Improved subsalt imaging in the Eastern Mediterranean Sea with converted wave attenuation

Monica Hartmann, Jana Caskey, Benjamin Cole, James McLeman, Tom Rayment, DUG Technology; Ares Ouzounis, ExxonMobil Technology & Engineering Company*

Summary

Subsalt imaging of the Eastern Mediterranean Sea is challenging due to poor illumination caused by the complex overburden of the Messinian evaporites and their interaction with Miocene mobile shales. Subsalt stratigraphic interpretation is hindered by the presence of high amplitude converted wave arrivals, generated by the large impedance contrast between the sediments and the salt, obscuring true subsalt geology in the final P-wave image. In this paper, a converted wave attenuation workflow is designed to address this noise. A dual-leg 3D visco-acoustic forward modeling approach with separate background and scattering velocities together with a base-of-salt reflectivity is used to generate kinematically accurate data domain noise models of the PSPP and PPSP arrivals. These are subsequently adaptively matched to input shots and subtracted. This workflow is demonstrated on a one-sided wide-azimuth dataset acquired in a deep-water salt environment from the Eastern Mediterranean Sea.

Introduction

In marine seismic surveys, a pressure (P-wave) source is traditionally deployed to transmit energy through the water column and into the Earth, with receivers (hydrophones) placed in the water to detect P-wave energy returning from the subsurface. However, mode conversion can occur in the subsurface at non-zero incidence angles due to changes in lithology. This phenomenon is described by the Zoeppritz (1919) equations.

Mode conversion occurs when a wave impinges on a boundary where at least one of the media is elastic. Mode conversion is much stronger where large contrasts in elastic parameters exist. If a wave travels as a P-wave and is mode converted on reflection to an S-wave, necessarily converting back to a P-wave at the seabed, then it is known as a PPSP arrival. Since conversion can take place by reflection and refraction, different combinations exist, such as PSPP, and PSSP, all of which can be detected with a hydrophone. The three modes identified are shown in Figure 1. Such converted wave arrivals are strong where there are large impedance contrasts, such as between sediments and salt, and at mid-to-high incidence angles. These arrivals can be used to aid the interpretation of the base of salt (Jonas and Davison, 2014). However, such arrivals appear strongly as noise on a migrated P-wave seismic section and can impact the usability of the final image (Ogilvie and Purnell, 1996). They can impede the interpretation of the subsalt hydrocarbon systems and therefore require attenuation.

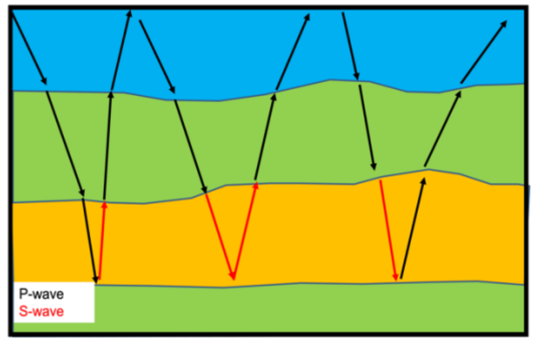

Figure 1: Example of mode converted ray paths.

However, attenuation of such noise is generally non-trivial. For some geologic settings the geometry of salts is such that converted waves are easily identified. However, in environments where tabular salt overlays flat sediments, these events are difficult to discriminate on post-migration stacks. Existing approaches to attenuate such noise based on move-out curvature discrimination (Ogilvie and Purnell, 1996), or careful pre-migrated data muting using travel times derived from raytracing (Lu et al., 2003), can be less robust in the presence of such complex salt bodies. Other methods involve picking a base of salt horizon and converting it to its PPPP, PSPP/PPSP, and PSSP equivalents in the time domain which are used together with move-out modelling to isolate the converted wave events from the P-wave events before migration. These noise models are then P-migrated and adaptively subtracted in the image domain (Hegazy et al., 2018). Dual-leg 3D acoustic wave-equation modelling can be used to predict the converted wave noise kinematics in complex geological settings by using different velocities for the upgoing and downgoing energy (Huang et al., 2013; Kumar et al., 2018). These data domain noise models are used to attenuate the converted wave noise before migration or can be PPPP-migrated and adaptively subtracted in the image domain.

In this paper we demonstrate a method to produce data domain models of the converted wave noise using the 3D Born dual-leg visco-acoustic two-way wave equation but with an image domain reflectivity model derived from the base salt interpretation. These noise models are then adaptively subtracted from the data before migration. The efficacy of this approach is shown on a real dataset from the Eastern Mediterranean Sea.

Converted Wave Attenuation

Method

In 2022, a one-sided wide-azimuth (WAZ) dataset was acquired with two source vessels with crossline offset of 1400m in the Eastern Mediterranean Sea. Each vessel was equipped with two enhanced low frequency sources. The recording vessel carried a 14 x 100 m x 8050 m cable spread. The survey design led to high signal-to-noise and enhanced low frequencies compared to acquisition with conventional sources, and increased azimuth over narrow azimuth (NAZ) surveys previously acquired in the area; all of which improved illumination of subsalt plays (Ou et al. 2023). In spite of acquisition design efforts to improve illumination, high amplitude converted wave energy generated at the salt boundaries obscured portions of the subsalt stratigraphy. The evaporitic sequence in this region formed during the Messinian Salinity Crisis (5-6 Ma) and is up to 3 km thick. The salt geometry can vary from simple, consisting of two horizons, to highly deformed sequences of overhangs accompanied by intra-salt reflectivity (El-Bassiony et al., 2018).

A large amount of energy at intermediate incident angles transmits through the top of salt as S-waves; beyond the P-wave critical angle most energy is transmitted to S-waves. At the base of salt both P and S-waves are reflected toward the surface. This generates the three possible modes PSPP, PPSP and PSSP. To attenuate these converted wave modes, a kinematically accurate data domain model of them is derived. This involves first obtaining the geometry of the surface responsible for their conversion and/or reflection and creating a reflectivity model specific to this surface. This reflectivity is then given to a 3D dual-leg visco-acoustic Born two-way forward modelling finite-difference scheme.

The traditional implementations of such modelling schemes result in background and scattered propagating energy travelling at a speed dictated by a common velocity model. However, the use of a common velocity model is not a strict requirement. The kinematics of the different converted wave modes resulting from a known reflector can be modeled by supplying different velocities for the background and scattered energy (representing the P- and S-velocities). S-velocities were obtained through the scaling of the salt portion of the P-velocity based on the Vp/Vs ratio of a nearby well. Three forward modeling simulations can therefore be run to obtain the PSPP, PPSP, and PSSP (and subsequent higher-order scattering of these arrivals) noise models. However, only the PSPP and PPSP models were generated as the PSSP energy was much lower amplitude than the primaries and the other converted wave modes. The PSSP energy was not apparent in the stack sections and exhibited higher curvature than primaries allowing it to be safely addressed with a pre-migration hi-resolution parabolic radon technique.

The acoustic nature of the modeling engine means that the noise model of the converted wave reflection energy will be kinematically correct but will exhibit a different amplitude variation with angle (AVA) compared to the recorded data. An elastic propagator, however, would have produced the correct kinematics and dynamics but with significantly increased computational expense. To compensate for this, an adaptive subtraction of the converted wave noise model is required which can be performed either in the data domain or the image domain. In this workflow, a pre-migration least-squares *t-x* global matching was applied in the common channel domain separately to the PPSP and PSPP models which were then bottom muted based on onset arrival times. This was followed by adaptive local matching operating simultaneously on both noise models in the shot domain with an additional joint match in the common midpoint (CMP) domain with normal moveout applied to flatten and help preserve primary reflections. The matched models were then subtracted to attenuate the PSPP and PPSP converted energy from the final deghosted and demultipled shot records prior to the final reverse-time migration (RTM).

Due to the uncertainties in the salt interpretation and initial velocity models, careful parameterization of the adaptive subtraction was required. Converted waves were often difficult to identify before migration due to structural complexity, however, removal before migration was necessary to produce shot records free of the converted energy for future processing. Although the final interpretation volume would be produced via high-frequency RTM, a small volume of data in an area with clear converted wave interference was migrated to help evaluate the subtraction parameters.

Results

Figure 2 shows the results of the modeling and subtraction before migration in two different geologic settings. The first example is from an area with a post-salt package of approximately 1 km and salt of 2 km thickness, where a) is the input shot gathers, b) is the output shot gathers after converted wave attenuation, and c) is the PSPP and PPSP noise models summed. In these areas of thicker, deeper salt the converted waves are obvious in the shot domain. The second example is from an area where the salt is less than 100m from the water bottom and only 300m thick, where d) is the input, e) is the output, and f) is the summed noise models. Little discrimination from primary events is observed in this area and so without the noise models the converted energy is difficult to identify.

Converted Wave Attenuation

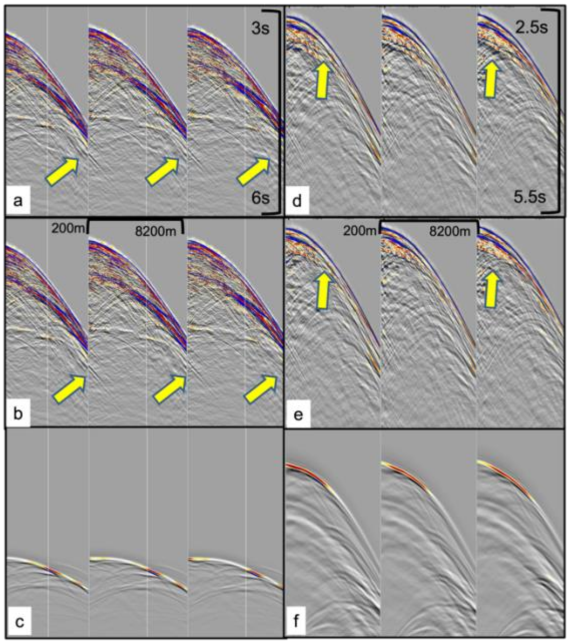

Figure 2: a) Shots after demultiple from an area of deeper, thicker salt; b) Shots after converted wave attenuation; c) PPSP and PSPP summed modeled shots; d) Shots after demultiple from an area of shallow, thinner salt; e) Shots after converted wave attenuation; f) PPSP and PSPP summed modeled shots.

In Figure 3 the depth slices shown are from a shallow salt area. Here the geometry of the converted wave energy was relatively parallel and close to the base of salt. Converted wave energy can be observed within the green oval crosscutting true subsalt geology (Figure 3a)) but has been successfully removed by subtraction (Figure 3b)). The RMS amplitude was extracted within a 100m window around the converted wave onset which is parallel to the base of salt. Prior to subtraction, high amplitude energy, within the pink oval, attributed to the converted wave energy, was observed (Figure 3c)); after removal of the converted wave noise, the RMS map is much more structurally consistent, as expected, across this geologic package (Figure 3d).

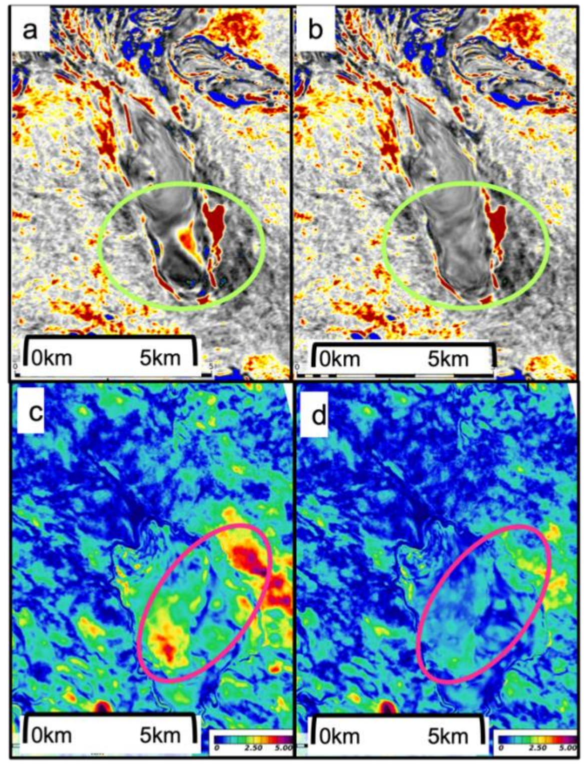

Figure 3: a) Kirchhoff preSDM depth slice of input; b) Kirchhoff preSDM depth slice after subtraction of converted wave noise prior to migration; c) RMS amplitude extraction of the Kirchhoff preSDM within a 100m window around the converted wave onset before subtraction, hotter amplitudes are more red; d) RMS amplitude extraction of the migration after converted wave attenuation within a 100m window around the converted wave onset, cooler amplitudes are more blue.

The stacked sections (Figure 4) from an area of thicker salt illustrate the motivation for converted wave suppression due to the similarity with the underlying primary energy. The same sedimentary trend was used for both P and S-velocities while the salt model varied based on the Vp/Vs ratio (Figures 4a) & b)). In the Kirchhoff preSDM 15° to 30° angle stack section of the input (Figure 4c)) a high amplitude event can be seen obscuring the subsalt primary reflectors. Although this energy is parallel to nearby primaries it has been well attenuated using our workflow (Figure 4d)). In the Kirchhoff preSDM image gathers, the energy of the base of salt P-wave event decreased from 15° onwards highlighted by the yellow oval. At the same offsets a converted wave event just below the base of salt, (green oval) has increased in amplitude. The deviation from primary curvature and lack of amplitude at low incidence angles compared to primaries can be observed (Figure 4e) & f)). The image gathers clearly show good separation and attenuation of the converted wave noise from the P-wave image.

Conclusions

In this paper we have demonstrated a workflow capable of attenuating the high-amplitude converted wave energy generated by strong impedance contrasts, such as a sediment-salt contrast. The application of this workflow to a dataset from the Eastern Mediterranean Sea highlights that contamination of converted waves in the migrated image can be addressed using 3D visco-acoustic modeling and adaptive subtraction prior to migration. This can improve continuity of subsalt events and improve confidence in the interpretation and evaluation of the prospectivity of subsalt structures.

Acknowledgments

The authors would like to thank ExxonMobil, QatarEnergy, the Government of Cyprus, and DUG Technology for their many collaborative discussions and the authorization to present this work.

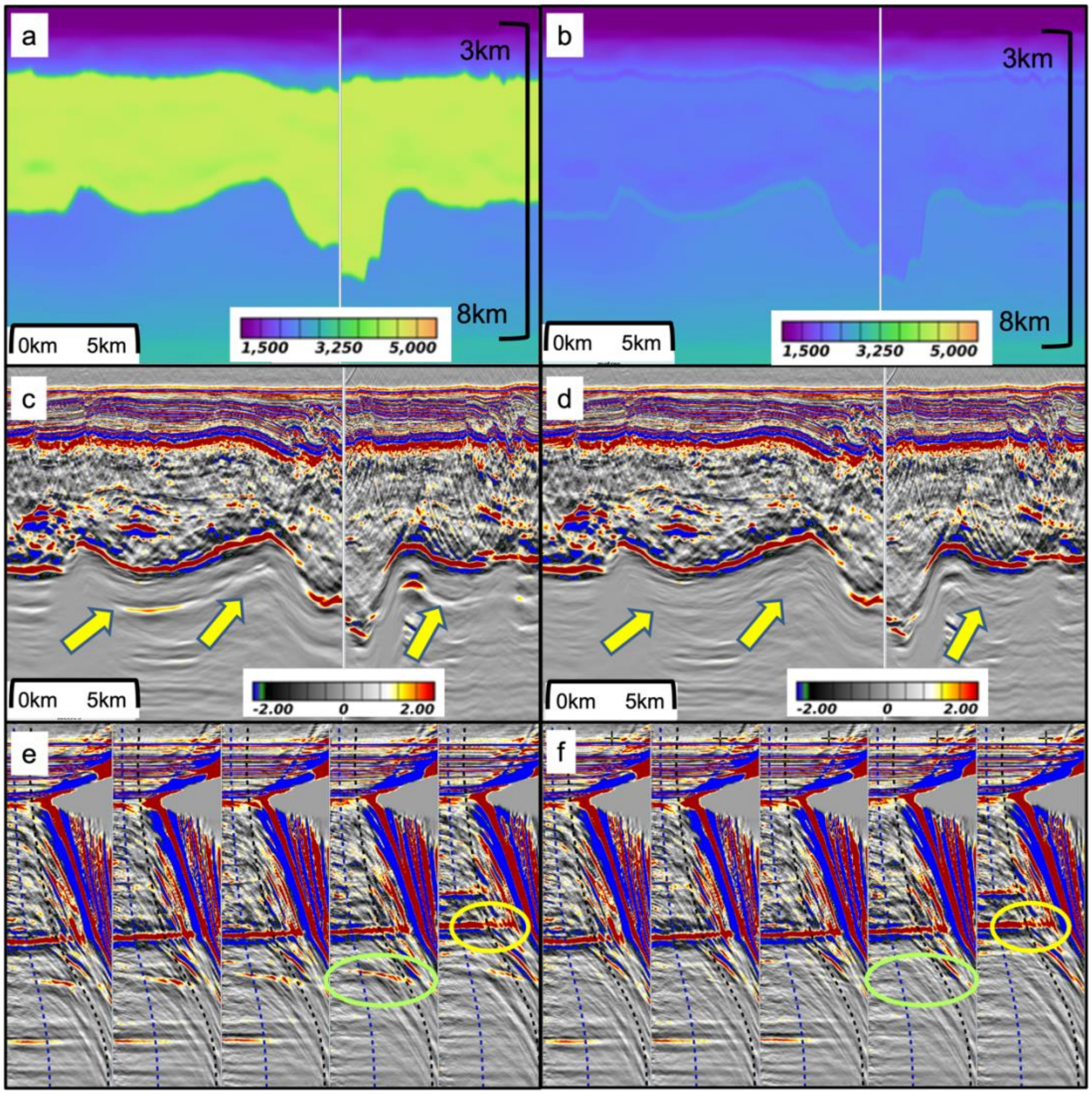

Figure 4: a) P-wave velocity; b) S-wave velocity; c) Kirchhoff preSDM mid angle stack of input; d) Kirchhoff preSDM mid angle stack of output e) Kirchhoff preSDM gathers of input with 15 and 30 degree angles plotted; f) Kirchhoff preSDM gathers with 15 and 30 degree angles plotted after subtraction.