Reducing the gap between seismic imaging and geology: Horizon consistent velocity analysis and modelling for pre-stack time and depth migrations

Paolo Esestime[1*], Chris Benson[1], Milos Cvetkovic[1] and Sarah Spoors[1] **present a migration workflow which links the velocity modelling for PSTM with PSDM, and allows geological constraints to be applied at the PSTM stage.**

Seismic velocities and migration techniques have great impact in the reservoir imaging at any stage of the exploration for hydrocarbons. The effectiveness of a migration algorithm is commonly measured by the ability to boost the signal continuity, against noise and other disturbances such as diffractions from out-of-plane events (Jones, 2010). By contrast, migration is a process applied to reposition the energy from where it originated, to resolve the geometry and positioning of the events. The success of the process is heavily reliant on the velocity field used.

The consistency between the velocity field and events is a quality indicator in seismic inversion exercises, for both the low frequency background and the high frequency intervals identified in velocity logs. The migration itself can be seen as an inversion procedure, with the velocity gradients required to be consistent with vertical trends and amplitude events (Guillaume et al., 2011; Benson et al., 2015).

The understanding of geological velocities progresses with exploration and the increasing number of wells and geophysical data available, which gradually establish lithological and rock physics properties, together with tectonic and burial history. Several pre-stack algorithms are available for time migration (PSTM) as well as for depth migration (PSDM), which allow the velocity analysis and modelling sequence to more closely integrate geophysical and geological data.

Nowadays, pre-conditioned migration velocities are common in the depth imaging, during the processing of PSDM. The approach is applied for complex geology and relies on seismic and non-seismic data, also combined through different joint inversion techniques (Droujinine et al., 2008; Foss et al., 2008; Houghton et al., 2014). We present a migration workflow, originally designed for regional 2D seismic and applicable to 3D, which links the velocity modelling for PSTM with PSDM, and allows geological constraints to be applied at the PSTM stage (Figure 1).

The uncertainties in migration velocities

When seismic migration is performed, the seismic wavefronts or ray-paths are propagated through a velocity field V(x; y; z; t), used as vector (Bednar, 2005). The NMO correction is a precursor for any velocity analysis and modelling, including migration (Al-Chalabi, 2014), and it generates a root-mean squares velocity (V_{RMS}) at each CMP. V_{RMS} are sensitive to noise, frequency scattering, non-hyperbolic wave propagation (anisotropy), the presence of dipping acoustic interfaces and decreasing velocity with depth. Ultimately, for practical reasons the V_{RMS} are calculated in a selection of CMPs, where the picks may have an inadequate vertical resolution.

In recent years, several modern processing techniques are available to mitigate noise and dispersion, such as de-ghosting, Q compensation and Q migration. In the past, Dip Move Out correction (DMO) (Liner, 1999) was used to correct the NMO in the case of steep dipping events. This problem is currently handled within the migration algorithm. The correct estimate of NMO and V_{RMS} is mandatory, in order to boost signal against noise in the stack process. However, gathers may be flattened by several V_{RMS} iterations, because the V_{RMS} never completely accounts for the energy paths.

Seismic migration techniques, in time (PSTM) as well as in depth (PSDM), require a lateral correlation of velocities from single gathers through the entire seismic section or volume. V_{RMS} are immediately available after gridding and smoothing, but such editing, to reduce inconsistencies from the gathers, can result in unwelcome bias and loss of genuine heterogeneities, potentially related to geological features. The conversion of V_{RMS} into Interval Velocities (V_{INT}) allows a more efficient lateral extrapolation (Dix, 1955). Downward propagation of erroneous picking and the presence of velocity inversions can destabilize the V_{INT}. In addition, no correlation can be inferred to the V_{RMS} within nearby gathers, as the V_{INT} are calculated separately for each gather location

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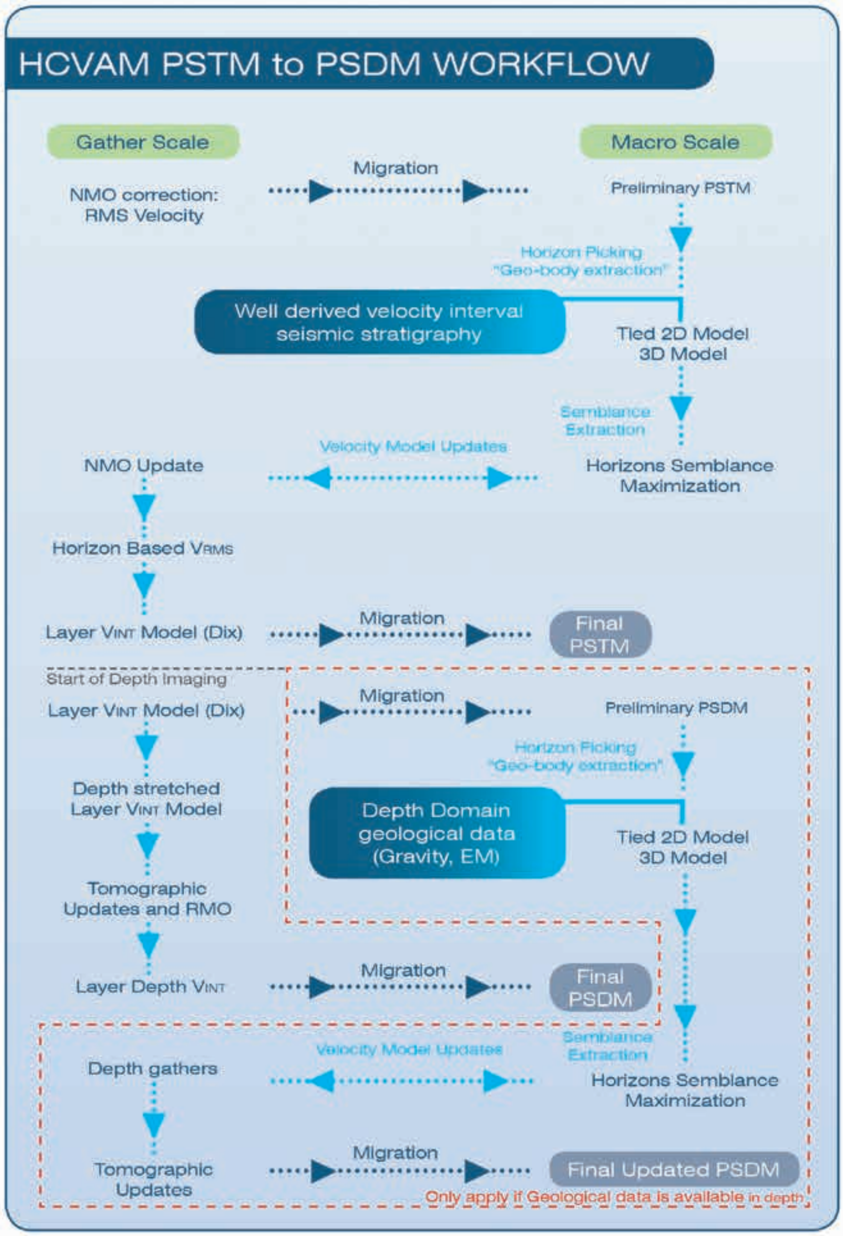

Figure 1 *Schematic representation of the Workflow used in the Horizon Constrained Velocity Analysis and Modelling (HCVAM) for Pre-Stack Time Migration (PSTM) and Pre-Stack Depth Migration (PSDM).*

(Hubral and Krey, 1980; Koren and Ravve, 2006; Lambaré, 2007). Additionally, V_{RMS} and V_{INT} are both measured in time, with no relation to depth intervals and therefore cannot be considered an estimate of true interval velocities (Al-Chalabi, 1974).

In case Pre-Stack Migration is performed with a velocity field derived from V_{RMS} or V_{INT}, this may lack a proper lateral and vertical correlation, resulting in geometrical inconsistency between velocity gradients and horizons, with potential error in the measure of the velocity bulk. The choice of the migration algorithm and its parameters can reciprocally weigh or balance these two factors in the velocity errors. However they can be discriminated and eventually removed only by understanding and constraining the velocity field with additional geological and geophysical data.

PSTM to PSDM velocity model building workflow

This workflow allows the analysis and modelling of the velocity field both at the scale of single gathers and at the scale of the entire section or volume 'Macro Scale' (Figure 1).

The final velocity model is required to respect the picks imposed from the NMO correction analysis and overcomes its limitations by correlating the velocity consistently along horizons and geo-bodies.

A primary semblance velocity analysis is performed on gathers, as a measure of the time where the amplitude value of

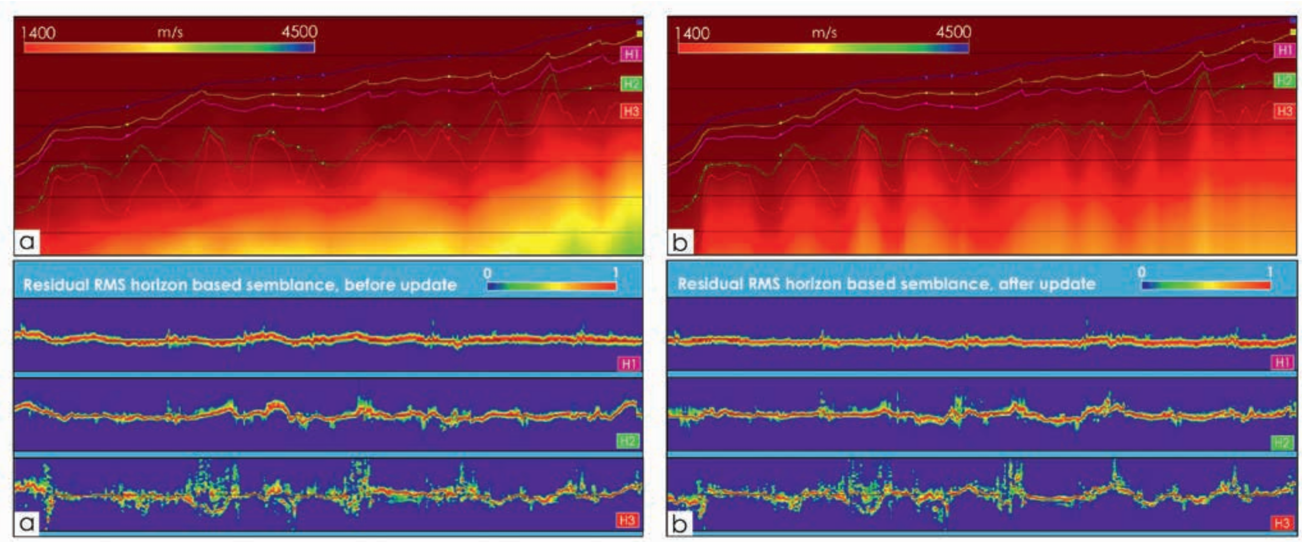

Figure 2 *The V_{RMS} model and the horizon semblances are compared before a) and after b) the update. In b) the geometry of the V_{RMS} field is more consistent, with the semblance values closer to, and maximized along the horizons.*

an event is maximum (Neidell and Taner, 1971; Mulder, 2002), which also allows the calculation of the initial V_{RMS}. Semblance is then extracted along horizons, as measure of coherency in the energy along the section (Yilmaz, 2008 and references therein; Mithai, 2012; Wang, 2015) (Figures 2a and 2b).

An initial V_{RMS} field is required to run the preliminary migration of the seismic in order to pick the key geological horizons or the amplitude bodies (Figures 3a and 4a). A number of seismic stratigraphic units are identified and embedded in a model which is tied three-dimensionally. Additionally, the model can be instructed with interval velocities obtained from lithological and stratigraphic formations. Well check-shots can help to set the position of the key horizons and to produce an average interval velocity for each formation (Figure 5a).

Horizon-based semblance velocity picking is then performed along all identified events to give a vertically sparse V_{RMS} field and picks are reviewed at the gather scale. Dix conversion is performed on the horizon based V_{RMS} to obtain Layer V_{INT} model, finally tied at the intersections (Figure 1). Ultimately, the process will flatten the gathers, under a new set of V_{RMS} based on the intervals from the model. This has a primary objective of removing geometrical inconsistency in the velocity field, to discriminate additional criteria for constraining the bulk of the field (Figure 3b). As a consequence, the finally obtained V_{INT} field is firmly based on layers from the model, reducing the uncertainty in both the geometry and the bulk velocity field. Geometrical anomalies, related to highly variable bathymetry and artefacts in the deep section, are reduced (Figures 4a and 4b).

The Layer V_{INT} used in the PSTM can be 1-D stretched to form an initial depth velocity model for input to the depth imaging process (Figure 1). This has the potential to reduce the update iterations required to reach the final V_{INT} to depth migrate the data.

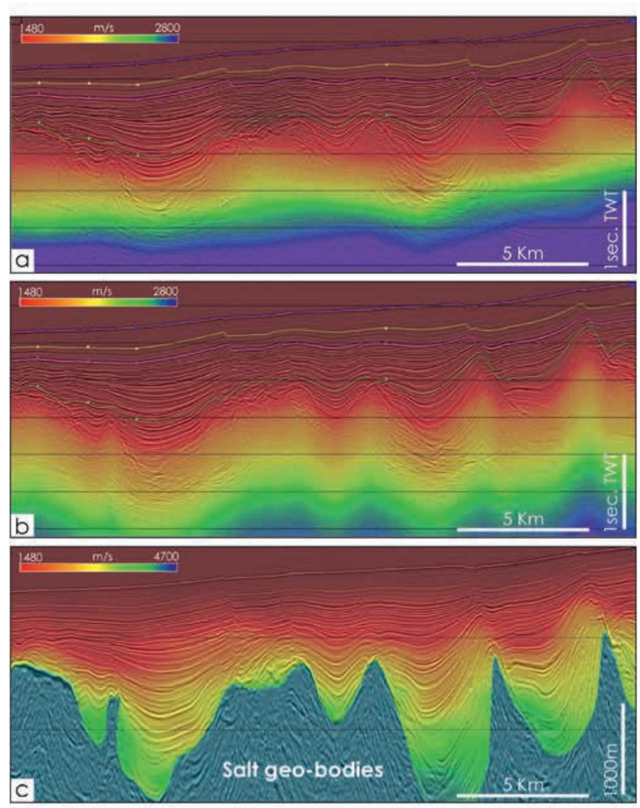

Figure 3 *In the Offshore Gabon, mobile evaporites present geo-bodies with anomalous shallow velocity of ~4500m/s. The amplitude sections with V_{RMS} field overlain show the constraining of the V_{RMS} field from PSTM to PSDM. a) Unconstrained V_{RMS} field for preliminary PSTM; b) Horizon constrained V_{RMS} field for PSTM, without corrections for in salt velocity bulk. c) Depth V_{RMS} field updated by grid tomography (Kirchhoff) after inserting the salt geo-bodies. Top Salt is not included in the tomography update.*

As the velocity field gets closer to the true bulk and geometry (Figure 5a), the deep section can benefit from a reduction of noise, showing additional or more continuous

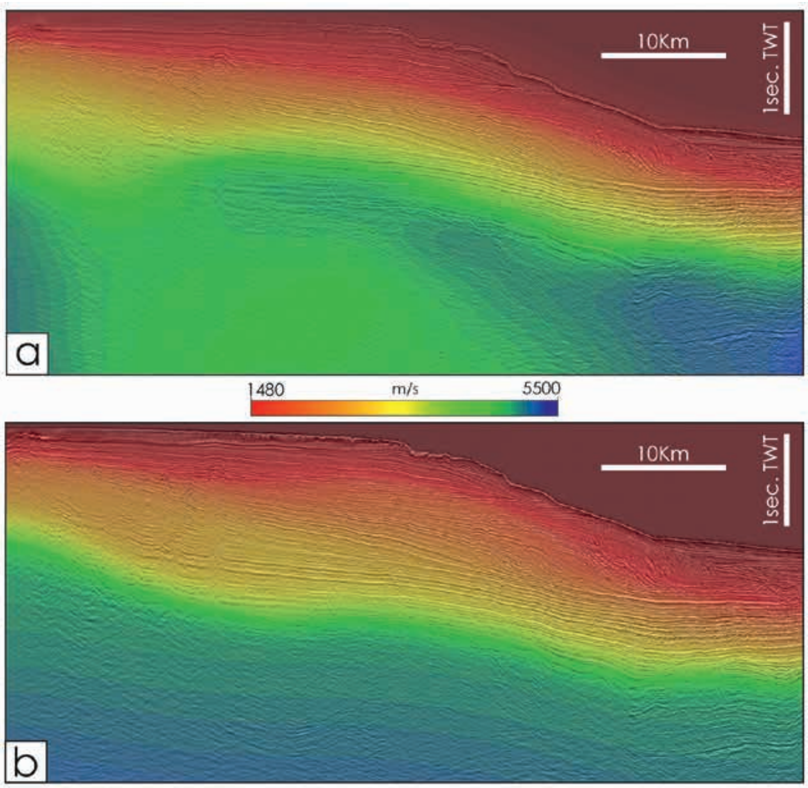

***Figure 4** Offshore South Africa: PSTM sections overlaid with to V_{INT} models before a) and after b) the complete workflow of constraining and updates.*

events, and radically changing the depth imaging results (Figure 6), which appear more consistent to structural and stratigraphic elements. If the well velocity inputs are sparse but representative (Figure 5b), the final depth image can reliably tie the horizons regionally, even when the wells are distant by hundreds of kilometres (Figures 5a, 5b and 7).

The integration of geological information can progress from the time migration into depth. In fact, geo-bodies and surfaces, from non-seismic data, which are given in depth, will be integrated during the PSDM, rather than in the time domain of PSTM, to avoid depth to time conversions made with the unconstrained V_{RMS} (Figure 1).

In frontier areas with limited exploration and in the case of regionally extensive seismic data, the seismic stratigraphic units can be isolated using picked horizons with reference to changes in the vertical velocity gradient, using the analysis of vertical semblance from the gathers. Such horizon-based V_{RMS}, created without additional data, can still be used to create the

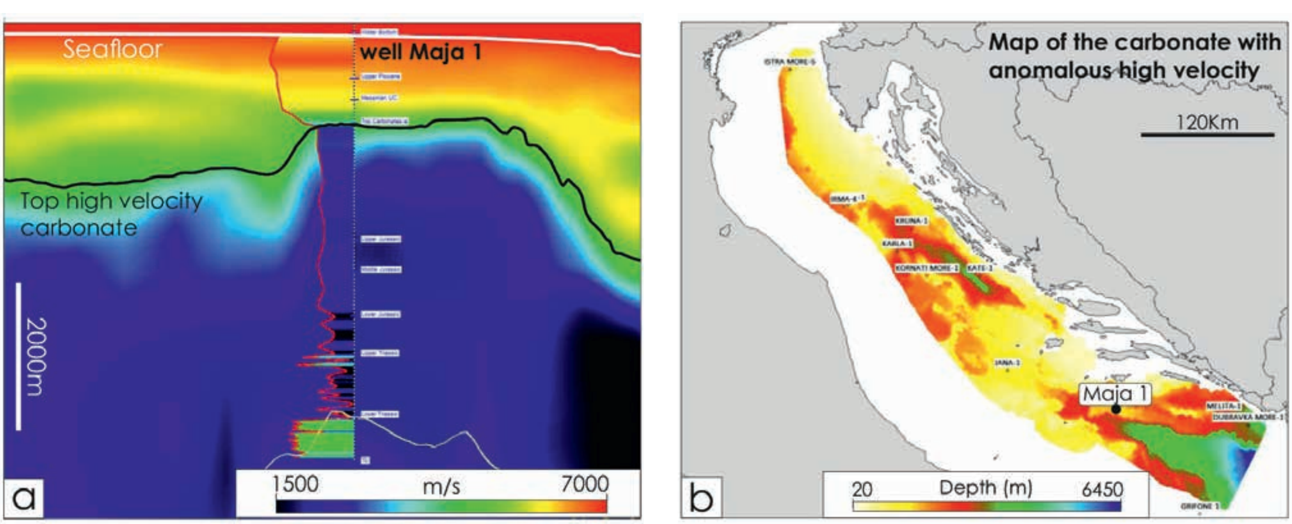

***Figure 5** Offshore Croatia, Adriatic Sea: a) Layer Depth VINT used for final PSDM showing geometrical consistency with horizon and good correlation of the velocity bulk between interval velocities from check-shot data (well Maja 1). b) Depth Map of the anomalous high velocity layer, which is related to a regionally distributed thick carbonate. The map includes the complete set of wells used to constrain the velocity field.*

layer-based model of V_{INT} for time migration (Figures 2a, 2b and 3b). These velocities will still be valid for the initial time to depth stretching, before running tomographic updates in the depth domain.

Quality control of the geologically constrained time interval field is achieved by converting back to V_{RMS}, re-extracting the horizon interval velocities, and then comparing both the horizon and vertical velocity trends against the gather flattening and the picked initial V_{RMS} field. The objective here is to ensure the velocities remain on trend for each horizon and maintain overall gather flatness. In more structurally complex areas, a greater number of horizons may be required to maintain control of the velocities across these structures, preserving structurally consistent velocity gradients (Figures 3a, 3b, 4a and 4b).

Benefits of the horizon-consistent velocity field

The workflow presented is created to integrate geological information into time and depth migrations, and it is thought to be flexible for the variety of data and geological settings. This has a number of benefits:

- The geometry and position of the events is refined in time as well as in depth. A noise reduction may be appreciated in respect to the initial unconstrained migration (Figures 6 and 7).
- The final migration velocity field is geometrically consistent with the trends of the amplitude events (Figures 3b and 4b). The inadequacy of the bulk in the velocity field may emerge after this correction, leading to additional geological and geophysical constraints being introduced (Figure 5a).
- The final velocity field used in the PSTM produces reliable depth conversion, mitigating the error of a current common practice, to obtain fast geological interpretation, and to compensate for the bathymetrical distortions in TWT.
- The final velocity field for PSTM is stable as an input to tomographic update iterations for PSDM, giving a more efficient workflow going from time to depth imaging.
- Horizons and geo-bodies can be extracted, even in case of sparse geological data not dense enough to be representative of the stratigraphy and structural setting. Well-logs and other the stratigraphic information can be compared with velocity boundaries obtained from the seismic stratigraphy and identified by gather vs. horizon semblance updates.

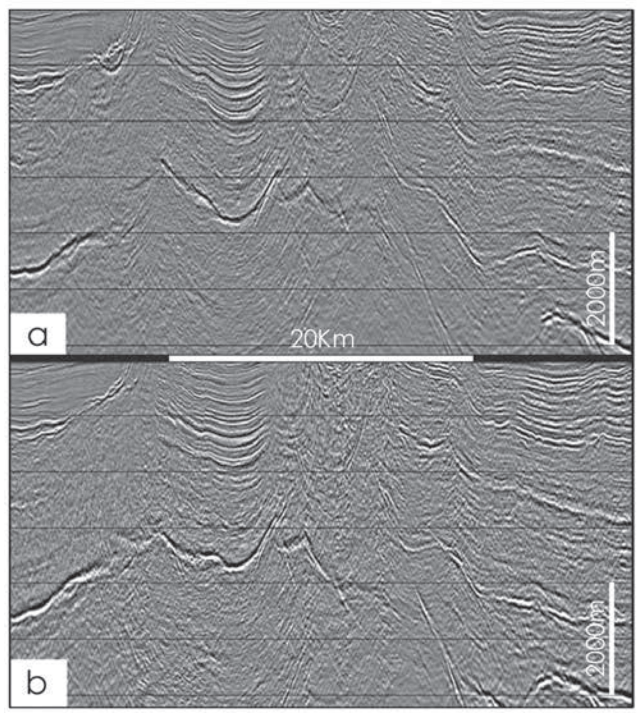

Figure 6 *Offshore Croatia: Depth sections show the unconstrained Kirchhoff PSDM a), and after using the geological constrained velocity field from the wells in Figure 5b, b).*

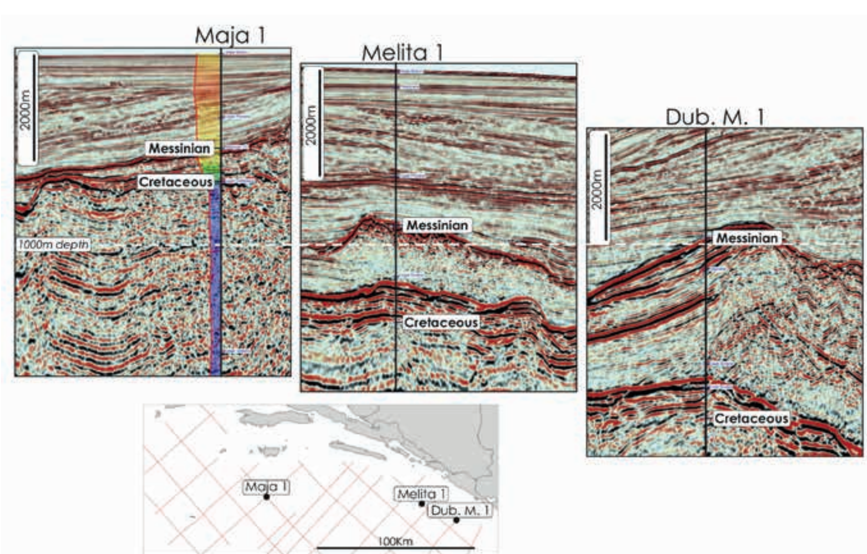

Figure 7 *Final PSDM, in depth, showing a good regional tie for the wells used in the velocity model (Figure 5a).*

- The geological constraints are inferred as mild boundaries, to honour the NMO condition (Figure 5a), reducing the risk to bias the model with horizons and geo-bodies that do not relate to relevant velocity contrasts.
- Vertical or horizontal smoothing is in principle not applied at any stage, but if required, small smoothing operators can mitigate for minor artefacts in the velocity field.

Conclusion

We have presented a workflow that integrates geological data and interpretation for both time and depth imaging, improving the signal-to-noise ratio and reducing the risks of undesired bias in the geometry of the horizons.

The workflow has been designed for 2D seismic, which is the most challenging when modelling the velocity field for PSTM and PSDM, and it is based on the correlation of the seismic semblance from single gathers to events identified in the stack section. The horizons can be constrained by wells, joint inversions with other potential fields, and even seismic inversion, opening the opportunity of integrating geological data and interpretation at the early stages of a time migration.

The horizon-based velocity analysis creates geometrically consistent velocity models tied in 3D, reducing the positioning uncertainty of steep horizons, and imaging the geological structures with greater accuracy and detail.

The model is tied in the time domain as an integral part of the velocity estimation process, reducing the work of editing at intersections, and avoiding mistie. 2D seismic data benefit from a velocity field analysed and modelled in a systematic manner along the entire grid, improving its consistency at a macro scale, and honouring regional variations in the geological setting.

Any stage of the workflow can be easily controlled, removing time-consuming iterations and the quality control of the picking in the V_{RMS} vertical functions. The adjustments needed to achieve a stable interval velocity field are no longer required, as well as the final mistie analysis, again challenging with 2D seismic. The building of a depth velocity field for PSDM links easily to the PSTM production, via depth stretching of the final tied PSTM velocity field.

The process for both PSTM and PSDM constitutes a regional constrained inversion, developed over extensive grids; as a consequence, the final V_{INT} model obtained during the PSTM stage, requires less iterations to derive the final PSDM velocity model. The process is efficient and the depth image reliable, making the 2D-PSDM an effective tool, even in underexplored areas with minimal geological data.

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