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Time processing and depth imaging of vintage seismic data: the northern Adriatic Sea case history

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ABSTRACT The exploration of biogenic gas in the Adriatic Sea is highly developed and the investigation of the residual potential and located complex areas, requires an improvement in the quality of available data. This paper illustrates a 2-year seismic re-processing program intended to assess the residual gas potential in this still productive hydrocarbon area by leveraging on integrated geological and geophysical workflows, modern processing techniques and High Parallel Computing capabilities. Legacy or vintage data sets can usually be re-examined using new processing technologies and the re-processing of available data is the only solution to re-evaluate the residual potential of developed-explored areas.

Key words: seismic processing, depth imaging.

1. Introduction

ADRIA 3D (Bertarini *et al*., 2019) is the available legacy seismic data set and covers an area of approximately 13,000 km^2; it consists of a merge of 13 different surveys acquired during the last 25 years extending from Caorle (Venice) to Ancona. Different acquisition configurations, minimum-phase wavelets, amplitudes in-homogeneities, time shift misalignments, acquisition footprints and a large quantity of multiple seismic events were the major issues of the vintage data. Thanks to enhanced denoise and innovative regularisation techniques applied in combination with advanced imaging capabilities, it was possible to deliver high quality time and depth data.

For the first time, in addition to the vintage time volume, a true amplitude Pre-Stack Depth Migration (PSDM) volume was produced on such an extensive quantity of data [Pre-Stack Time Migration (PSTM) and PSDM have already been performed on vintage data of ‘Sismica riconoscitiva’ and MS (Mediterranean Sea) data, see reference Diviacco *et al*. (2019)], leading to a better understanding of the real geometries of the main targets and their correct depth positioning. State-of-the-art tomographic technologies, together with a huge amount of pre-existing well information, were used to create a geologically consistent velocity model of the whole area down to a maximum depth of 12 km.

A fully integrated multi-disciplinary approach, with a strong integration between geologists and geophysicists, was also mandatory for the success of the project, exploiting the huge technical know-how built up by Eni during decades of exploration in this area.

2. Hydrocarbon occurrence

More than 250,000 km of 2D seismic lines, 35,000 km^2 of 3D seismic data and 7,000 wells have been acquired and drilled so far for the hydrocarbon (HC) exploration in the Italian area. Most of these data are located on the foreland and foredeep belts that represent the main HC provinces of the peninsula: Po Plain, southern Apennine, Sicily, and the Adriatic area.

HC occurrences in Italy have been grouped into three main categories:

1. oil and thermogenic gas associated with the Mesozoic carbonate formations;
2. thermogenic gas within the Oligo-Miocene portion of the Neogene siliciclastic foredeep wedges;
3. biogenic gas associated with the Plio-Pleistocene successions.

Based on these abundant data, it has been possible to perform a detailed reconstruction of the polyphase tectono-sedimentary evolution of the Adria plate foreland that provided a robust understanding of the petroleum system of this area.

The geological framework of the north Adriatic Sea is the result of the overlay of two distinct tectonic events: Mesozoic extensional phases and the Cenozoic compressional cycles (Fig. 1). The former is characterised by the prevalent deposition of carbonate units, while the latter by the deposition of prevalent terrigenous units (Fantoni and Franciosi, 2010 and reference therein). In this general geological framework, several effective petroleum systems are present. Some of them are of paramount economic importance, making Italy one of the most endowed HC provinces in southern Europe (Bertello *et al.*, 2010).

Oil discoveries have mainly been found in the western Po Plain, in the southern Apennines, and in Sicily; while gas accumulations are largely concentrated in the Apennine foredeep, in the Po Plain, northern/central Adriatic Sea and in the Sicily offshore. The northern sector of the Adriatic Sea is characterised by the massive presence of biogenic gas fields (Fig. 1), that appear

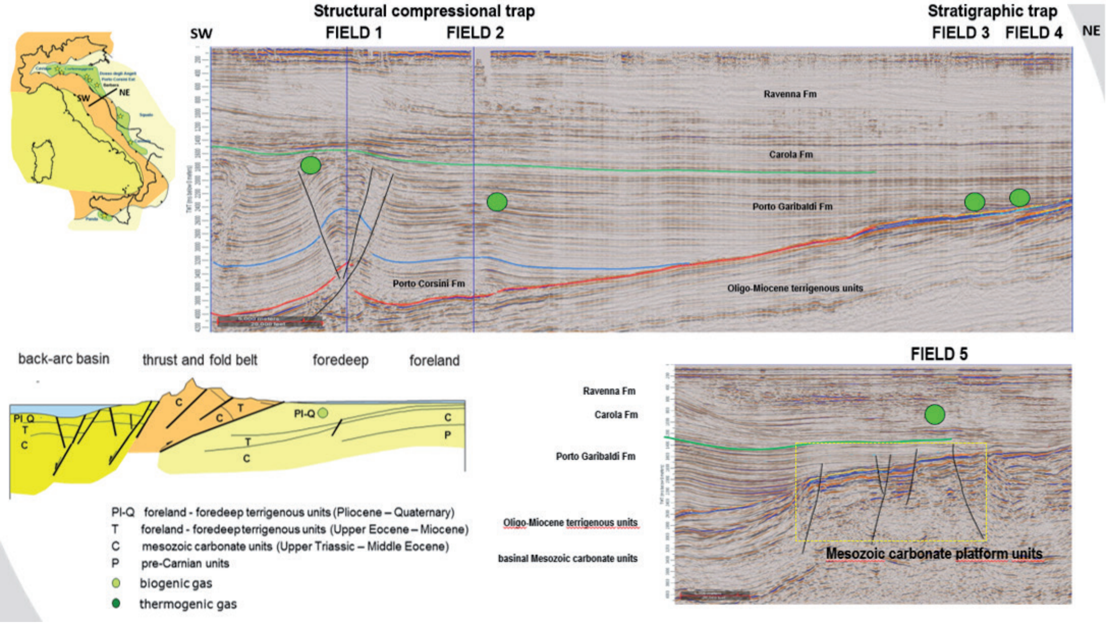


Fig. 1 - A SW to NE seismic section passing through the north Adriatic basin showing the different types of HC traps in the Plio-Pleistocene succession. Pure structural compressional traps in the foredeep area and both structural and stratigraphic traps in the foreland. Traps are highlighted in the section by the green marks.

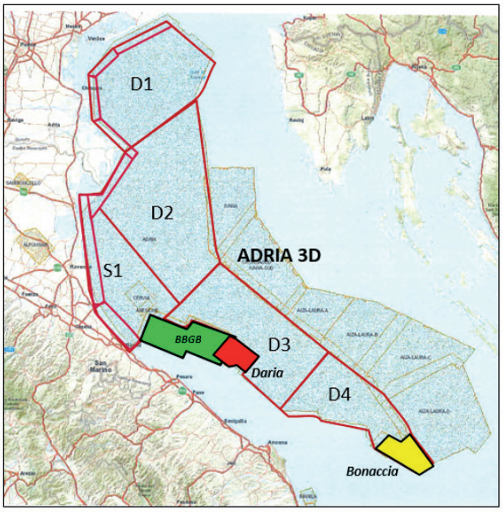
to be the only type of HC accumulation so far discovered in this area. The gas bearing levels are normally associated with Direct HC Indicators on seismic data: amplitude and phase anomalies, pull downs, polarity and frequency changes, absorption effects and, frequently, flat spots, which seismically represent the reflecting gas-water contact of an HC trap (Cazzini *et al*., 2015).

Starting from the internal part of the deformed foredeep of the Apennine compressional stages, these gas accumulations are mainly hosted by structural traps constituted of faulted anticlines verging NE-ward, as highlighted in the left part of the SW to NE seismic section in Fig. 1. Moving further east, within the external part of the foredeep, the gas accumulations are mainly retained in stratigraphic traps connected to the onlap of terrigenous succession over the foreland ramp monocline (Fig. 1), to end-up with the more extreme portion of the foreland area, where traps are related to gentle anticlines that have formed by differential compaction of the Plio-Pleistocene turbiditic deposits over pre-existing structural highs of the substratum inherited from Mesozoic tectonics or over Pliocene normal faults (Cazzini *et al*., 2015). Indeed, the largest producing fields are related to these inherited carbonate paleo-highs enhanced by Pliocene normal faults (FIELD 5 in Fig. 1). The main goal of this reprocessing project was indeed to improve the quality of seismic data in order to obtain a clearer image of these important structures for a better geological and resource economic evaluation.

3. Available data

The seismic investigation of the northern Adriatic Sea started in the early 1970s with the acquisition of the first 2D lines. This acquisition campaign, unofficially named Phase 1, continued throughout the 1970s and the 1980s with the acquisition of more than 600 2D lines for a total amount of almost 9,000 km.

In late 1980s, a new campaign started, named Phase 2, with the acquisition of a few small single 3D marine surveys focused on single plays detection. In particular, in this broad temporal window, the 3D surveys of Daria and Brenda-Basil-Giulia-Bettina (BBGB) were acquired (Fig. 2). Over the years the explorative interest was continuously growing and likewise the need to acquire further single surveys. Then, in 1990 Eni decided to commission the ADRIA 3D project to avoid expensive additional single acquisitions.



- **Phase 1** *(early 70's and 80's)*
  - *9000 km of 2D lines (not included in the map)*
- **Phase 2** *(late 80's)*
  - *3D Daria*
  - *3D Brenda-Basil-Giulia-Bettina*
  - *3D Bonaccia*
  - *3D Cervia*
- **Phase 3: 3D ADRIA** *(early 90's)*
  - *Full acquisition area of* ***13000*** *sqkm*
  - *13 different blocks (shallow/deep)*

Fig. 2 - Acquisition map of the north Adriatic Sea surveys, with a detailed image of the 3D ADRIA acquisition sub-surveys.

The whole survey covered an area of almost 13,000 km^2 from Caorle (near Venice) to Ancona and at that time it was the biggest 3D marine survey ever acquired in the world. Because of its massive extension and its water depths ranging from 4 to 85 m, the acquisition was divided into 10 different seismic survey blocks going from shallow to deeper water. Different acquisition vessels, configurations, and strategies were used to acquire the data, depending on the bathymetry of the operative zone. The acquisition campaign ended in late 1990s, when the 3D survey of Bonaccia was acquired as an SE extension of the ADRIA 3D survey (Fig. 2).

In this new re-processing project, the following surveys were processed at the same time (Fig. 2):

- 3D Adria - S1AS, S1AN, S1AC, S1, D1, D2, D3, D4;
- 3D Brenda-Basil-Giulia-Bettina (BBGB);
- 3D Daria;
- 3D Bonaccia.

Table 1 shows acquisition setups for every single survey involved in the project. All the deep-water surveys coded as D1, D2, D3, D4, and the Bonaccia 3D have the same 40°-acquisition azimuth with respect to the north, assuring a similar seismic illumination of the subsurface. Shallow water surveys S1AS, S1AN, S1AC, instead, display a mean azimuth value of 150° in order to suitably cover the shallow complex coastline area.

Table 1 - ADRIA 3D and single-3D surveys acquisition parameters.

Survey	Vessels	Azimuth	Bin size
3D BBGB	dual boat with 4 sources and 3 streamers	22.5°	6.66×30 m^2
3D Bonaccia	single boat with 2 sources and 6 streamer	40°	6.25×18.75 m^2
3D Daria	single boat with 2 sources and 1 streamer	40.47°	13.33×37.5 m^2
S1AS	dual boat with 4 sources and 1 streamers	147.73°	12.5×25 m^2
S1AN	dual boat with 4 sources and 1 streamers	173.70°	12.5×25 m^2
S1AC	dual boat with 4 sources and 1 streamers	173.57°	12.5×25 m^2
S1	dual boat with 4 sources and 2/3 streamers	49.49°	13.33×25 m^2
D2	dual boat with 4 sources and 4 streamers	40.51°	13.33×37.5 m^2
D3	dual boat with 4 sources and 4 streamers	40.51°	13.33×37.5 m^2
D4	dual boat with 4 sources and 4 streamers	40.51°	13.33×37.5 m^2

4. Time re-processing

Several processing and re-processing projects have already been completed during the past years in this area but each one on a single-survey based approach and, due to the limited computational resources in the late 1990s and early 2000s, combined with the extension of the area, it was not possible to carry-out a single processing project gathering all the involved surveys making up the ADRIA 3D. As a consequence, all single surveys underwent independent processing projects and were combined post-migration without a proper preliminary amplitude and phase matching step.

As mentioned before, the main reasons for the commissioning of the new processing project was to finally create a new time volume over the whole northern Adriatic Sea area in order to analyse seismic amplitudes for both qualitative and quantitative interpretations and to produce new re-processed pre-stack time data to be used as input for the PSDM algorithm. Vintage time volumes were processed and migrated using old fashioned migration algorithms that limited the accuracy and the precision of the imaging itself. Most of the overlapping area between the surveys were poorly migrated (because of low fold coverage) and merged together without a proper signal amplitude and phase matching.

The relative results were characterised by a drastic reduction of signal continuity and amplitude coherency passing from one survey to another. In addition, they were unable to properly take into account the geological complexity of the area which led to biased images of the targets. One of the key challenges in projects involving different surveys is minimising the impact due to the different intrinsic characteristics related to: amplitudes, phase and time alignment of the pre-stack data, improving at the same time the image quality. A new strategy was considered in order to minimise those differences based on a quantitative analysis of the seismic signal differences in the overlapping and merging areas between the different surveys. It was possible to estimate the parameters to improve seismic event time alignments and to optimise the application of amplitude and phase matching filters. The differences were severe only for some surveys, due mainly to the different acquisition configurations (e.g. between ADRIA 3D and the Brenda-Basil-Giulia and Bettina survey).

Bearing in mind that the objective of this mega merge re-processing project was to create a new PSTM and PSDM volume over the whole area of the ADRIA 3D, a homogeneous processing sequence was required to minimise the differences between all the involved surveys. Project workflow was divided into three main stages: pre-merge phase, characterised by denoise and de-multiples steps; the step in which all the surveys were matched and merged together and, to conclude, the post-merge sequence with both time and depth pre-stack migrations and post-processing (Fig. 3).

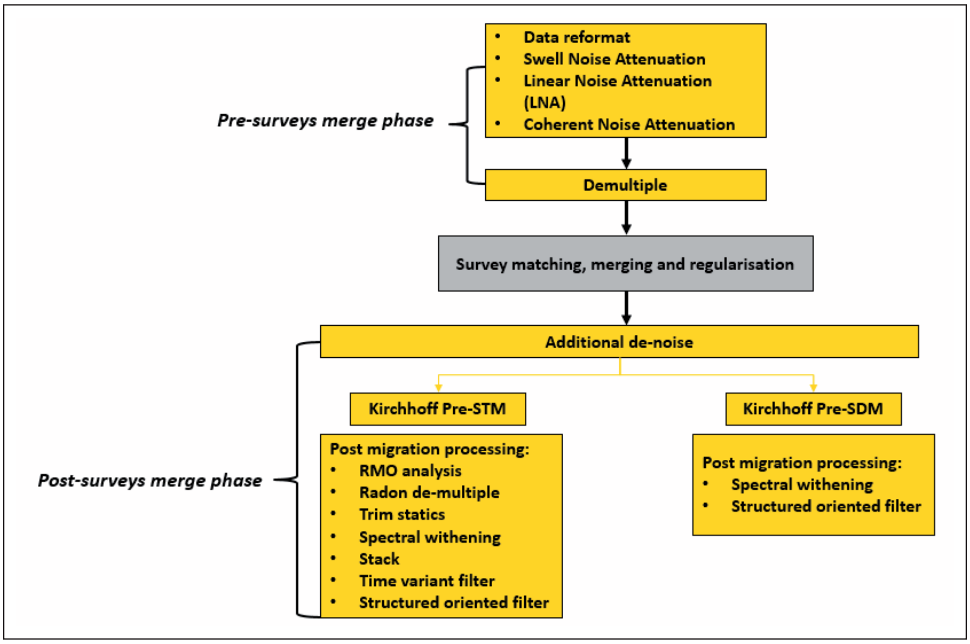


Fig. 3 - Diagram of the reprocessing workflow.

All survey blocks were processed independently up to the final binning stage, where the data were finally matched in amplitude and phase and merged together with 4D regularisation. The same denoise and de-multiples algorithms were used to process all the single survey blocks with optimised processing parameters for each one of them.

Noise was predominant at all levels (Stephen, 2000). Due to the relative 'shallow water' environment, different types of noise widely affected the seismic data: constant swell noise, mud-roll, seismic interference, rig noise, and linear noise. Different algorithms were used multiple times and in various domains to remove the noise on the pre-stack time data; FX denies (Schoneville *et al.*, 2008), Tau-P transform, FK filters were only a few of the tools applied during the denoise sequence (Fig. 4).

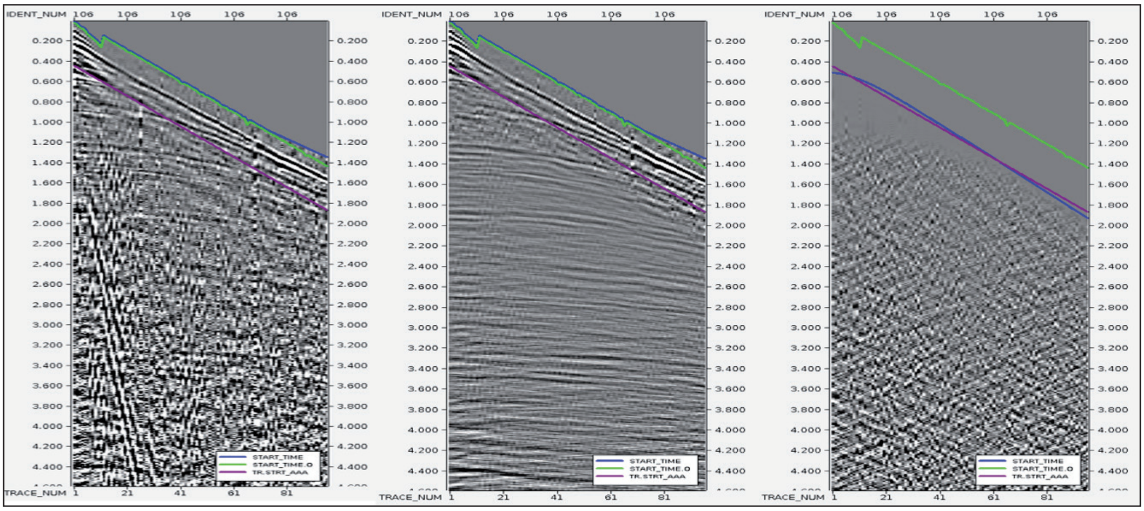


Fig. 4 - Denoise example on shallow data set. From left to right: input shot gather, after denoise and noise component removed from the data (difference gather).

Multiples attenuation was another important step for the pre-merge sequence. With a water bottom ranging between 5 and 80 m, the first multiple bounce come in at around 200 ms, meaning that all primaries could possibly be masked or distorted by the multiple energy. To effectively remove this noise, different algorithms have been tested and used: shallow water surface related multiple attenuation (SWME), conventional surface related multiple attenuation (SRME) (Verschuur *et al.*, 1992), and Tau-P gap deconvolution algorithms, each one selected in relation to the particular survey bathymetry. However, recognising the multiples from the primaries was not an easy task. The use of synthetic seismograms worked up from the huge available well logs database was required as quality control tool to check if some primary events have also been spoiled after the denoise and de-multiple steps.

Once noise (Fig. 5) and multiples reflections were removed from data, it was possible to proceed with the matching and the regularisation steps of all the single surveys. After numerous tests, in order to preserve as much as possible the amplitude variation of each single survey, it was decided to take the D3 survey block of the ADRIA 3D as the reference survey to match the other ones using only a single amplitude scalar value and a unique time shift correction for the rest of the other surveys.

Data coverage regularisation was computed in two steps to better balance the weights and fold of the different surveys involved in this reprocessing. During the first step, each survey was regularised individually on the final grid using a 4D Anti-Aliasing Fourier Interpolation flow, where all the offsets were regularised and interpolated using their neighbour offset planes (in a 4D way). After this first regularisation step, the single fold offset planes of all the surveys were matched in amplitude and time and merged together with a second regularisation using a 3D Anti-Aliasing Fourier Interpolation process and this choice led to a better spatial homogenisation of the surveys in the whole area. After a pre-migration additional denoise step to better remove the residual noise in common-offset domain, the processing workflow ended with the final PSTM and post-processing sequence (Fig. 6).

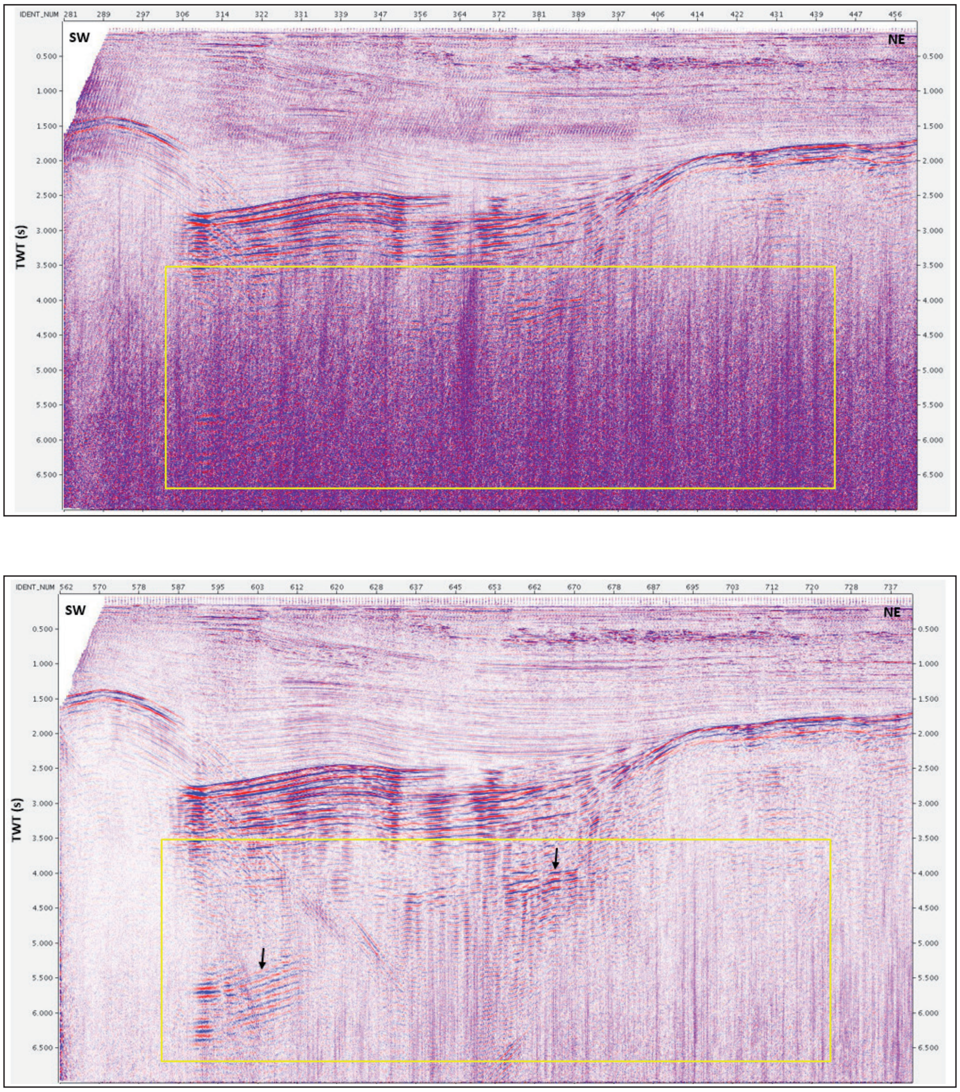


Fig. 5 - Denoise on pre-stack seismic data set: input common-offset section, before (top) and after (bottom) the denoise step. Strong noise affects the deeper part of the section from 3.5 to 6 s covering the main seismic reflections (yellow box). After denoise, seismic events are now clearly visible (black arrows in the bottom image).

However, the biggest improvement over the vintage data sets was achieved with the application of PSTM compared to the vintage Post-Stack Time Migration (PoSTM) volume. Indeed, the new volume is now full fold, with balanced amplitude and phase in the overlapping areas between the different surveys and devoid of any sharp edge effect, which could lead to a biased interpretation of the seismic signals. Passing from a survey block to another, imaging of the thrust anticlines is considerably improved resulting in a clearer image of thrust front-side (Fig. 6). These results were also achieved thanks to the post-processing steps on common-mid-point gathers as output of the PSTM migration. The sequence involved a first step of residual move-out analysis to optimise the traces stacking along the offset axis in the gathers, followed by a Radon step for residual multiples removal, spectral whitening and structured oriented filter to boost the high frequencies content and increasing the signal-to-noise (S/N) ratio enhancing the good quality of the final PSTM volume.

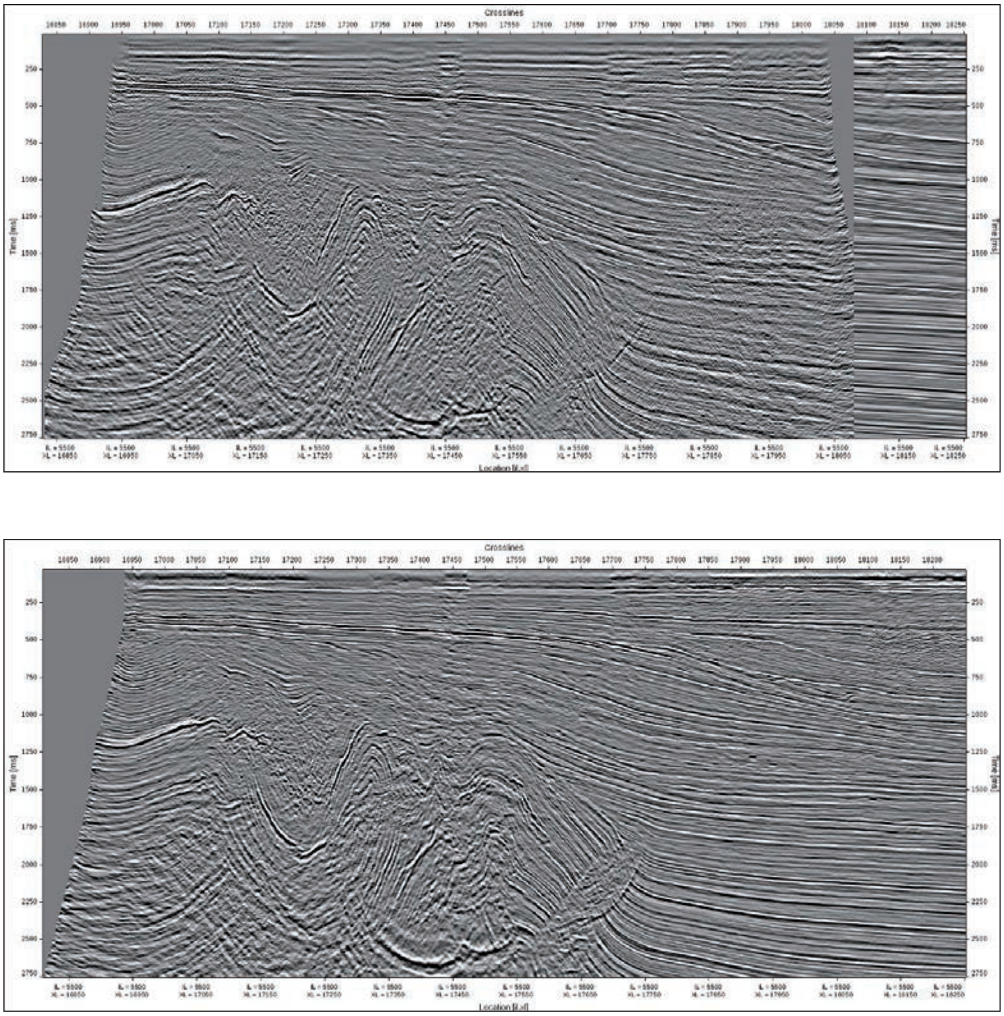


Fig. 6 - Vintage PoSTM volume (top) compared with the final PSTM volume (bottom). Thrust front image is now more focused on the new PSTM volume.

5. Depth imaging

Over the past two decades, the 3D PSDM has changed industry's perspective on how to approach the migration of seismic data in areas of complex geology. The technique has allowed building an accurate interval velocity model to economically perform 3D depth imaging in order to full exploit the HC potential in these difficult areas. Leveraging on modern high parallel computing capabilities, a first PSDM volume has been produced in this project using an accurate well-constrained velocity model to better characterise the geometries and the correct depth positioning of new and still producing fields.

The success of the depth imaging depends on building an accurate velocity model. If the correct velocities are used, primary events on common-reflection-point (CRP) gathers are imaged at the same depth at different offsets, aligning horizontally and stacking coherently (Stork, 1992; Kosloff *et al.*, 1997). Therefore, target reflectors become well-imaged and properly positioned. In addition, a correct true depth is achieved (Fig. 7).

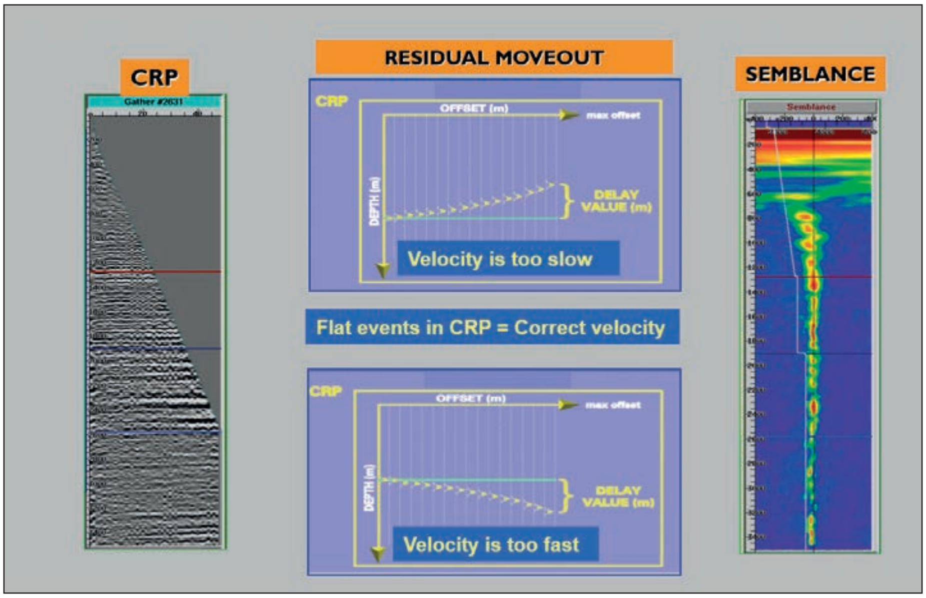


Fig. 7 - If the migration velocity is too slow, the curvature of the seismic event or the residual move-out (RMO) in the offset-depth domain shows an up-going curvature. On the contrary, if the velocity is too fast the curvature is downwards (centre). When the data are migrated with the correct velocities the curvature is zero and the reflection is completely flat in the CRP gather (left). Furthermore, the semblance signal is aligned at the zero value of the semblance panel, indicating that the RMO is null.

PSDM velocity model building is a non unique approach and, as a consequence, careful quality control (QC) and information about wells must be taken into consideration at all times during the process. Kirchhoff PSDM and a well-oriented velocity model building solutions were adopted in this project to depth migrate the new re-processed seismic data set. This strategy was adopted for two main criteria:

- complex geology of the Adriatic foredeep, characterised by the highly distorted thrusts belt;
- presence of rapid lateral velocity variations related to the thrusts and very localised gas accumulations.

To preserve the important HC indicators for delineation of new potential discoveries, and for an effective PSDM processing, good quality pre-processed data are required. Tomography is based on picking the residual move-out information of events in the CRP gathers associated with primary reflections only. If some reflections of multiples are still present when data are depth migrated with velocities very different from the layers in which the multiple has been generated, they will have a strong residual move-out (RMO), which will superimpose on the primary events, biasing the final tomographic result towards velocities that are not representative of the real geology. In addition, a still low S/N ratio badly affects the quality of the semblance signal on which the RMO extraction process is based. It is of particular importance that a robust noise attenuating and amplitude preserving processing workflow is implemented in order to improve the velocity analysis reliability and avoid inserting multiples move-out information in the velocity analysis process. Once the pre-processing was satisfactorily completed, attention turned towards defining an accurate velocity model for the PSDM solution. An iterative top-down workflow was adopted to progressively fix the upper layer velocities and horizon positions before moving on to define the next series of deeper formations. The workflow started with the inclusion of the vintage PSTM velocity volume to build the initial velocity model for PSDM.

Model refinement methods based on tomography make use of the residual move-out of events in the CRP gathers produced by PSDM (Docherty *et al.*, 2000). The general rule is: if the event appears as a frown in depth gathers, the overlying velocities in the existing model are too fast; if an event appears as a smile, the velocities are too slow. If the correct velocity is used, primary events on depth migrated gathers align horizontally along the offsets axis and stack coherently, with the result that target reflectors are well-imaged and in the proper depth position. On the contrary, if they show a residual curvature, the velocity model needs to be still updated moving progressively downwards. The applied workflow assumed that the initial velocity model was updated using the Kirchhoff PSDM grid tomography algorithm, which has emerged as one of the most favoured and robust methods for velocity refinement. It is based on image gathers and semblance analysis and seeks a global solution for minimising residual move-out in a least-squares sense. However, tomographic inversion is not a perfect solution. An inversion may often be ill-conditioned, meaning that the data are not dense enough in all orientations to resolve velocities with sufficient certainty. Furthermore, limitations related to uniqueness, convergence, and stability of the solution are always something we need to keep in mind when using the technique. The incorporation of a structural framework as the main geological horizon in the velocity model building process, confers an important advantage because it enables the incorporation of geological constraints to the solution. In this project, a series of key horizons were selected to define boundaries between tomographic iterations in the shallower terrigenous succession (Fig. 8):

- sea bed extracted from UKOOA data;
- top Pliocene, specifically the Top PL3-A;
- Messinian Unconformity, which represents the event separating the terrigenous from the evaporitic domain.

After several iterations targeting from the sea bed to the Messinian unconformity, a criticality was identified that could have potentially affected the stability of the imaging results: because of the old-fashioned acquisition layout, the maximum offset available to assist the velocity estimation process was of 3600 m only, limiting the accuracy of the tomography only in the shallower section of the subsurface. The net effect is that residual curvature estimates from image gathers were

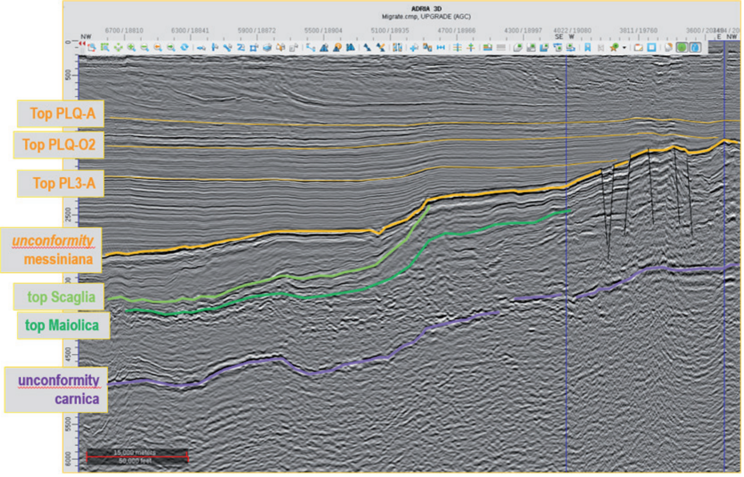


Fig. 8 - Available regional horizons used for the PSDM processing to constrain the tomography.

relatively insensitive to velocity change at depths greater than the maximum available offset. In the light of this issue, an alternative strategy was used to build the velocity model in the deeper evaporitic domain below the Messinian unconformity. Calibrated sonic-logs velocity profiles from a sub-set of wells were used and propagated in order to build the velocity model in this deeper section down to a maximum depth of 12 km. This approach was very useful to avoid the short-offset limitation of tomography, providing a reliable well-driven interval velocity model.

Because of the above mentioned factors affecting the non-uniqueness of the tomographic solution, a strong integration with all available well-information in the estimation of the depth imaging velocity field was mandatory. In particular, well top markers were a valuable constraint for the final updated model. Indeed, at the final stage of the tomographic velocity model building process, a statistical analysis of the mis-ties between the seismic imaged depths and the well-tops of the main regional horizons was done in order to scale the seismic velocity model and adjust the final depth image (MacKay *et al.*, 2006). In a very well explored area like the north Adriatic Sea, a significant and homogenous distribution of more than 90 wells out of the 300 with velocity measurement has been selected for this purpose.

Fig. 9a represents the cluster of 28 wells that have been used to calibrate the Pleistocene unconformity regional horizon (Top PL3-A in Fig. 8) in one of the project sub-areas. The majority of the well is located along the trend of the over-thrust belt in order to better constrain the velocity model in this complex geological area. Fig. 9c shows the histogram distributions of mis-ties or depth errors between the depth-image and well top-markers for the Pleistocene unconformity, before and after the calibration process. It is easy to note that mis-tie passed from a mean value of -23 m (depth image shallower on average than well top-markers) to a mean value of -0.23 m, which represents a reduction of the mean errors in depth at well locations of almost 99%. Fig. 9b represents the velocity scaling factors map used to calibrate the velocity model and correct the depth positioning of the Pleistocene unconformity. It may clearly be seen that the values were consistent with the main geological domains, meaning that the previous tomographic iterations were stable and did not introduce unintended velocity anomalies. Indeed, velocity needed to be decreased by about -3% (blue colour represents negative scaling values) in the entire foreland and increased (red colour represents positive ones) in the foredeep region where the thrust structures are located (Fig. 9b).

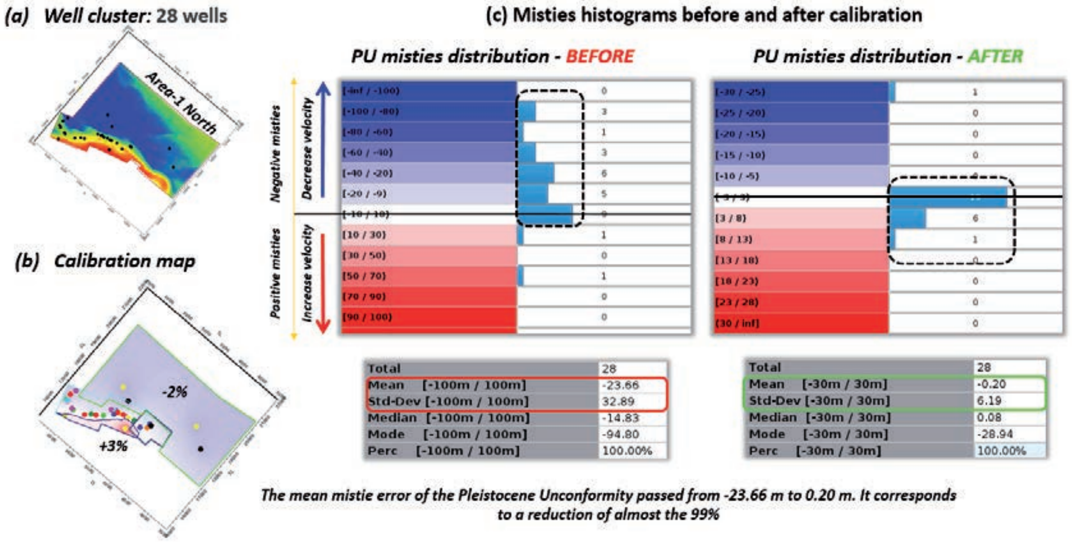


Fig. 9 - Calibration results of the Pleistocene unconformity: a) the well cluster used for the calibration process; b) velocity scaling factors map and c) the mis-ties histogram distributions before and after the calibration step.

With this winning strategy in place, the final velocity model obtained by tomographic updates and well calibration was used to produce the final PSDM volume. The migration full-fold area was massive, with ten surveys involved, covering an area of approximately 13,000 km^2 until a maximum depth of 12 km.

Fig.10 shows the vintage PSTM volume, in which it is possible to note pull-down effects on the seismic signals due to the presence of localised gas clouds, and on the right, the same section but relative to the new PSDM volume with superimposed the new PSDM velocity model. The pull-down effects have been fully-resolved in this case, through some updates of high-resolution non-hyperbolic tomographic inversions and it can be seen how the tomography was successful in identifying and inserting the low velocity anomalies within the model due to the abundant gas presence. Furthermore, proper layer geometries were restored for a better characterisation of the gas mineralisation.

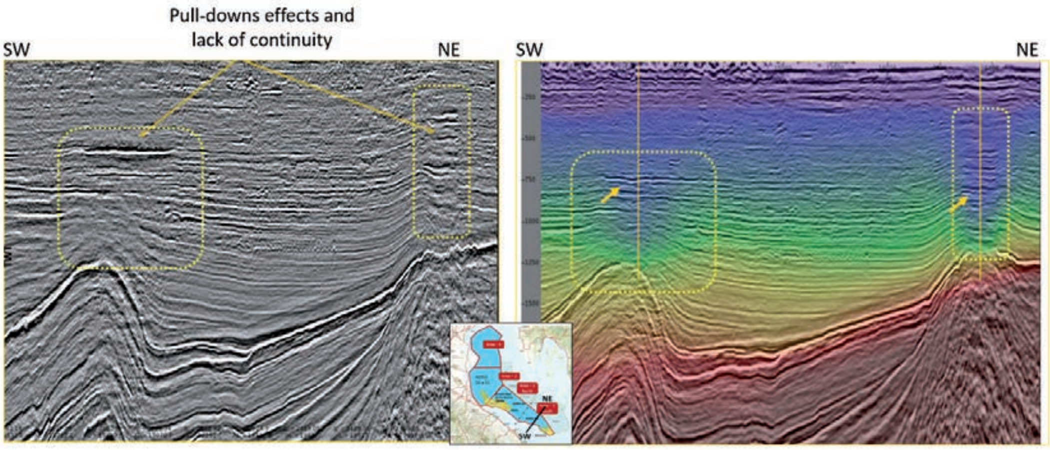


Fig. 10 - Gas cloud effect: vintage PoSTM volume (left) compared with the new PSDM volume (right).

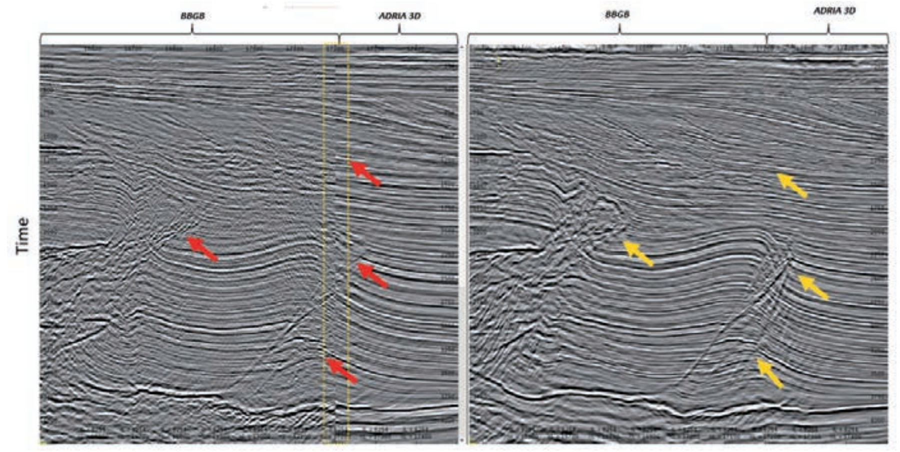


Fig. 11 - Final depth imaging results: on the left vintage PoSTM volume section and on the right the new PSDM converted in time for comparison. Yellow marks represent the area in which the imaging is considerably improved with respect to the vintage data. It is easy to note how the sharp contrast when passing from one survey to another has been resolved (yellow dotted lines).

The final PSDM showed a significant improvement over vintage volumes in terms of focusing of the structures, continuity and S/N ratio, especially in the areas with complex geology and where the acquisition surveys overlapped (Fig. 11). Despite the immense size of the processing area, the use of effective proprietary algorithms, working on high-performance computers allowed us to complete the PSDM study in a very competitive time frame with very good imaging results.

6. Integrated studies - Paleoscan interpretation and analysis

As part of the multi-disciplinary integrated workflow, several geological and geophysical studies have been carried out during and after PSTM and PSDM volumes reprocessing. New horizons interpreted on the new data were used to extract seismic attributes on the new PSDM volume, to recognise areas in which the amplitude absorption on the seismic data points out the presence of gas within sandy layers. Spectral decomposition with RGB blending technique was used to detect stratigraphic features and bright anomalies, defining their real extensions (Chopra and Marfurt, 2016). An AVO (amplitude versus offset) sensitivity study was performed using new depth seismic data, to assess the amplitude vs. offset response on key conventional and unconventional layers, helping to further de-risk future exploration activities. From 2014, Eni has decided to adopt Paleoscan (Ellis) as a complementary tool for advanced fast seismic interpretation. The software can process huge seismic data sets in a relatively short time to produce a 3D high-resolution geological model (Geomodel) even with low S/N ratio (Figs. 12a and 12b). From this geo-model, it is then possible to extract a large number of horizons from the different seismic facies to be used for further analysis of the geological and geophysical studies' workflow.

Using the semi auto-tracking system, several horizons in the target terrigenous sequence from the sea-bottom to the Messinian unconformity were identified, in order to guide the final geo-model creation. Thanks also to the improved S/N ratio of the seismic data in this area, only minor interpretation adjustments and iterations were necessary to finalise the model and extract

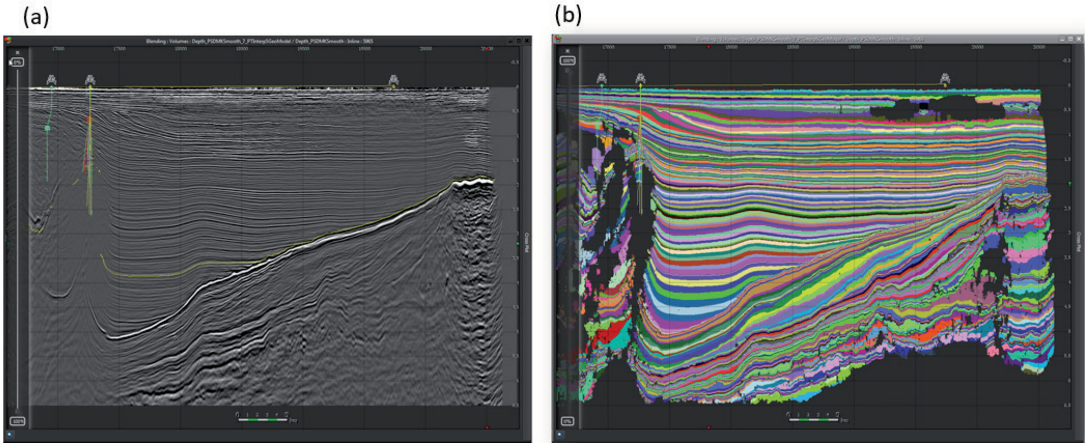


Fig. 12 - On the left, the ADRIA 3D PSDM volume, and on the right, the final Paleoscan 3D geomodel: a) seismic section from the PSDM ADRIA 3D seismic volume; b) the result of the final Paleoscan geomodel. It is possible to appreciate the result of the interpretation looking at the 'colour' boundaries, which represent the thickness of each sequence. In this line, the clinoform sequence towards the top of the section and all the seismic events pinching against the Messinian unconformity, are particularly evident.

seismic consistent surfaces. The tool allowed calculating a large number of stratigraphic and structural seismic attributes, extracted on every detected surface and simultaneously analysed while scrolling through the volume within the depth interval of interest (Fig. 13). The Spectral Decomposition analysis was performed using an Eni proprietary algorithm (High Definition Spectral Decomposition), producing a set of discrete frequency volumes that were visualised and evaluated using RGB blending techniques on a selection of signal consistent surfaces. The analysis was performed using a set of standard attributes (such as Envelope, Sweetness, Spectral Decomposition with RGB blending technique) that allowed us to detect stratigraphic features and bright anomalies associated with sand bodies, helping the geologists during the interpretation process. For example, the Envelope attribute highlighted strong and bright anomalies, while spectral decomposition allowed a better recognition of the real extension of the amplitude anomalies. Well data (logs, markers) were integrated too, to produce several high-resolution amplitude and attribute maps capable of identifying bright spots, pinch outs and structural closures of the most important hydrocarbon prospects (Figs. 13).

7. Integrated studies – Thin reservoir and AVO studies

An AVO sensitivity study (Ball *et al.*, 2016) was performed on a few key conventional and unconventional (thin layers) targets within the Pliocene sequence. Firstly, a complete rock physics analysis was carried out on wells where all the elastic and petrophysical curves were available: compressional velocity (*Vp*), shear velocity (*Vs*), density (ρ), clay volume (*Vcl*), porosity (*Phi*) and water saturation (*Sw*). The main objective of this step was to assess the theoretical AVO behaviour from the well reflectivity on the selected targets and to relate it to variations in petrophysical properties. Based on these results, the modelled AVO signature and the pre-stack seismic AVO response were compared. The pre-stack gathers AVO responses matched the theoretical AVO response from well reflectivity (half-space modelling) at all analysed wells locations. Intercept (I) and Gradient (G) cross-plots calculated by fitting the

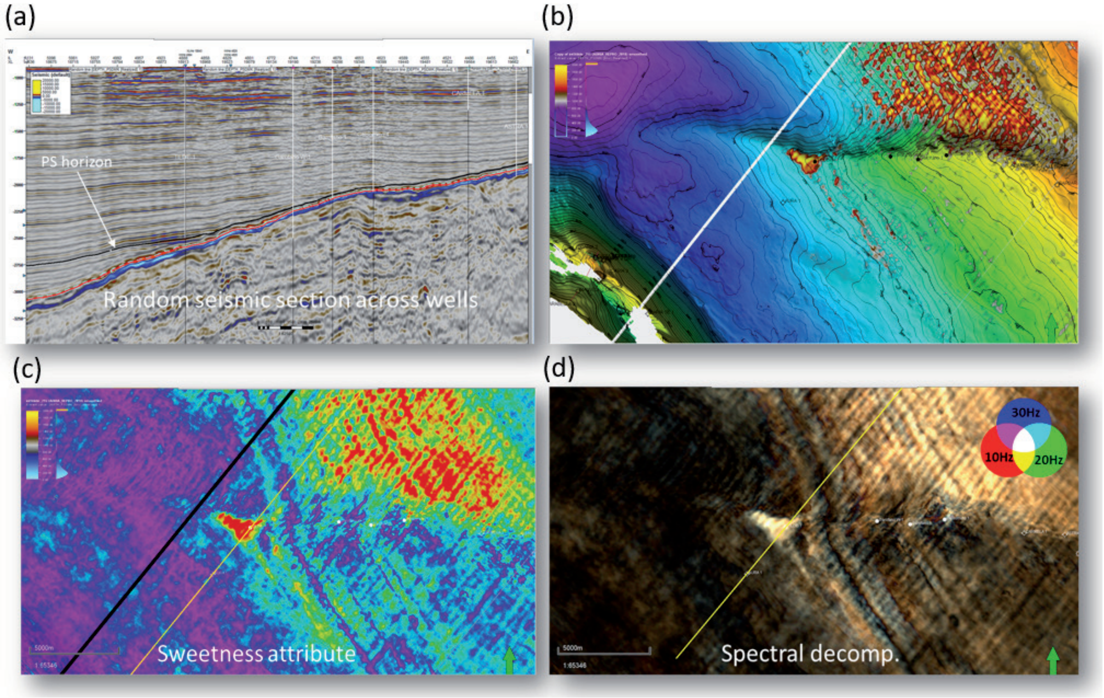


Fig. 13 - Example of analysis using different seismic attributes and Paleoscan horizons (prospect Tilde): a) a random seismic section, connecting wells (Tilde-1, Garofano W. 1, Garofano-1, Gelsomino-1, Astra-1), with a tracked horizon extracted from the Paleoscan geomodel; b) the same horizon in depth domain, with contour lines, co-visualised with the highest values of the Envelope seismic attribute anomalies (low values are made transparent); c) amplitude extraction (extract value at sample location without windowing) on the horizon map of the Sweetness attribute (high values are in red); d) example of Spectral Decomposition result blended in RGB mode (10, 20, 30 Hz) and extracted on top of the horizon.

pseudo-CDPs (common-depth-point gathers are the equivalent of CRP gathers) with the 2 terms Aki-Richards equation, were extracted over time windows centred on target horizons, to define AVO background trend lines and the Scaled Poisons' Ratio Change attribute (SPRC = a*I + b*G). Both I/G cross plots and SPRC values defined anomalous AVO zones and the presence of HC saturated lithology. The integrated approach of rock physics analysis on key wells and pre-stack seismic study suggested that HC saturated conventional targets show good Class 3 or Class 4 signature AVO anomalies, while thin HC beds do not show significant AVO anomalies, falling into the seismic background trend (Fig. 14). Decimetric mineralised thin layers are critical to discriminate both at log and seismic scale. Therefore, they are also not responsive to AVO with the state of the art data and knowledge, given the poor visibility embedded in a low porosity and high water saturation background.

8. Conclusions

The main goal of this huge re-processing project was the production of a single, homogeneous and amplitude-balanced PSTM and PSDM volume, covering most of the north Adriatic Sea, merging 13 different single block surveys.

To achieve this result, many geophysical challenges had to be faced and solved. The most

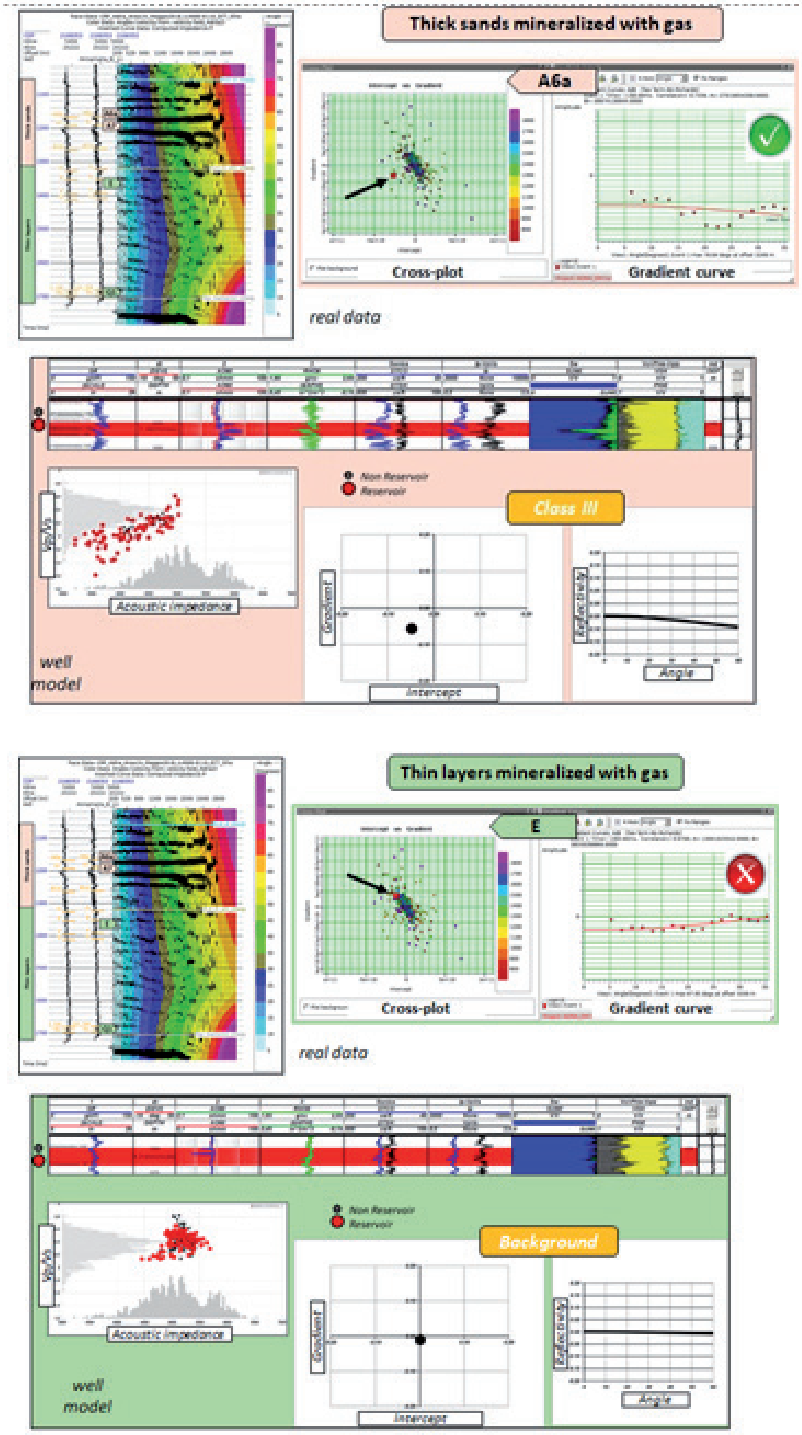


Fig. 14 - Integrated AVO sensitivity studies on thin layers: the upper panel shows the pre-stack data at well location and the cross-plot and gradient analysis of the target event; the bottom panel shows the main logs tracks, a *Vp*-*Vs* vs. acoustic impedance cross-plot and the AVO half space model for the target event. Thick sands mineralised with gas (a) show Class 4 (or Class 3) anomalies; thin sands mineralised with gas (b) show no AVO anomaly and almost flat signatures. Gradient analysis on the pre-stack seismic data matches the expected response from AVO well reflectivity models.

difficult was the multiple attenuation while preserving the primary reflections and the frequency content. Because of the very shallow water depth, several methods had to be implemented to successfully remove the different periods of multiples.

Other important challenges were: the denoising, which required multiple passes of noise attenuation in different domains to tackle the persistent burst of unwanted energy; the matching of the volumes before the regularisation that allowed the homogenisation of all the surveys.

An amplitude and frequency balanced seamless volume was produced on over 11,000 km^2, giving a significant improvement over the existing vintage data sets.

For the first time, a True Amplitude PSDM well calibrated volume was produced over this area, leading to a better understanding of the real geometries of the targets and their correct depth positioning. This PSDM processing sequence was designed to obtain the best depth imaging of the subsurface, in terms of focusing and geological reliability. State-of-the-art tomographic technologies, together with a huge amount of well information, were used to create a geologically consistent velocity model of the whole area down to a maximum depth of 12 km.

The seismic volume obtained by the PSDM shows great improvements in the target area compared to the existing vintage PSTM in terms of focusing, continuity and S/N ratio.

Moreover, the final velocity model was calibrated with the main targets and consistent with the well data. The horizon matching with the related well markers is satisfactory and the mis-ties were reduced to a few metres.

ADRIA 3D seismic survey has been acquired with a dated technology, which nowadays would be designed with a larger spread, longer cables and higher fold. Therefore, the possibility of further improving the overall quality of the imaging using the current data is limited and an analysis of cost /benefit ratio should be carried out before undertaking new activities on the data set. If the acquisition of new seismic data is believed to be the best solution to improve the quality of the data, the difficulties and costs of acquiring new seismic data in the Adriatic Sea are well known.

The strong integration between different departments of geology, geophysics, and exploration was crucial under many aspects: to validate the accuracy of the time processing, to solve the complexity of the geology and to build a reliable velocity model. The considerable technical expertise and knowledge of the area coming from decades of activities was a key factor in the success of this project.

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