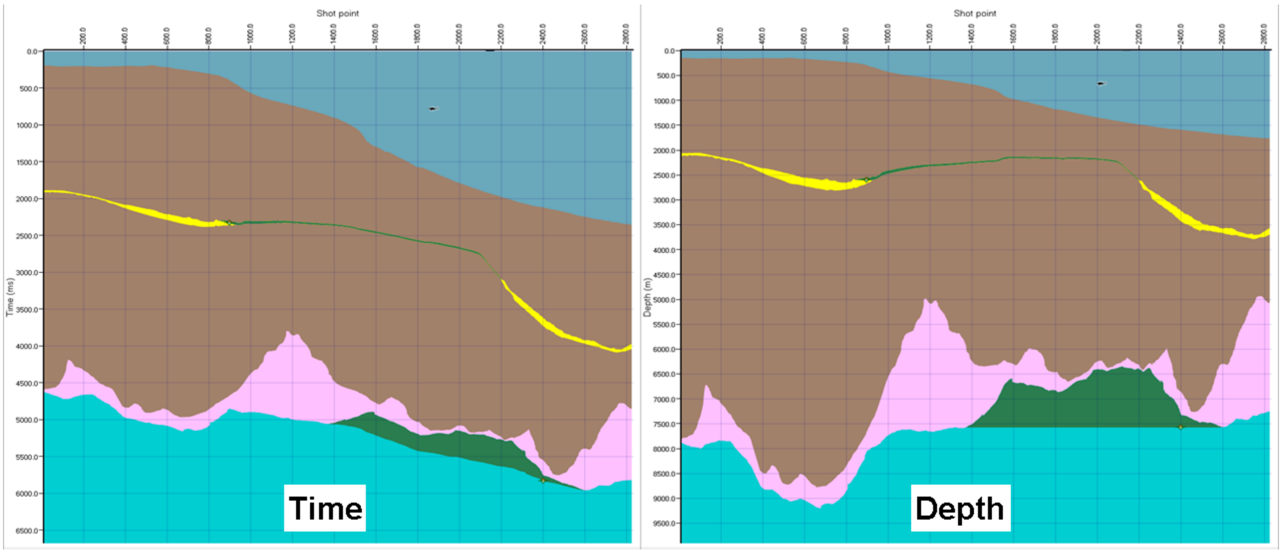

Figure 3. Impact of depth conversion on the structural model for the 2D seismic line from the Campos Basin, Brazil.

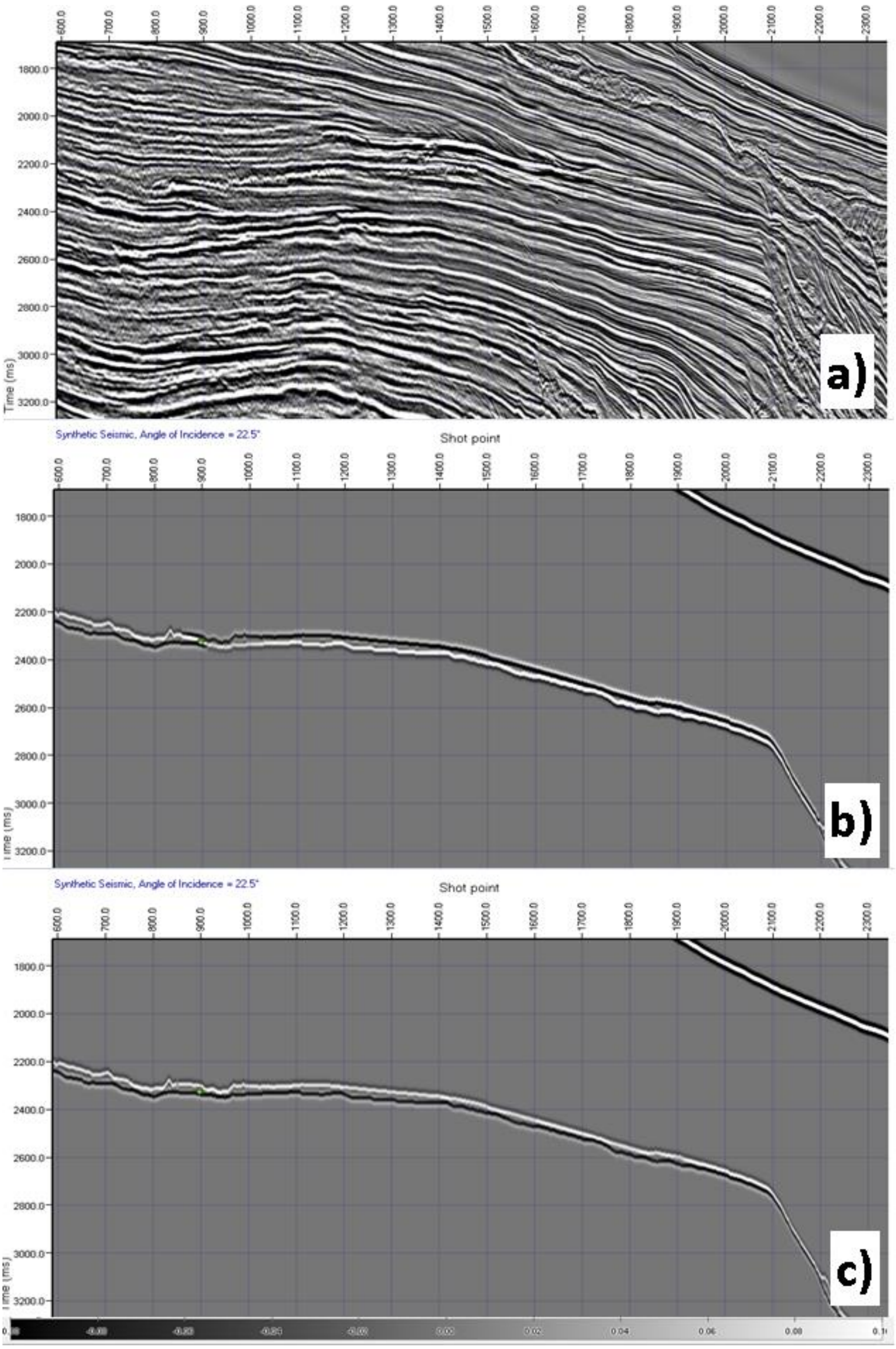

Figure 4. Amplitude modelling of a post-salt target (Campos Basin, Brazil) with rock properties largely based on a well-based velocity database. The full stack seismic a) shows anomalous cross-cutting events and compares more favourably to the mid-angle synthetic using an unconsolidated oil sand b) as opposed to a mid-angle synthetic using an unconsolidated brine sand c).

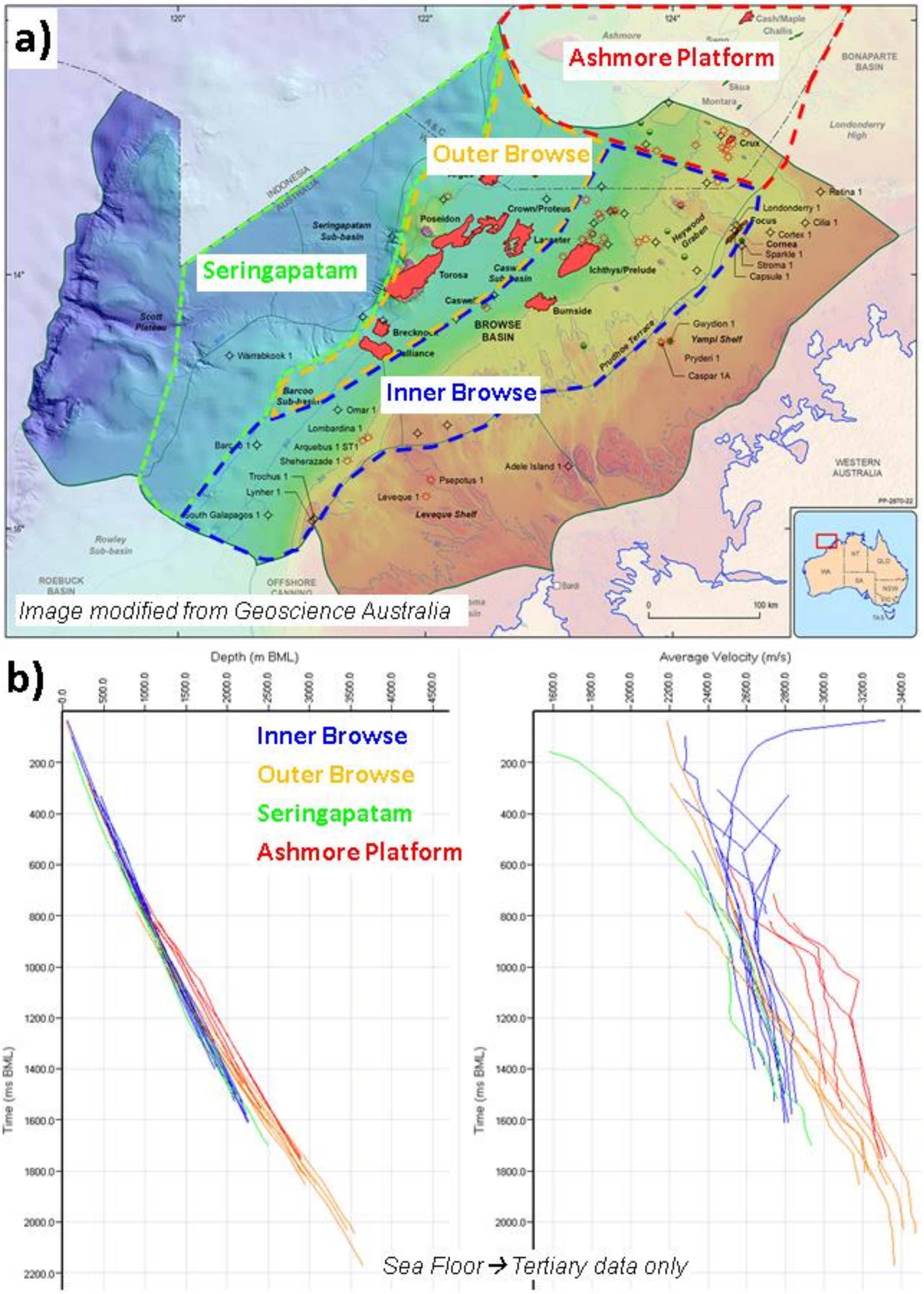

Figure 5. Browse Basin well velocity database. VSP data from the sea floor to the base Tertiary after QC and redatuming to sea floor show a natural grouping by sub-basins a). Separate V_0-k trends are therefore needed for each sub-basin based on lithological variation identified mostly within the Tertiary section b).

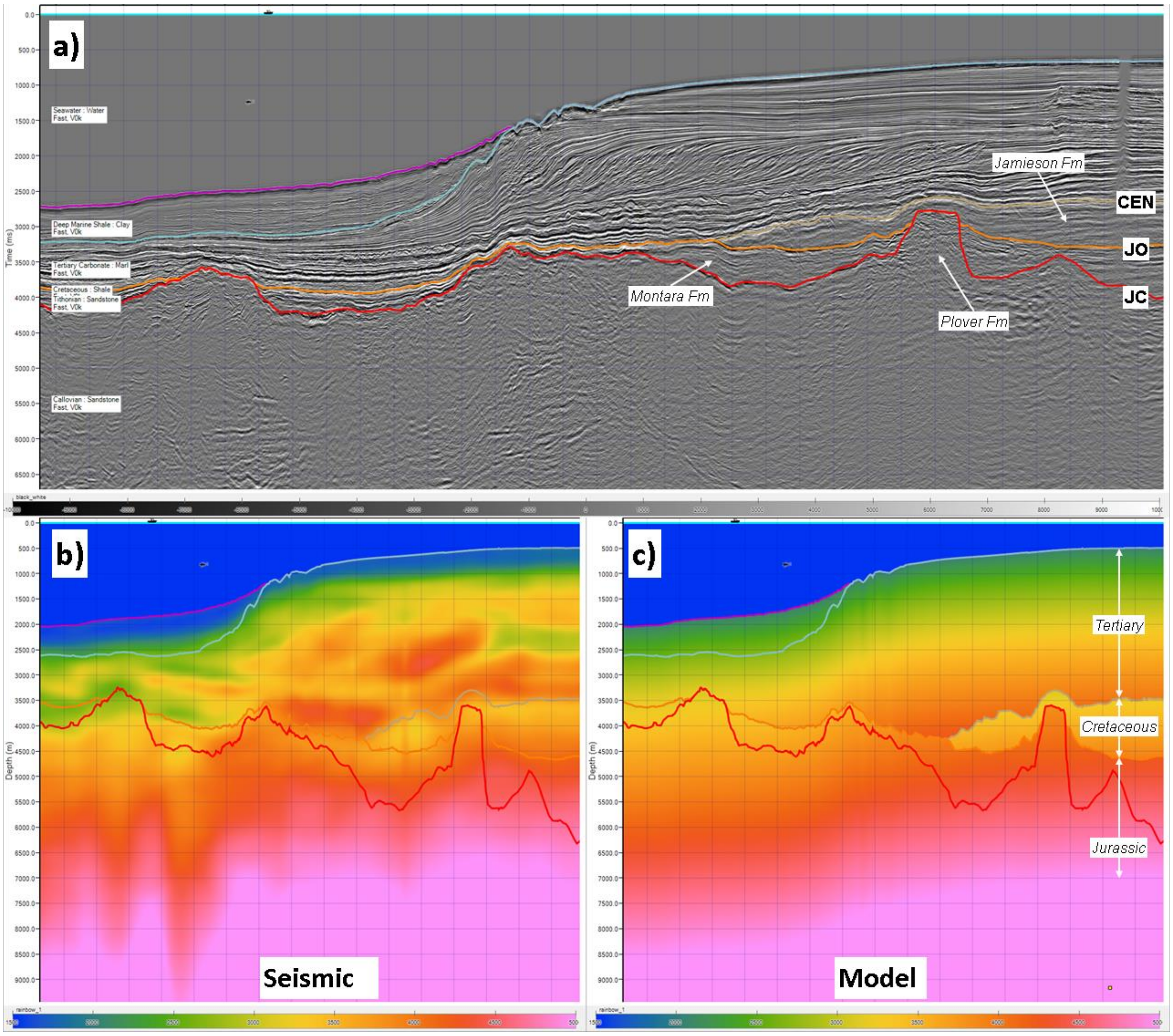

Figure 6. QC of PSDM reprocessing in the Browse Basin comparing time domain seismic a); depth domain seismic velocities b) and modelled interval velocities (based on V_0-k trends derived from VSP data) c).