Integrated prestack depth migration of VSP and surface seismic data

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Summary

Multi-offset VSP and surface seismic data from the Rocky Mountain Foothills of southern Alberta, Canada, has been used to obtain the anisotropy parameters and develop a robust depth-velocity model for the anisotropic depth migration of both data sets. The higher-resolution VSP migrated section was spliced into the surface seismic result, yielding an enhanced depth image at the target level. The section was then interpreted to build a 2-D structural model. Numerical VSP and surface seismic data were computed over the model to test a new, prestack depth migration algorithm for the integrated depth imaging of VSP and surface seismic data. This algorithm, which is Kirchhoff-based, uses a common velocity model to migrate the two data sets to a single output grid, eliminating the need for splicing the VSP section into the surface seismic image. Results from the depth migration of the numerical data show that the resulting integrated image yields a result that is superior to those obtained from the migration of either data set alone. There is enhanced resolution at the target level due to the higher bandwidth of the VSP data and also increased structural detail, as the events from both data sets complement each other when integrated. This method may prove especially useful now that simultaneous recording of VSP and surface seismic is becoming more popular.

Introduction

In order to obtain good depth images of the subsurface, particularly in areas of complex geology such as fold and thrust belts, salt domes and volcanics, VSP and surface seismic data should be used together to constrain interpretation and build robust velocity models for use in prestack depth migration (PSDM). Multi-offset VSPs have successfully been used to determine the anistoropy parameters[1,2,3] which can then be used in anisotropic PSDM. Since the Fresnel zone is smaller and the bandwidth larger (due to less absorption of the higher frequencies as a result of shorter one-way travel paths through the near surface and the subsurface) VSP data are higher bandwidth than surface seismic data[4]. There are several examples in the literature demonstrating that migration of VSP data can yield good quality, high frequency images that tie well with reflectors on surface seismic migrated sections when the VSP image is spliced in the surface seismic section[5,6].

In this work two approaches to VSP and surface sesimic depth migration were tested. First VSP and surface seismic field data were used to build an anisotropic depth-velocity model for the prestack depth migration of both data sets. The higher-resolution VSP image was then spliced in the surface seismic result in the conventional way. Then a new approach to the integration of VSP and surface seismic depth imaging was developed. Instead of splicing the VSP image into the section derived from the surface seismic, a new migration algorithm and a single velocity model were used to migrate both data sets into a common output depth image. Results from the migration of numerical seismic data show that the integrated image is superior to that generated from the VSP or surface seismic data alone. It has better reflection continuity and focussing, and enhanced resolution at the target.

Method

The VSP and surface seismic data used in this study are from the Rocky Mountain Foothills of southern Alberta, Canada. The structural geology is characterized by steeply-dipping anisotropic clastics of Mesozoic age, which overlie Paleozoic carbonates. The exploration target in our case lies in the hanging wall of a thrust sheet, in the Upper Paleozoic. A plan view of the surface seismic line, the VSP well and the shot locations for the multi-offset VSP[3] are shown in Figure 1. Only the 4 shots closest to the well (NE1, NE2, SW1 and ZERO) were used for depth imaging purposes. Travel-time inversion of first-arrival data from all seven VSP shots was used to determine Thomsen's anisotropy parameters[3]. These parameters, together with models for the stratigraphic dip and slow velocity, were then used to build a migration-velocity model for the anisotropic PSDM of both the VSP and surface seismic data. Figure 2a shows details of the surface seismic depth-migrated section at the target level. Figure 2b shows the VSP depth-migration result spliced in the surface seismic section. Note the improved resolution of event 'A' on Figure 2b, due to the higher bandwidth of the VSP data. This event also ties very well with the surface seismic through the use of the same migration-velocity model. However, some of the coherent events below 'A' and 'B' that are present on the surface seismic section (Figure 2a), are not imaged on the corresponding VSP result (Figure 2b).

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In order to test the new, integrated prestack depth migration algorithm, a numerical model was developed based on the interpretation of the field data. Details of the model at the target level are shown in Figure 3a. Model velocities were assigned from sonic logs from the VSP well and other wells nearby. The VSP well and shots NE1, NE2, ZERO and SW1 were projected onto the plane of the seismic line for 2D modeling purposes. Synthetic surface seismic and VSP data were generated using commercial numerical modeling software, and the acquisition geometry was similar to that used during the field survey. Since the primary objective was to investigate the depth image at the reservoir level (Figure 3a), only 12 surface shots were computed, located at 100 m intervals for offsets up to $\pm$600 m from the well. Receivers were placed along the surface at 20 m intervals. In the well, 134 receivers were placed at intervals of 15 m, starting from the bottom (depth = 3636 m). The initial VSP data were collected for shots NE2, NE1, ZERO and SW1, to simulate what had been recorded in the field VSP survey. Next, for comparison, the experiment was repeated using the same 12 shots as were recorded into the surface seismic spread. No down-going waves were generated in the VSP case and no attenuation mechanisms were included. The traces were then convolved with a zero-phase wavelet with a peak frequency of 35 Hz for the surface seismic and 45Hz for the VSP data to represent the typical frequency content of the VSP and surface seismic field data. The data sets were then migrated using the newly developed algorithm.

Examples

Figures 3b, c, d, e and f show the migration results for the target (Figure 3a), with Figure 3b being the migrated section of the surface seismic data. Due to the small number of shots and corresponding sparse subsurface illumination, events 'A' and 'B' are weak. Also, due to the low dominant frequency, focussing and resolution of events, in particular the thin layer 'A' at the target level, is poor. In comparison, the migrated VSP data set, even with only 4 shots (Figure 3c) shows improved resolution at the target 'A' due to the higher frequency content, in agreement with the real data example (Figure 2b). Due to the limited recording aperture, the pop-up structure 'C' is only partly imaged, in contrast with the surface seismic result (Figure 3b). When these two sections are summed (keeping the original bandwidth in each dataset), the resulting image (Figure 3d) is superior to that obtained from either data set alone. It shows higher resolution than the surface seismic result since it benefits from the higher frequency content of the VSP data set, and the crest of the pop-up structure 'C' is imaged better than on the VSP migrated section due to the wider aperture obtained with the surface seismic data. If VSP data are recorded at each of the 12 shot locations as recorded for the surface seismic, then the corresponding migrated section (Figure 3e) has improved coherence compared to the section in Figure c, where the number of VSP shots was restricted to 4. Integration of the migrated sections shown in Figures 3b and 3e, where both VSP and surface seismic acquisition consisted of 12 shots, consequently results in the best overall image, shown in Figure 3f.

Conclusions

Multi-offset VSP and surface seismic data has been used to determine the anisotropy parameters and build a robust migration velocity model for the anisotropic prestack depth migration of both data sets. The VSP section tied well with the surface seismic result and showed higher vertical resolution. A new, migration algorithm for integrated VSP and surface seismic depth migration has also been developed and successfully tested on numerical Foothills data. The integrated VSP and surface seismic section yielded a better image than that obtained from the migration of either data set alone, showing enhanced resolution and more structural detail. This methodology is currently being tested on the field data. This integrated approach to imaging VSP and surface seismic data will also yield improved migration velocity analysis and may prove a useful tool for simultaneously acquired VSP and surface seismic data.

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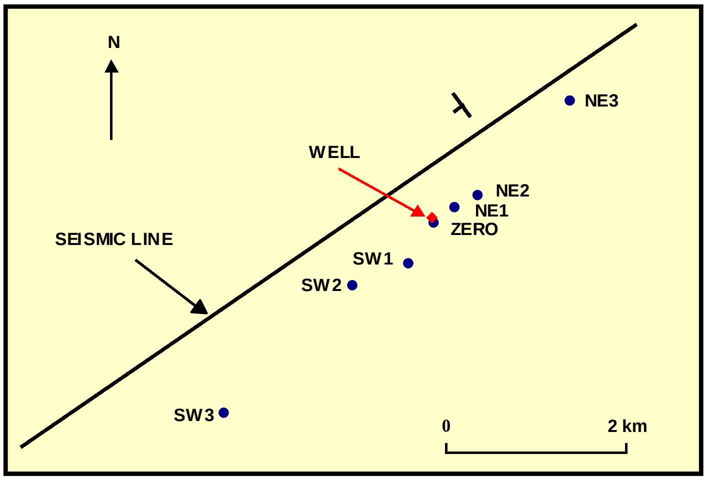

Figure 1. Plan view showing the surface seismic dip line, the VSP well and the shots from the multi-offset VSP. First-arrivals from all the VSP shots were used during traveltime inversion to determine the anisotropy parameters. Only shots SW2, ZERO, NE1 and NE2 were used to obtain the VSP depth migrated image.

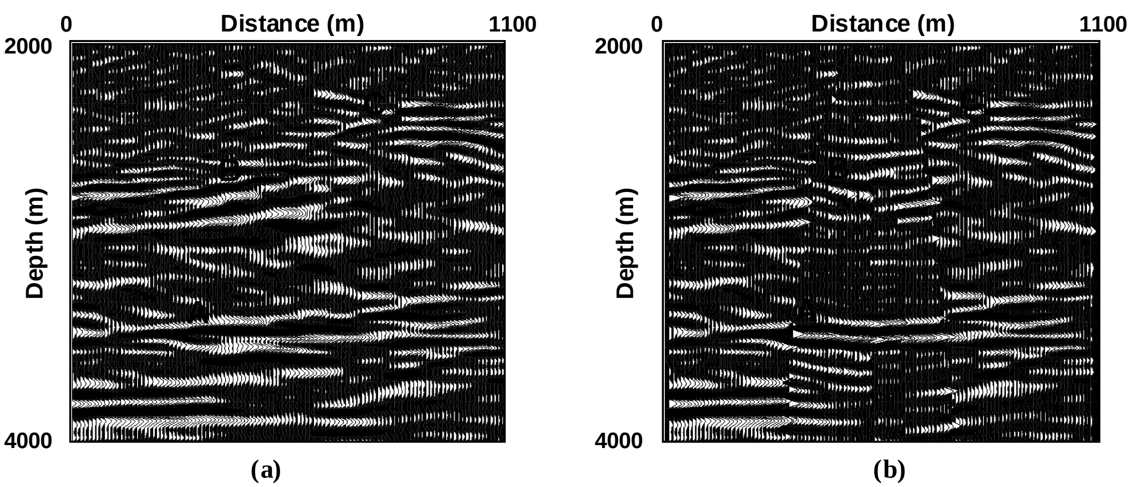

Figure 2. Anisotropic PSDM images of the target area. (a) shows the surface seismic result and (b) shows the VSP result spliced in the surface seismic migrated section shown in (a). Both VSP and surface seismic data were migrated using different migration algorithms, but with the same velocity model and anisotropy parameters. The imaging targets are marked by ‘A’, ‘B’ and ‘C’. Event ‘A’ is a sliver of lower-velocity clastics of the Fernie group surrounded by Paleozoic carbonates. ‘B’ is another Fernie layer sitting on top of the Paleozoic thrust sheet and ‘C’ is interpreted as a pop-up structure within the Upper Paleozoic, again overlain by rocks of the Fernie Group. Note the improved resolution of event A on (b) due to the higher VSP bandwidth. However, the events below A and B that can identified on the surface seismic (a) are not evident on the VSP section (b).

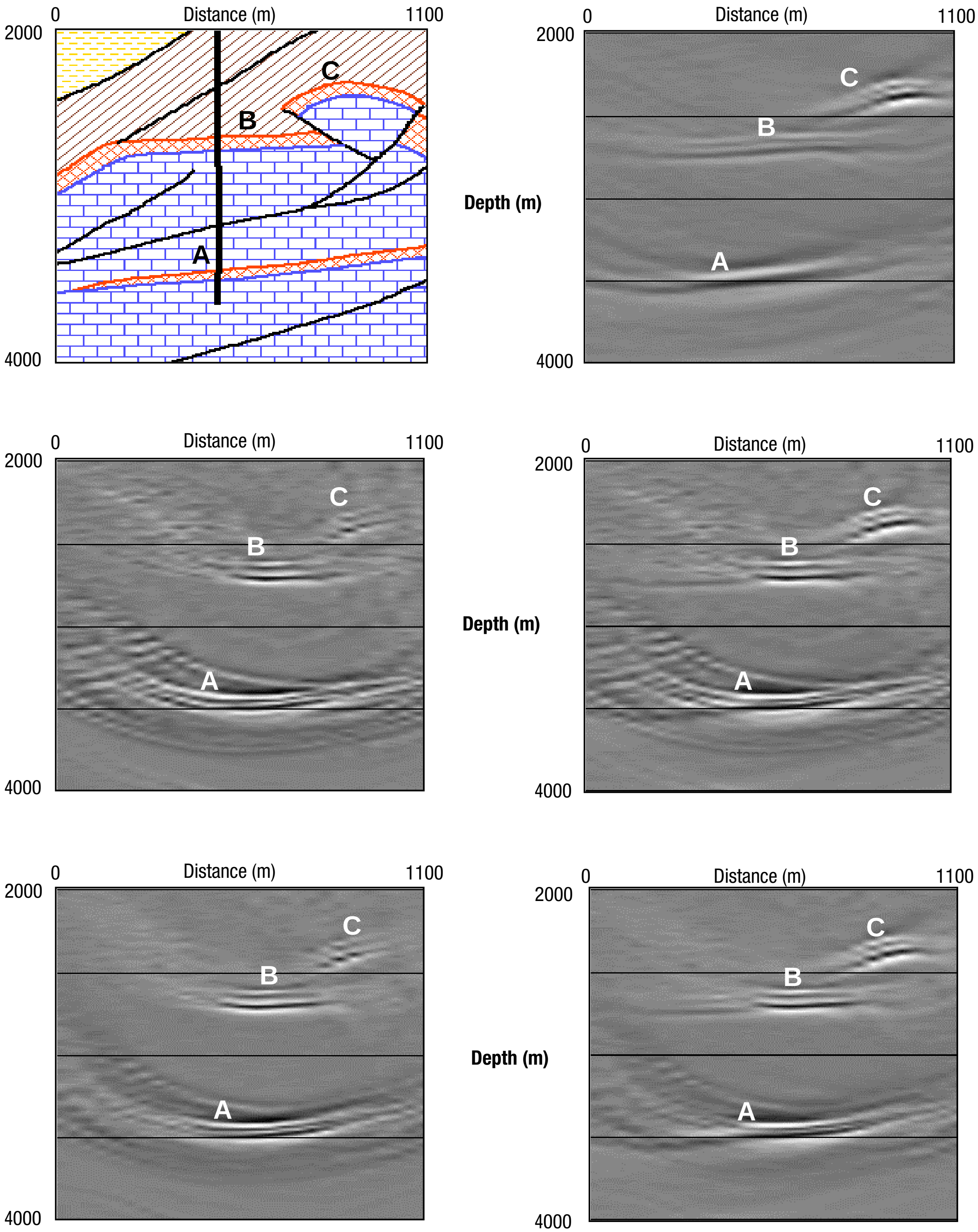

Figure 3. PSDM results for the numerical model data sets. (a) A detailed view of the target area from the structural model, (b) migrated surface seismic section, (c) VSP migrated section - only 4 shots were used in acquisition, (d) integrated VSP and surface seismic image. The higher VSP bandwidth resulted in better resolution of events ‘A’ and ‘B’. Note also how the pop-up structure is now well imaged when compared to (c) due to the contribution from the surface seismic. (e) VSP migrated section – all 12 shots used for surface seismic acquisition were also used to acquire the VSP, (f) integrated VSP and surface seismic section from all 12 shots. This image is superior to that shown in (d), since the increased number of shots for the VSP led to better event coherency and improved focussing, implying that better images should be obtained if VSP and surface seismic data were acquired simultaneously.