Imaging dipping sediments at a salt dome flank - VSP seismic interferometry and reverse-time migration

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Summary

We present results of applying seismic interferometry to image dipping sediments abutting a salt dome. We create a set of synthetic traces representing a multi-level, walk away Vertical Seismic Profile (VSP) for a model composed of a simplified Gulf of Mexico vertical-velocity gradient and an embedded overhanging salt dome. The sediment reflectors in the model dip up towards the salt dome flank. To process these data, we create a set of redatummed traces using seismic interferometry. This is done without having to perform any velocity analysis or moveout corrections. Each of these redatummed traces mimics the output of a down-hole source and down-hole receiver pair. The linear $v(z)$ gradient enables the redattumed data set to illuminate and capture reflections from both the salt-dome flank and the upward turning sediments. We then apply pre-stack depth migration to these traces to produce the final image of the beds and the salt dome flank. The final migrated results demonstrate that the reflected turning ray energy from both the salt flank and sediments are adequate to create structurally correct images using the combination of seismic interferometry and prestack depth migration.

Introduction

Seismic interferometry uses the time symmetry of the wave equation together with source-receiver reciprocity to estimate the impulse response between two passive receivers. This allows the estimation of the wave field that would be observed at one receiver if the other receiver were a source (see Wapenaar, 2004). Recent developments in seismic interferometry (Derode et al., 2003, Wapenaar et al., 2005) have allowed for obtaining novel data sets from traditional recording geometries.

For example, after we invoke source-receiver reciprocity a walk-away VSP geometry becomes a reverse VSP (RVSP) for which the geometry is similar to a Time Reversal Mirror (Fink, 1999). With this data set it is straight forward to apply the principles of Time Reversed Acoustics, a field of study related to seismic interferometry. Willis *et al.* (2006) use this idea to image a salt-dome flank using Vertical Seismic Profiling (VSP) data. By summing the autocorrelations of traces recorded in the borehole due to sources at the surface, they create a zero-offset section as if it were acquired with coincident source and receiver pairs in the borehole. Essentially, the correlation-and-summation operation thus redatums the data to the borehole, without having to perform any complicated processing. They then create an image of the salt-dome flank by applying post-stack depth migration from the perspective of the borehole. The efficacy of this method relies on capturing the turning-ray reflection energy from the salt-dome. Willis *et al.* (2006) conclude that in a medium with a $v(z)$ velocity gradient, as in the Gulf of Mexico (GOM), this method is very effective.

Lu et al. (2006) expand this zero offset redatumming GOM methodology to the non-zero offset redatummed case using seismic interferometry. The images from the common, down-hole shot gather generally have a better signal to noise ratio because the non-zero offset gathers illuminate the salt dome flank from different directions. This delineates the contour of the salt dome flank much more effectively. Bakulin and Calvert (2004) apply this type of technique to eliminate the complications from the heterogeneous near subsurface by redatumming the wave field to receivers in a near-horizontal well just beneath the overburden. Hornby et al. (2006) show the results of applying seismic interferometry to obtain an image the vertical salt dome flank on GOM field data.

In this paper we show that the VSP seismic interferometry and migration method (Lu et al. 2006) is also capable of imaging the upward dipping sediment layers on a salt dome flank.

Methodology

We created a 2-D data set representing a multi-level walk away VSP for a model composed of a simplified Gulf of Mexico vertical-velocity gradient and an embedded overhanging salt dome survey. The sources are located at the surface and geophones in the borehole as shown in Figure 1. Five reflectors are introduced on top of the $v(z)$ gradient as 15%-higher velocity spikes. In this case, the reflectors dip up towards the salt dome flank. Our aim is to image the salt dome flank as well as the dipping reflectors. Accurate determination of the salt/sediment contact can greatly help in reservoir development and reserve estimation.

Our methodology consists of two main steps: 1) redatuming the shots to the bore hole and 2) imaging the salt dome flank and the reflectors.

The first step is achieved by applying the principles of seismic interferometry to create a new data set consisting of common shot gathers as if the sources were located in the borehole and the receivers were also located in the borehole. Note that the original data consist of common

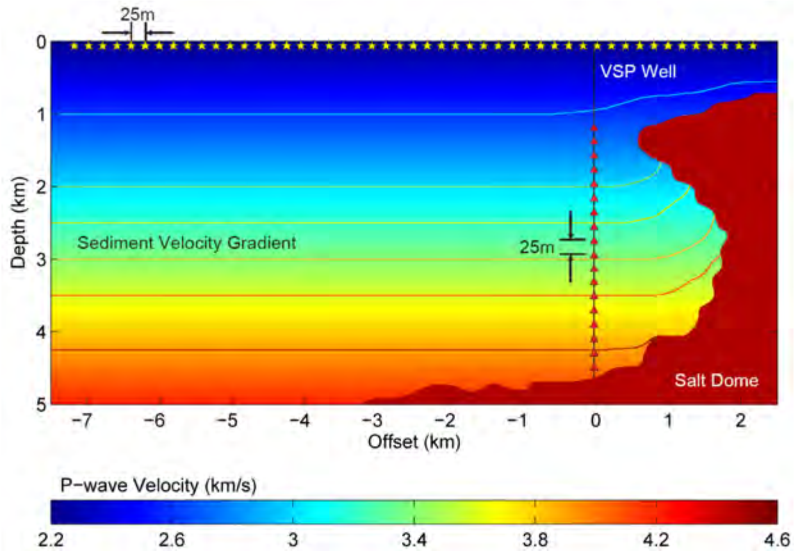

Figure 1: A simplified Gulf of Mexico model of dipping sediments at a salt dome flank with VSP acquisition geometry.

shot gathers with the shots at the surface. We first sort those into common down-hole receiver gathers. Three representative common, down-hole receiver gathers at depths of 2, 3 and 4 km, are shown in Figure 2. These are actual VSP traces and serve as the input data for the seismic interferometry operation.

The seismic interferometry operation step is then subdivided into several sub-steps. First we choose one of the actual down-hole receiver locations to be a redatummed source location. Then we select another actual down-hole receiver location to be a redatummed receiver location. For each actual surface source location, there is a pair of traces corresponding to the actual receiver at the redatummed source location and the actual receiver at the redatummed receiver location. These two traces are cross correlated. For example we could choose the actual source location to be at offset -2000m, the redatummed source to be at depth of 3 km, and the redatummed receiver to be at depth 2 km. We would take the trace at offset -2000m in the middle panel of Figure 2 and cross correlate it with the trace at offset -2000m in the left panel.

The redatummed source and receiver locations are held fixed and this process is repeated for each actual surface shot location. Then all of the correlation traces created by this process are summed together. This single stacked trace becomes the redatummed receiver trace for this set of redatummed source and receiver. In our example above, this stacked trace is located at a depth of 2 km in the lower panel of Figure 3.

This process is repeated for all redatummed receiver locations for this redatummed source location. This creates a redatummed, common down-hole source gather, such as in the lower panel of Figure 3. To obtain a full redatummed down-hole survey, we repeat this for all possible redatummed source locations. Note that for this step we do not have to apply velocity analysis or complicated processing such as statics corrections at the surface for the propagation path to the borehole.

This procedure gives kinematically correct results (see Wapenaar *et al*., 2005), which is acceptable for structural imaging applications. For stratigraphic and time-lapse applications more work is needed to insure correct relative amplitudes. In any case, the success of the seismic interferometric redatumming step is determined by how much of energy is reflected off the reflectors near the salt flank and captured at the receivers in the borehole. This is generally only possible in a medium with a $v(z)$ vertical velocity gradient.

In other geometries and velocity regimes, other solutions are possible. For example, Bakulin and Calvert (2005) successfully capture the reflection energy and imaged horizontal reflectors using a horizontal well.

The final step is accomplished using prestack, reverse-time depth migration. The back propagation step is performed by injecting the redatummed traces, reversed in time, into a finite difference modeling code at the appropriated depth locations of the redatummed receiver locations. Since our background velocity medium is a simple, linear $v(z)$ gradient, the forward extrapolation of the shot travel times is performed analytically. The migrated image is constructed by extracting and accumulating the time and

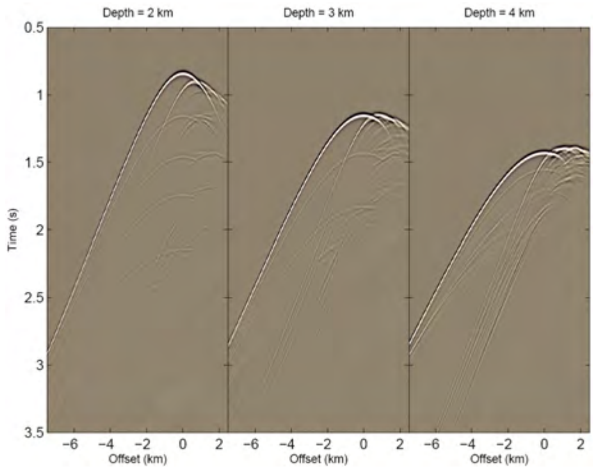

Figure 2: Common down-hole receivers gathers at depths of 2, 3 and 4 km. Sources are at the surface.

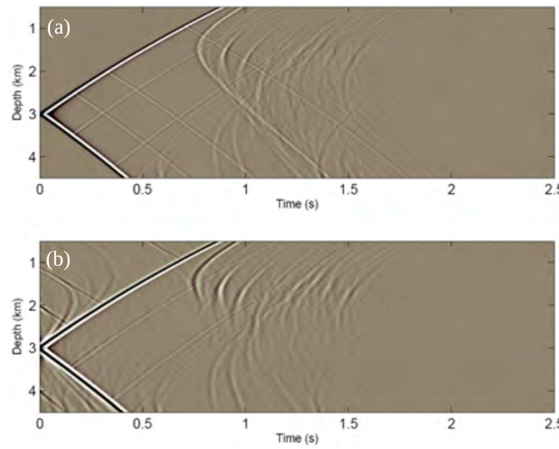

Figure 3: Common down-hole shot gathers (a) obtained by placing a source in the bore hole at 3 km depth, and (b) redatummed using seismic interferometry.

depth coincident values of the forward and back propagated wavefields.

For the migration step, we need a generalized velocity model of the background medium between the flank and the borehole.

Example

We now apply our processing methodology outlined above to a synthetic data set created using the simplified Gulf of Mexico salt-dome model of Figure 1. The salt dome has a P-wave velocity of 4480 m/s. The background velocity is described by $v(z) = v_0 + Kz$, where v_0 is the velocity of the top layer and K is the velocity gradient. The receivers are placed from a depth of 0.5 km to 4 km at 25 m intervals.

Performing the seismic interferometry redatumming procedure described under step 1 in the previous section, we obtain 161 redatummed, common down-hole source gathers. One of these gathers at a depth of 3 km is shown in Figure 3b. For comparison, we show the actual common source gather modeled with the source in the bore hole at 3 km depth. We observe that these common source gathers are very similar.

We observe that in Figure 3b, the three linear down going events coming off of the first arrival are absent in the redatummed traces. These events are the downgoing reflections off of the bottom of the flat laying sediments located at the borehole. The omission of this energy is due to the fact that this energy is not excited by a surface source. An actual down-hole source creates upgoing energy which is reflected back downward. (To be theoretically more complete, if we could put sources underground and all around the edges of the model, we would, in fact, be able to reconstruct these down going reflections. Van Manen et al. (2004) used this exact concept of sources all around the model for efficient simulation of wave propagation.)

In order to prepare the redatummed traces for migration, we muted the anticausal (before zero time) events and the direct arrivals. Also problematic were the strong, late time, reflections off the leftmost, shallow salt edge. After the muting, we applied prestack, reverse time depth migration (as described in step 2 above) to the redatummed, common down-hole source gathers. The velocity model used only the background $v(z)$ medium (without the salt or reflectors).We applied the same processing to the actual down-hole common source gathers and the redatummed common source gathers. Figure 4(a) shows the final image using actual down-hole sources and receivers. Figure 4(b) shows the final image using the redatummed data. Both images show excellent delineation of the salt flank and the illuminated portions of the dipping sediments.

Conclusions

We outline a methodology to accurately image a salt dome flank and sediment reflectors dipping up towards the salt dome. We used seismic interferometry to create a set of redatummed, down-hole common source gathers from a conventional walk away VSP data. The redataumed traces capture essential portions of the reflected energy from the salt and dipping sediments. The final migrated images show a remarkable structural clarity of the salt flank and the dipping sediments.

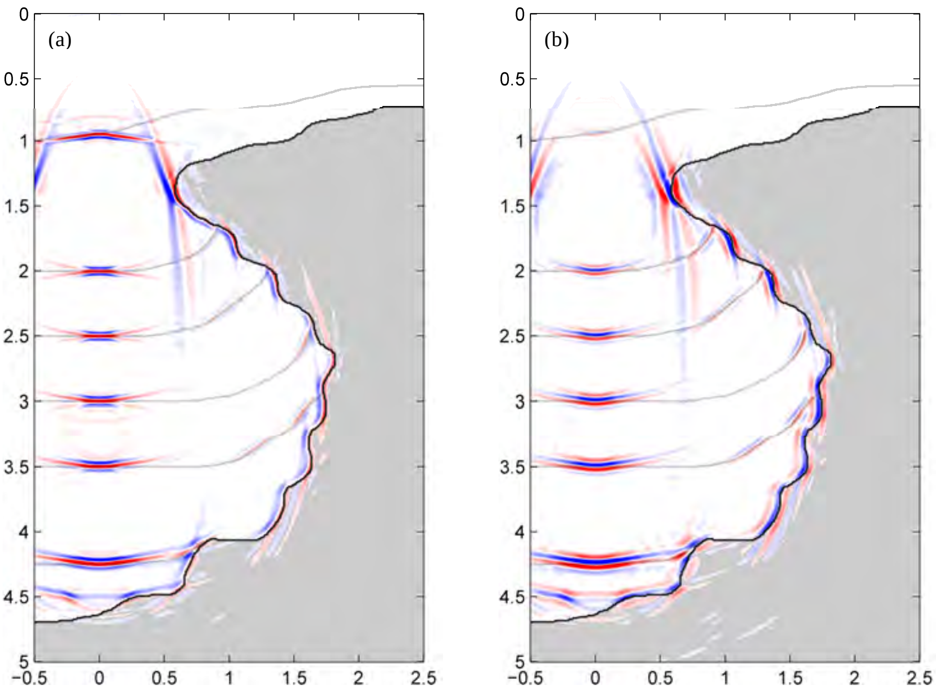

Figure 4: Images of the dipping sediment beds at salt dome flank (a) from reverse time migration of the data created with down-hole sources and receivers (b) from reverse time migration of the redatummed data.

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