Analysis of elastic wave field propagation through gas clouds

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Summary

To maximize the understanding of our seismic images it is very critical to carefully analyze the various wave types propagating through the earth's subsurface. Especially in the situation where the overburden contains complexities like gas clouds, the understanding of the behavior of elastic waves, especially with respect to mode conversion, becomes crucial. In our analyses we make use of Vertical Seismic Profiles to identify the propagation of different converted waves.

Introduction

Compressional or pressure waves (P-waves) as well as transversal or shear waves (S-waves) show different characteristics as propagating through gas clouds. P waves get highly attenuated in the presence of gas clouds, and because of this phenomena, the imaging of gas clouds surrounding layers, especially below gas clouds becomes a challenging process. On the other hand, S-waves propagate through gas clouds unaffectedly. An example of this phenomenon is given by MacLeod et al. (1999), where the Alba field was successfully imaged with converted waves.

Numerical Modeling Examples

To increase our understanding of elastic wave propagation in complex subsurface structures, such as gas clouds, we will do an extended numerical analysis for an elastic subsurface model, which is designed such that P-wave propagation through the gas cloud is severely distorted. Elastic finite difference numerical modeling was used for the generation of all synthetic data. In all examples in this abstract, an Ocean Bottom Cable (OBC) configuration has been used, simplifying the elastic wave equation since shear waves do not propagate in fluids. The objectives in the following examples are to improve the understanding of elastic wave propagation and conversions and to "simulate" the effects on elastic waves in the presence of a gas cloud.

Figure 1a illustrates a simple model with an ocean bottom and a very simplified gas cloud. Modeling data including a gas cloud is very challenging because of the complex heterogeneous characteristics of gas clouds. In its simplest form, a gas cloud can be represented as a low velocity heterogeneous entity, containing velocity gradients at the edges, which already generates complex wave propagation effects. To illustrate this phenomenon, three snapshots are shown for increasing sequential times (see Figures 1b, 1c and 1d) for an acoustic medium, thus allowing only P-wave propagation. As the sea-bottom in this example contains a dipping part, this causes two diffraction points at the edges of the fault. Figure 1b shows clearly that as the wave front hits the two diffraction points, two new waves are generated, which are propagating upward towards the surface. Furthermore in Figure 1c and Figure 1d, it can be clearly observed that the wave front gets distorted and is bending inwards, due to the low velocity character of gas clouds. Note also that in Figure 1d the two waves that were generated through the diffraction points (sharp edges of the sea-bottom) are traveling back downward due to reflection at the free surface (multiples).

For a more thorough study on the behavior of elastic waves, another example was composed in which the gas cloud was designed as a more complex entity than in the first example. A full elastic model was created. Figure 1e, 1f and 1g show, respectively, the P-wave and S-wave velocity models and the density model that were used in the elastic numerical modeling. The size of the models are 10 [km] width and 3,5 [km] depth, with a flat sea-bottom at depth level of 80 [m]. As can be observed from these figures all vertical axes have been exaggerated for the purpose of easier identification of the model structures and modeled waves. In this example the gas cloud has been designed as a very complex heterogeneous entity, in which all neighboring gridpoints have randomly different P-wave velocity values (a series of point scatterers with velocities ranging between 1000 [m/s] to 2000 [m/s]). Note the color bars/legends on the velocity models and density models showing the range of values). For the design of the S-wave velocity/depth model, only a velocity gradient was defined (from low-to-high values, from gas cloud border to center of gas cloud). For the density model, again a heterogeneous model was designed (with densities ranging from 700 [kg/m3] to 1300 [kg/m3] per gridpoint). In this example no other density contrasts were defined around the gas cloud to simplify the density model.

In all the examples an Ocean Bottom Cable data acquisition was designed, and the "no-free surface" assumption simplification was imposed. This was selected to avoid surface-related multiples to be modeled for better interpretation purposes. Figures 1h, 1i and 1j show the results of acoustic modeling using respectively the models of 1e, 1f and 1g. Here some acoustic modeling was performed on respectively the P-wave model velocities and the S-wave model velocities. This separate acoustic modeling allows better interpretation of P-wave and S-wave propagation without having converted waves (for simplification purposes).

Figure 1h shows the response of acoustic modeling using the P-wave velocity model (Figure 1e) and the density model (Figure 1g). Similarly Figure 1j shows the response of acoustic modeling using the S-wave velocity model (Figure 1f) and the density model (Figure 1g)
Comparing Figure 1h (P-wave model velocities used) with Figure 1j (S-wave model velocities used) it can be observed that the S-waves of course propagate with a lower velocity in comparison with P-waves and propagate through the gas cloud without much disturbance. Figure 1h shows the distortion of the P-wave field and the P-waves energy that is “imprisoned” **inside** the gas cloud. Figure 1k shows a snapshot of acoustic modeling results using S-waves velocities in the modeling. Note that the amplitude of the transmitted S-wave front below the gas-cloud is weaker than the reflected S-wave front of the gas cloud.

Note that these examples are acoustic modeling results in which P-wave and S-wave velocities have been used to better understand the behavior of the waves handled separately. It is interesting to do detailed analysis for various sea-bottoms and analysis of sediments and determine the amount/strength of S-waves that are converted at the sea-bottom and transmitted at the sea-bottom into the subsurface. This is shown graphically in Figure 1l. If the conversion from P-waves into S-waves is strong at the sea-bottom, then these downgoing S-waves will propagate through the subsurface and in this way provide a better analysis and imaging of gas clouds. From the examples shown in the remaining part of this abstract it can be seen that the S-waves propagate within the gas cloud and get converted into P-waves at the bottom of the gas cloud. See also for possible raypaths illustrated in Figure 1l that may contribute optimally in improved seismic imaging using multi-component acquisition, and emphasizing the values of S-wave acquisition in addition to the standard acquisition of P-waves. Figure 2a shows a snapshot based on acoustic finite difference modeling in the models of Figure 1e and 1g (including a gas cloud). For the purpose of interpretation, part of the subsurface model (Figure 2b) has been depicted next to the snapshot for a better understanding of the effect of the gas cloud. As can be clearly observed Figure 2a, a weak reflection is observed from the top of the gas cloud, and its internal multiple reflection, propagating downward, can be seen. Furthermore a strong bottom of gas cloud reflection can be identified together with the transmitted P-wave energy. If the gas cloud would be excluded from the model then the result of wave propagation would be as depicted in Figure 2c, highlighting the fact that the gas cloud is slowing down the wave propagation due to its lower velocity character. In the remaining part of the examples in this abstract elastic numerical modeling has been performed studying the acoustic and elastic waves and the importance of wave conversion highlighting the values of S-wave propagation and acquisition in multi component recordings. Figure 2d and 2e show respectively the elastic modeling results for the Vz and Vx recordings (Vz being the vertical component of the geophone recordings at the sea-bottom and Vx being the horizontal component of the geophone recordings at the sea-bottom). From these pictures the headwave connecting the direct P-waves and S-waves can be observed. Furthermore the converted S-wave at the sea-bottom as indicated with arrows. Also the strong S-wave reflection from the top of the gas cloud can be easily noticed. The Vx component (Figure 2e) shows indeed a polarity change as moving from left to right as expected, and most important Figure 2e shows the propagation of the S-waves within the gas cloud unaffected and opposite to P-waves that get attenuated and distorted passing through gas clouds. Furthermore, some Vertical Seismic Profiles (VSP) have been modeled for a better representation and viewing of propagation paths of the various waves and their conversions. The zero-offset VSP that was modeled is shown with the blue color line in Figure 2f (Vz recording) and 2i (Vx recording). Identically, a 1000 m offset VSP was modeled indicating its lateral position in the shot records for respectively Vz and Vx recordings. The 5 interfaces as numbered in Figure 1e are also indicated on Figure 2g (Vz, zero offset VSP), Figure 2h (Vz, 1000m offset VSP), Figure 2j (Vx, zero offset VSP) and Figure 2k (Vx recording, 1000m offset VSP). It can be clearly observed in all four VSP’s that the energy is imprisoned in the gas cloud as expected from the theory. Note the gas cloud zone is indicated just above the first numbered interface. Furthermore the arrow in Figure 2h indicates the P to S conversion at interface numbered “2”. The event pointed by the red arrow in Figure 2k shows the propagation of the S-waves within the gas cloud. Note the strong conversion (in Figure 2j) to P-waves just below the gas cloud. Note also the time coincidence of the shot records at the “pseudo well” locations with the zero offset VSPs (blue color frames) and 1000m offset VSPs (red color frames). The 1000m offset VSP shows stronger effects of wave conversions and S-waves, as expected for increased offset between source and “pseudo well”.

Conclusions

Numerical modeling results show an improved interpretation and understanding of acoustic and elastic waves in the presence of gas clouds. Especially the use of Vertical Seismic Profiles in our analysis improves identification of propagating and converted waves.

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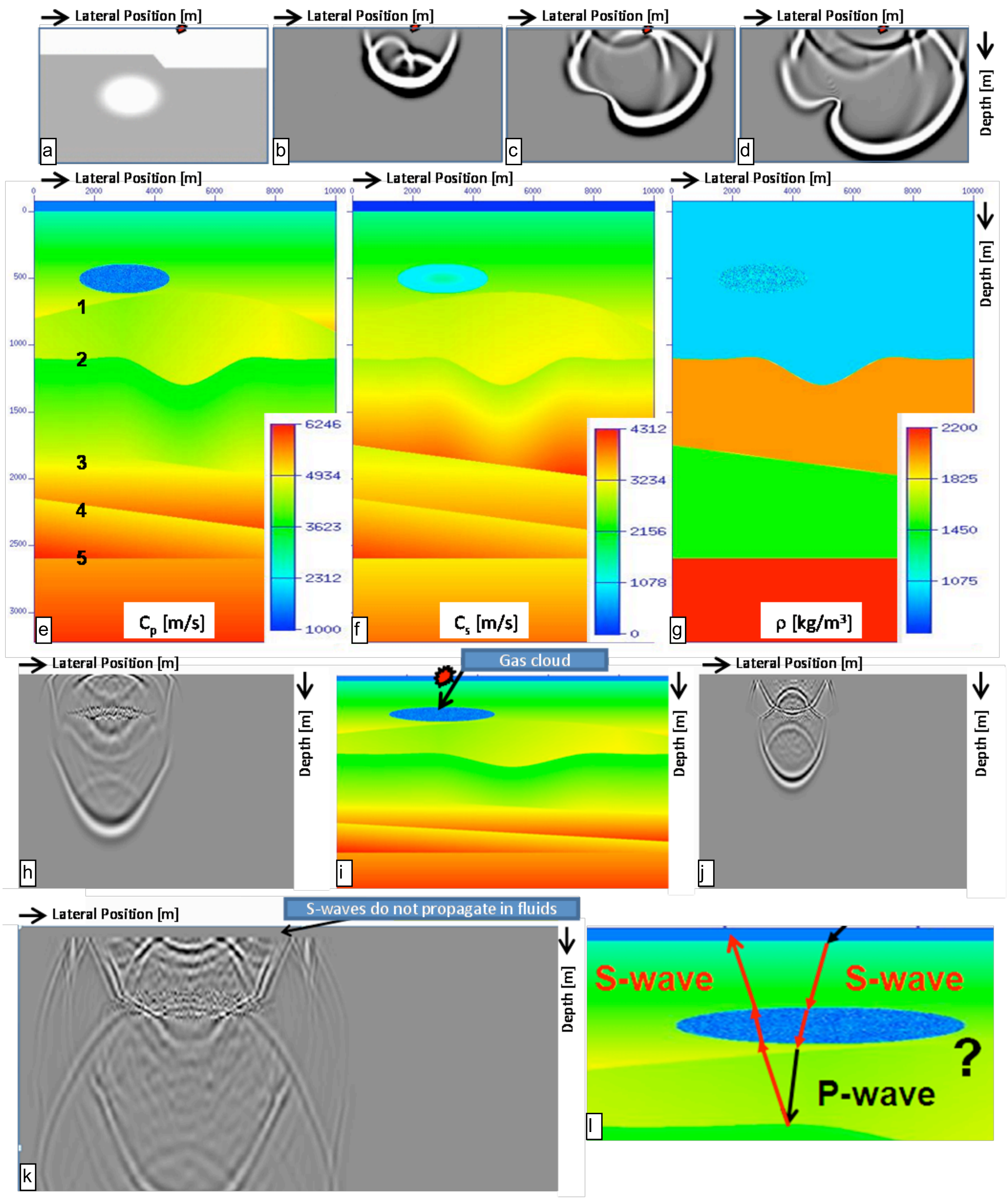

Figure 1 : Numerical modeling results in acoustic media where the P or the S wave velocity has been used to model the wave propagation through a gas cloud.

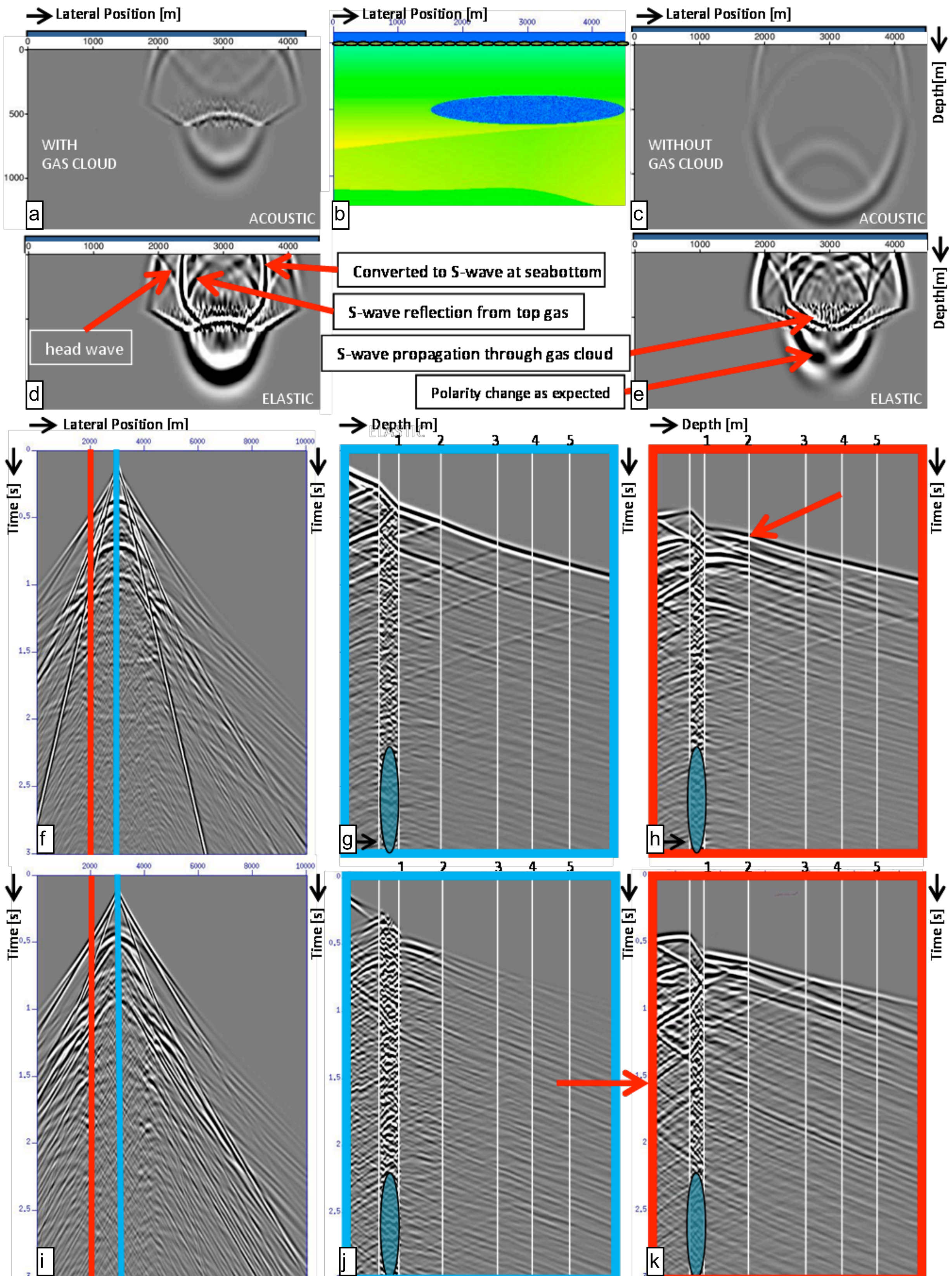

Figure 2 : Numerical modeling results in acoustic and elastic media. VSP profiles are used for a better interpretation of the complex wave mode conversions caused by the gas cloud.

EDITED REFERENCES

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