Assisting geological interpretation using seismic simulation

Dan Kosloff[1,2], Allon Bartana[1], Jaqueline O'Connor[1], Jeff Codd[1] and David Kessler[1*] describe several approaches for using seismic simulation for tracking down converted wave arrivals and identifying the locations where they were created to assist in the interpretation of seismic data.

Introduction

Seismic forward modelling is an important tool for seismic structural interpretation in complicated areas. In a typical workflow, a subsurface velocity model is created after a number of iterations of velocity model building followed by pre-stack depth migration. After this stage, interpretation is performed. Very often, data ambiguities remain where it is not clear whether certain events represent primary reflectors or rather coherent noise such as multiples or converted waves.

Seismic simulation can help to resolve these ambiguities. Using the derived subsurface velocity model, a synthetic seismic survey can be created. By comparing the events on the simulated time gathers to the gathers from the real data, the origin of each event on the gathers can be determined. Alternatively, the synthetic time gathers can be depth migrated and the real and calculated migrated sections can be compared.

To date, seismic data processing has been based on solutions of the acoustic wave equation. This corresponds to the assumption that the subsurface consists of a fluid instead of a solid. While this approach produces correct arrival times for Pressure waves (P-waves), it does not yield correct amplitudes and does not account for converted waves (S-waves). Consequently, synthetic data produced by acoustic forward modelling appears too simple with many events not present.

In this paper, we claim that in order to make seismic simulation realistic and useful, seismic forward modelling used to assist the interpretation of real data must be based on the equations of dynamic elasticity instead of on the acoustic assumption. Furthermore, we explain that a combined use of elastic and acoustic modelling can resolve most of the ambiguities of events on migrated gathers.

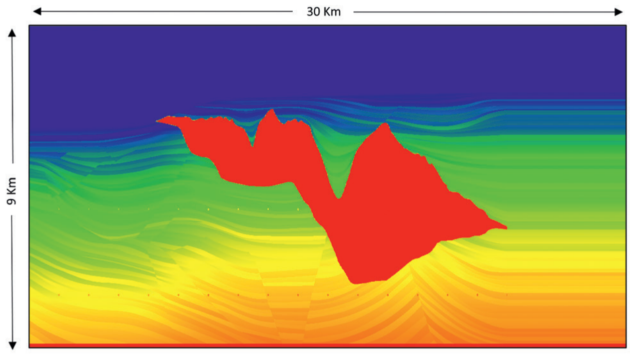

Figure 1 Sigsbee P-waves velocity model.

Seismic simulation

We demonstrate the interpretation workflow using the Sigsbee synthetic model (Paffenholz et al., 2002). The P-wave velocity section shown in Figure 1 was adopted from the original model. The S-wave velocity section was calculated by scaling the P-wave velocity by 0.6 below the water column and assigning a value of 0 ft/s in the water column. The density section was calculated using Gardner's equation with density of 1 g/cm^3 assigned to the water column and density of 1.7 g/cm^3 assigned to the salt body.

The grid spacing for the numerical simulation was 25 ft in the horizontal direction and 25 ft in the vertical direction. A two-ended survey was generated. The offset range was -40,000 ft to 40,000 ft. Shot gathers were generated with a shot spacing of 750 ft. A Ricker source wavelet was used with a high cut frequency of 25 Hz. The calculations were carried out to 10 seconds and performed without a free surface corresponding to the assumption that all multiples have been successfully removed.

Using the Sigsbee model, numerical simulation was done using Elastic wave propagation as well as Acoustic wave propagation for comparisons. Even with Pressure source at the water, Shear waves are generated at the water bottom. Figure 2 shows the Pressure wavefield and Shear wavefield generated when the P source is introduced in the water column at progressive times.

The results of numerical simulation are recorded shot gathers. Figure 3 shows a single shot gather generated using both Acoustic and Elastic simulations. As the Figure shows, there are many arrivals on the shot gather. The acoustic section contains fewer events. This leads to the conclusion that the additional events generated in the elastic simulation correspond to mode-converted waves in which part of the propagation path was traversed as a shear wave. Since the subsurface contains

[1] SeismicCity Inc. | [2] Department of Geophysics, Tel Aviv University
[*] Corresponding author, E-mail: dkessler@seismiccity.com
DOI: 10.3997/1365-2397.fb2020021

solid formations, such mode-converted waves exist in real data surveys. Hence the conclusion that realistic survey simulations must be performed with elastic forward modelling.

Data analysis workflow

For the present discussion, we assume that the time gathers from the elastic simulation represent the recorded data and that the velocity section represents the velocity which was determined by a velocity modelling process. The next step in a typical workflow is to obtain a migrated section by pre-stack depth migration of the shot gathers. Figures 4 and 5 show the migrated images obtained by acoustic pre-stack reverse time migration (Bartana et al., 2015). Figure 4 shows the PSDM section produced inputting the data generated using the acoustic wave equation and Figure 5 shows the PSDM section produced by inputting the data generated using the elastic wave equations. Most of the events on the migrated section conform to the velocity section. However, the PSDM result obtained using the elastic simulated data shows areas of no illumination as typically observed on real data. The PSDM result obtained using the acoustic simulated data is much better than what we normally observe on real data. The reason is that the simulation using the acoustic wave equation does not result in a realistic simulated dataset that can be compared to real data. More than that, there is an extra event below the salt (marked by an arrow) that requires explanation. With real data where the velocity is not so well determined, such events are often confused with the base of salt reflection.

We propose the following procedure to identify and explain the origin of events:

1. Perform elastic forward modelling to generate synthetic data then migrate the data with acoustic pre-stack depth migration. Check whether the real data and synthetic data migrated sections contain the same main events. If the real data and synthetic data have the same principal events go to the next stage. If not, the additional events on the real data section may be multiples or a result of an incomplete subsurface velocity model.

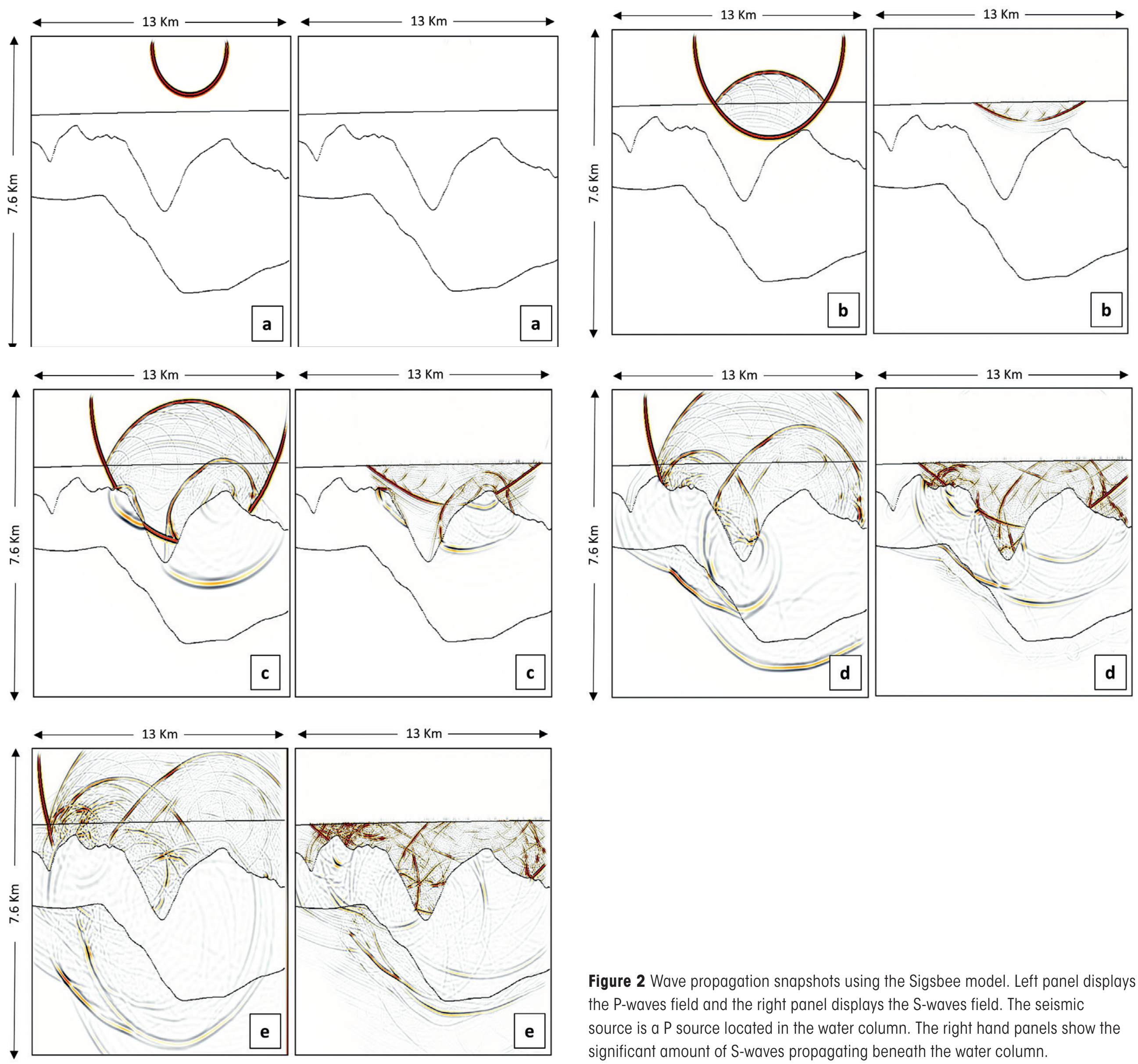

Figure 2 Wave propagation snapshots using the Sigsbee model. Left panel displays the P-waves field and the right panel displays the S-waves field. The seismic source is a P source located in the water column. The right hand panels show the significant amount of S-waves propagating beneath the water column.

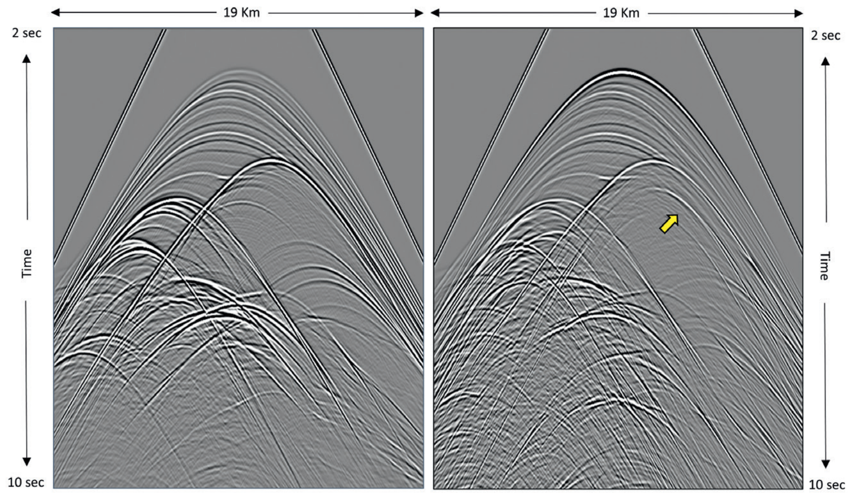

Figure 3 Recorded time section. Left – using Acoustic simulation. Right – using Elastic simulation. The arrow points to a converted wave recorded at 4.1 seconds.

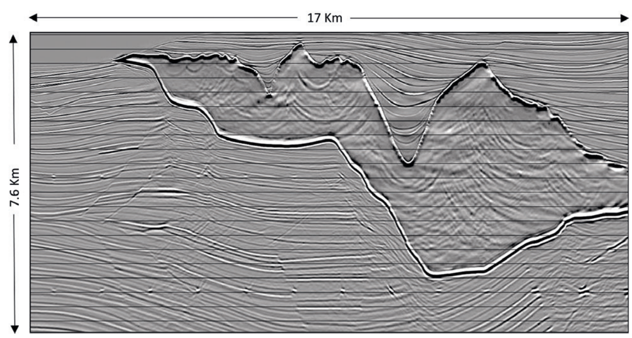

Figure 4 PSDM image of Sigsbee dataset simulated using the Acoustic wave equation.

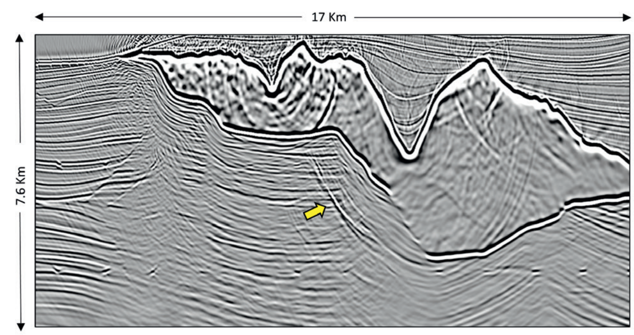

Figure 5 PSDM image of Sigsbee dataset simulated using the Elastic wave equation. The sub-salt parallel to the salt converted wave is clearly identified.

2. Perform acoustic forward modelling using the velocity section then migrate the data with acoustic pre-stack depth migration. Compare the migrated sections from the elastic and acoustic synthetic data. Events which appear on the elastic section and do not appear on the acoustic section correspond to converted waves. Figure 5 shows the migrated section from the elastic forward modelling. As the section shows, the additional, parallel to the base of salt event on the elastic migrated section, is absent. This leads us to the conclusion that this coherent event corresponds to a mode-converted wave.
3. Determine the origin of the converted wave event by examining wave propagation snapshots. Snapshots can be useful in tracking down the origin of events. Figure 6 presents P-wave snapshots from acoustic modelling (left panels) and P-wave snapshots from elastic modelling (right panels) at progressive times. As the survey is marine, initially only P waves are generated from the source. Upon transmission to the layers below the water column, energy is converted to S waves. When this S-wave energy is reflected, part of it is converted back to P waves either at subsurface discontinuities or at the water bottom.

We are using both recorded time sections as well as analysis of wave propagation snapshots to understand the seismic data. Let us for example consider the converted wave arrival which is marked by an arrow in the migrated section shown in Figure 3. Figure 6b displays the P-wave snapshots from the acoustic and elastic simulations respectively at a time shortly after the reflection from top of salt. The P reflection appears on both the acoustic and elastic simulations. However, on the right panel from the elastic calculation there is an extra event behind the P reflection (marked by an arrow) which does not appear on the equivalent acoustic snapshot. This event appeared first as a P wave at the top of the salt boundary. It is therefore interpreted as a converted wave at the water bottom which was then reconverted back to a P wave at the top of salt. Figure 6c shows snapshots at the time this event reaches the surface (4.1 seconds). A comparison of this time with the time of the event on the time section (Figure 3) confirms our interpretation.

The approach described can be used in a number of different combinations, such as comparing snapshots from pressure and S wave amplitudes, or examining snapshots from the back propagation part of reverse time migration.

Conclusions

Conventional seismic data processing is based on the acoustic assumption where the earth is assumed to consist of fluid formations. This approach is lacking as the earth's response is closer to the response of a heterogeneous elastic solid than to that of a fluid.

Experience has shown that seismic data contains a very large amount of converted wave energy which is not accounted for by the acoustic assumption. With migrated data, converted wave events can be mistakenly identified as genuine material interface reflections. In this work, we describe workflows based on

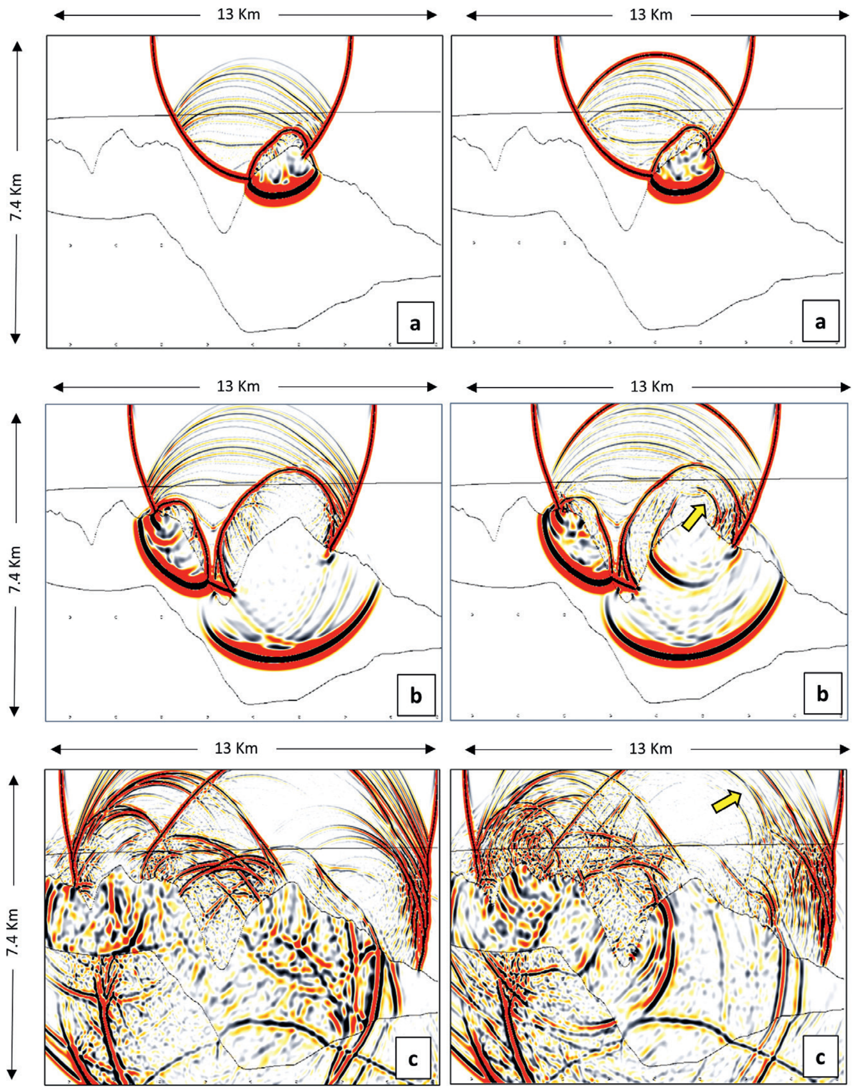

Figure 6 Wave propagation snapshots using the Sigsbee model. Left panel displays the P-waves field generated by using the Acoustic wave equation for simulation, and the right panel displays the P-waves field generated by using the Elastic wave equation for simulation.

forward modelling whose purpose is to avoid such misinterpretation of the data.

For the reasons previously discussed, the creation of realistic synthetic data by forward modelling should be carried out at least by the solution of the equations of dynamic elasticity instead of the acoustic wave equation (to represent attenuation, the equations of visco-elasticity need to be used). In general, acoustic forward modelling shot gathers appear too simple compared to actual field data. Some of the interpretation workflows do use both elastic and acoustic forward modelling thus allowing us to isolate events by turning on or turning off converted wave energy. This workflow can greatly assist in the interpretation of prestack depth migrated data and avoid crucial mistakes in the interpretation of the seismic data.

References

Paffenholz, J., McLain, B., Zaske, J. and Keliher, J. [2002]. Subsalt multiple attenuation and imaging: observations from the Sigsbee2B synthetic dataset. *SEG 72nd Annual Meeting*, Expanded Abstracts.

Bartana, A., Kosloff, D., Warnell, B., Connor, C., Codd, J., Kessler, D., Micikevicius, P., Mckercher, T., Wang, P. and Hozzhauer, P. [2015]. GPU implementation of minimal dispersion recursive operators for reverse time migration. *SEG 85th Annual Meeting*, Expanded Abstracts.