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Migration of surface-related multiples: tests on the Sigsbee2B dataset

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ABSTRACT

We present a theory to generate pseudo-primary shot gathers from multiple and primary reflections by performing a surface-consistent cross-correlation. The estimated pseudo-primaries exhibit the same kinematics as the original dataset with few transformation artifacts. We demonstrate that pseudo-primaries can accurately estimate missing traces as long as the gaps are within the acquisition spread. Pseudo-primaries can also help to extrapolate the data outside the acquisition spread. The image obtained by migrating the pseudo-primary gathers shows that multiple migration can provide valuable information under complex geology.

INTRODUCTION

When only primary reflections are considered for imaging, multiple reflections are usually attenuated as a preprocessing step (Verschuur et al., 1992; Weglein et al., 1997; Guitton, 2003; Sava and Guitton, 2003). However, multiples contain subsurface reflectivity information, and can be treated as signal. For instance, Brown (2004) shows how a joint inversion of both primaries and multiples can provide more knowledge of the earth's properties.

Multiples can be imaged by Kirchhoff (Reiter et al., 1991) or crosscorrelogram migration (Sheng, 2001), by transforming the traveltimes of multiple reflections to those of primary reflections. Multiples can be also imaged by shot-profile migration, considering the primary reflections as areal shot records and the multiple reflections as receiver wavefields (Berkhout and Verschuur, 1994; Guitton, 2002). Instead of being transformed into primaries implicitly, multiples also can be explicitly mapped into primaries by cross-correlation (Shan, 2003; Berkhout and Verschuur, 2003) or deconvolution (Shan, 2003). We call "pseudo-primary" any events resulting from the cross-correlation of multiples with the original dataset (primaries+multiples). The pseudo-primaries are similar to the original data and can be imaged by source-receiver migration (Shan, 2003).

In this paper, we estimate pseudo-primary shot gathers by cross-correlating primary and multiple reflections. These pseudo-primary shot gathers are then migrated with shot-profile migration. The images obtained from the pseudo-primaries are then compared to images of the primaries alone.

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We applied our method to the Sigsbee2B synthetic dataset. This dataset is challenging because of the complex geometry of the salt body (Figure 1). Two versions of the Sigsbee2B dataset were generated: one with surface-related multiples (FS) and one without (NFS). The multiples are known and can be obtained by subtracting the two datasets (i.e. FS-NFS). But with field data, surface-related multiples need to be separated prior to the migration using the method of Verschuur et al. (1992). From this dataset, we show that multiples can (1) fill acquisition holes, (2) extrapolate data beyond the acquisition spread, and (3) provide an image of the subsurface under complex geology.

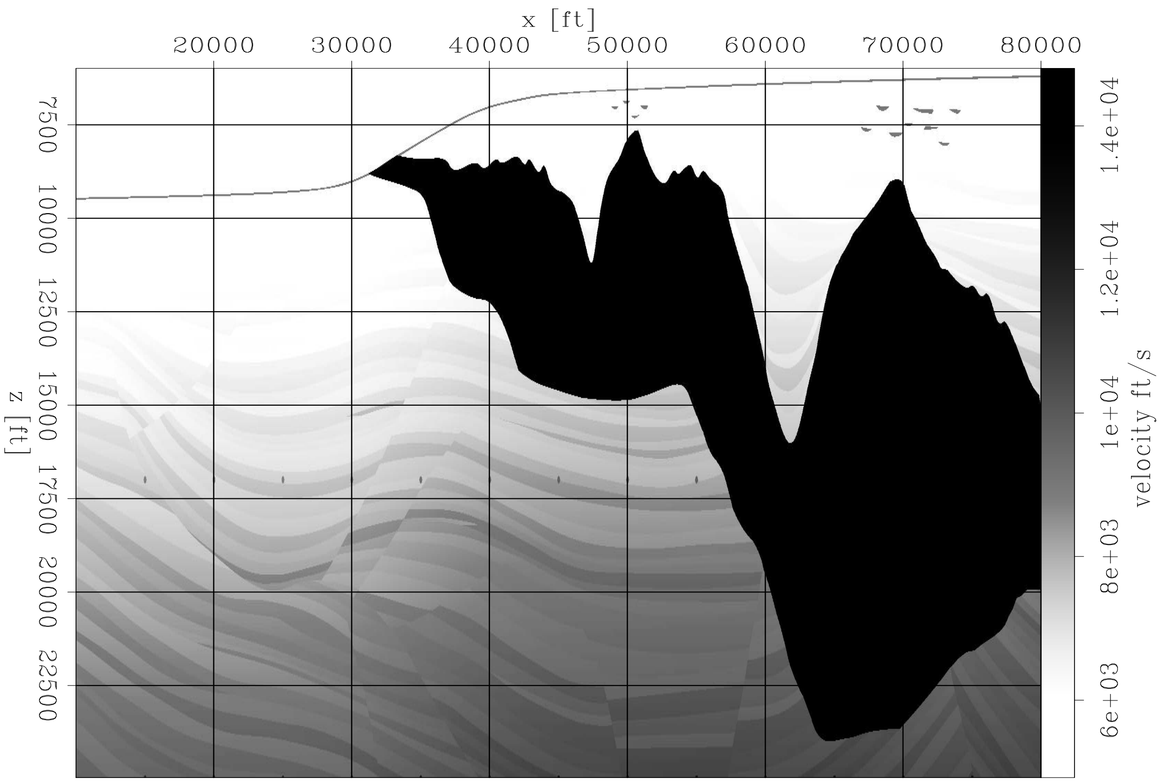

Figure 1: Stratigraphic interval velocity model of the Sigsbee2B dataset guojian2-stratigraphy [CR]

PSEUDO-PRIMARY FROM MULTIPLES

We can generate pseudo-primary shot gathers W by computing:

$$W(x_p, x_m, \omega) = \sum_{x_s} M(x_s, x_m, \omega)\bar{P}(x_s, x_p, \omega), \quad (1)$$

where ω is the frequency, x_s is the shot location, $\bar{P}(x_s, x_p, \omega)$ is the complex conjugate of the original trace recorded at the surface location x_p, and $M(x_s, x_m, \omega)$ is the multiple reflection data recorded at the surface location x_m. In equation (1), note that first-order multiples in M

are transformed into primaries (cross-correlation with primaries in P) and zero-lag components (cross-correlation with first-order multiples in P) in the pseudo-primaries W. Similarly, second-order multiples in M are transformed into primaries (cross-correlation with first-order multiple in P), first-order multiples (cross-correlation with the primaries in P) and zero-lag components (cross-correlation with second-order multiples in P) in the pseudo-primaries W, and so on.

In contrast to primaries in the original dataset, pseudo-primaries can illuminate different areas at different angles. They contain subsurface information that primaries do not. Because of recording geometries, it is often difficult to obtain near-offset data, as well as far-offset data. Pseudo-primaries created from multiples can help fill these acquisition holes.

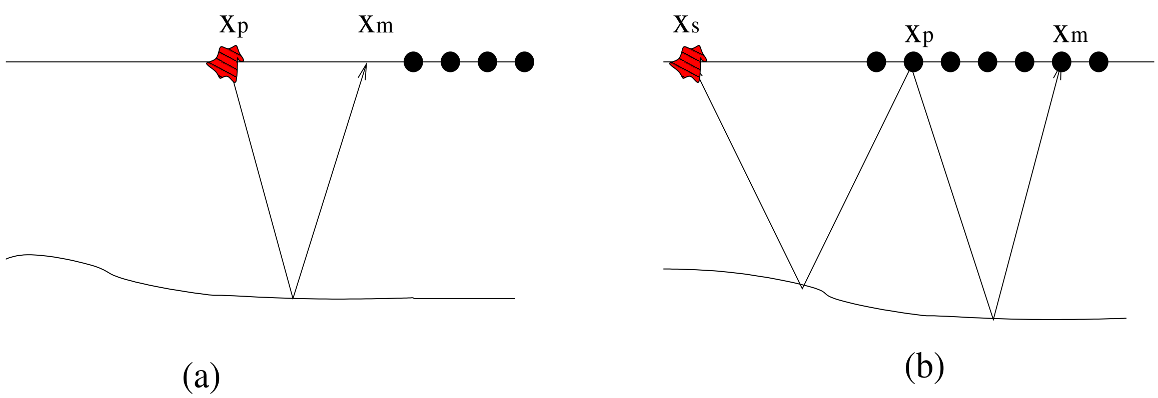

Figure 2: Near-offset recovery example : In (a), no trace is recorded at x_m for the shot at x_p. In (b), a primary reflection is recorded at x_p and a multiple reflection is recorded at x_m for the shot at x_s. With the pseudo-primaries, we recover the trace with a source at x_p and receiver at x_m. guojian2-nearoffset [NR]

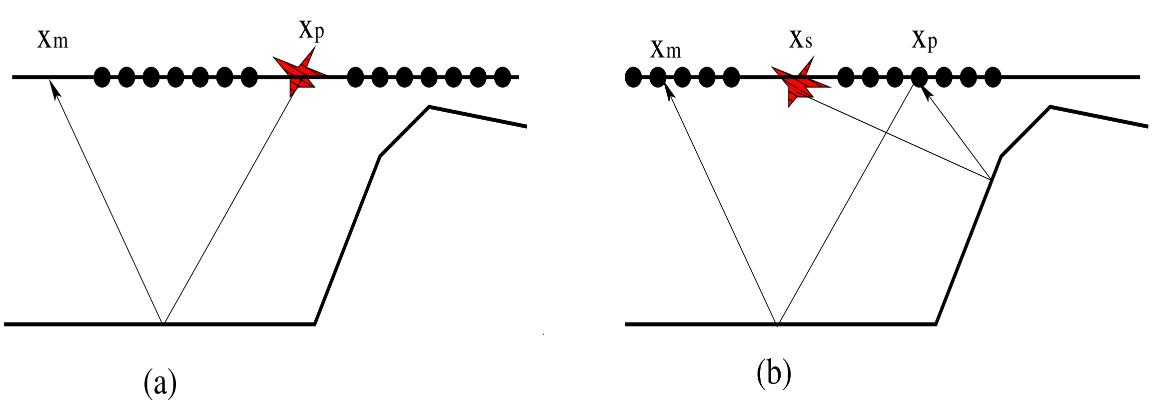

Figure 3: Far-offset recovery example: In (a), no trace is recorded at x_m, since it is outside the acquisition spread for the shot at x_p. In (b), both x_p and x_m are within the acquisition spread for the shot at x_s. A primary reflection is recorded at x_p and a multiple reflection is recorded at x_m. With the pseudo-primaries, we recover the trace with a source at x_p and receiver at x_m. guojian2-faroffset [NR]

Figure 2 illustrates how missing near-offset traces are recovered in the pseudo-primary dataset. In Figure 2a, near offsets are missing when the source is at x_p. In Figure 2b, the primary reflection is recorded at x_p and the multiple reflection is recorded at x_m for the shot at x_s. By cross-correlating the traces at x_p and x_m in Figure 2b, we obtain the pseudo-primary trace, whose shot and receiver locations are x_p and x_m, respectively. So the near-offset missing trace is recovered in the pseudo-primaries.

Figure 3 illustrates how missing far-offsets are recovered by the pseudo-primary dataset in some special cases. Using reciprocity, we can obtain the negative-offset data by mirroring sources and receivers. In Figure 3a, the primary reflection with a source at x_p and receiver at x_m is outside the acquisition spread. In Figure 3b, a primary reflection is recorded at x_p and a multiple reflection is recorded at x_m for the shot at x_s. Both x_p and x_m are within the acquisition spread. By cross-correlating the traces at x_p and x_m in Figure 3b, we obtain a trace of the pseudo-primaries, whose shot and receiver locations are x_p and x_m, respectively. So the far-offset missing trace is recovered with pseudo-primaries. Note that to recover the far-offset trace, as is illustrated in Figure 3, we need a steeply dipping reflector.

We now illustrate our technique on the Sigsbee2B dataset. Figure 4 shows four shot gathers with a source at $50,000$ ft: (a) the original dataset (primaries + multiples) with near and far offsets removed, (b) the surface-related multiples with near and far offsets removed, (c) the original dataset (primaries + multiples) with full offsets, and (d) the pseudo-primary dataset.

We mirrored the sources and receivers to get negative offsets. To demonstrate that pseudo-primaries can interpolate data inside the acquisition holes, we removed the offsets that are less than $2,000$ ft and greater than $20,000$ ft from the original dataset and the surface-related multiples, which are illustrated in Figure 4a and 4b. Figure 4d shows the pseudo-primary shot gather obtained by cross-correlating the original dataset with the multiple dataset without near and far offsets. Comparing the original shot gather in Figure 4c (no mute) with the pseudo-primary shot gather in Figure 4d, we conclude that the pseudo-primary shot gather is very similar to the original shot gather. Note that some artifacts and noisy events appear in the pseudo-primary gather. The noise arises during the cross-correlation of unpaired events at different surface locations. It might be better handled by the method of Berkhout and Verschuur (2003). The near-offset data are recovered very well in the pseudo-primary gather. For far offsets, notice that the event in the oval of Figure 4c, which is removed in Figure 4a, is recovered in Figure 4d. We think that this far-offset event is recovered in the pseudo-primary gather due to the presence of two large canyons with steeply dipping walls on the salt body (Figure 1), similar to the structure illustrated in Figure 3. Note that more shots would help to recover more events at far offsets in Figure 4d.

Figure 5 compares the original zero-offset dataset with the pseudo-primary zero-offset dataset. Same as Figure 4, the pseudo-primary dataset is generated by cross-correlating the original dataset with the multiple dataset without near and far offsets. These two zero-offset datasets have similar structures.

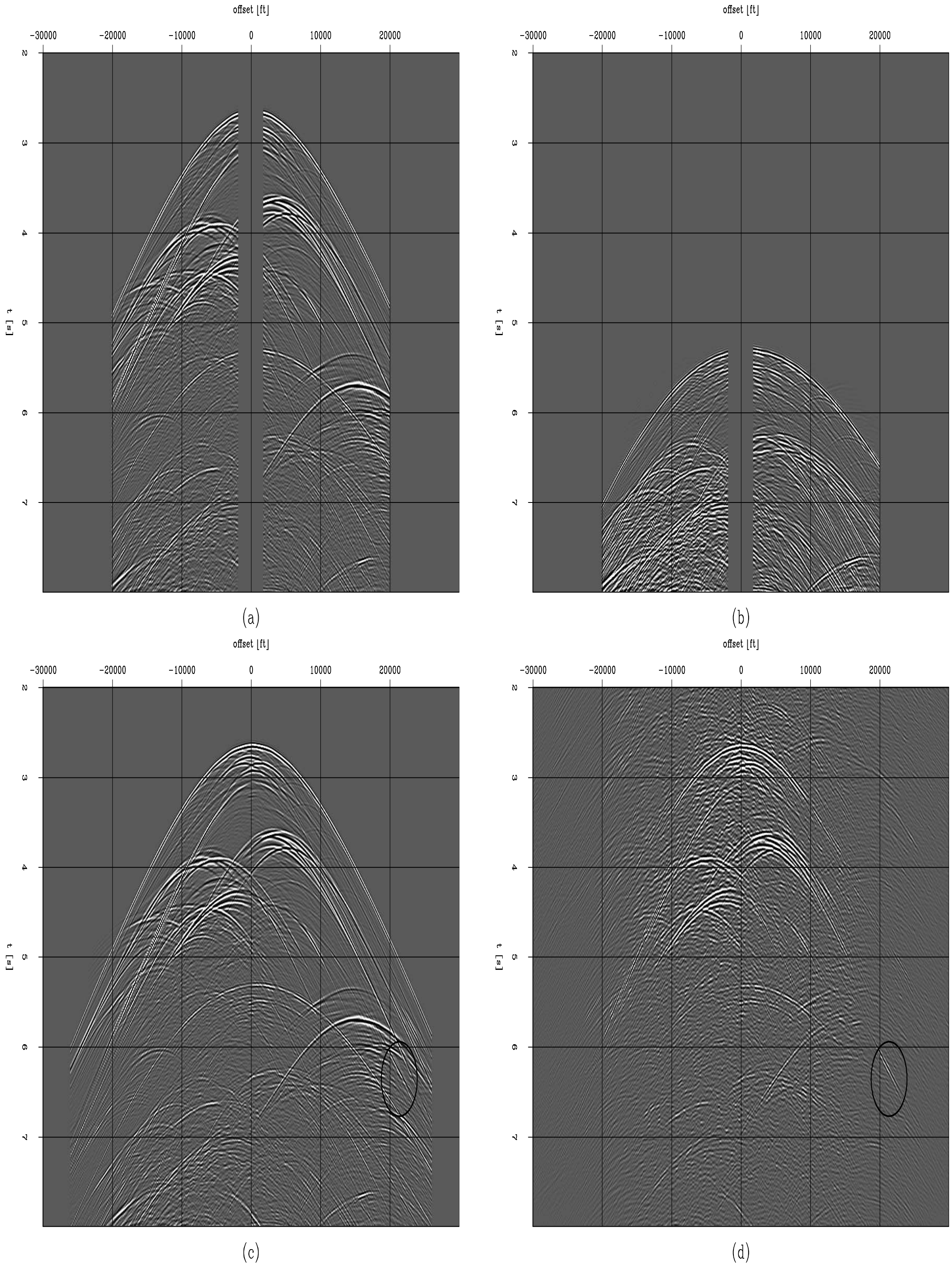

Figure 4: Comparison of shot gathers at 50,000 ft for (a) the original dataset (primaries + multiples) with near and far offsets removed, (b) surface-related multiples with near and far offsets removed, (c) the original dataset (primaries + multiples) with full offsets, and (d) the pseudo-primary, generated by cross-correlating the original dataset with the multiple dataset without near and far offsets. guojian2-shotgather [CR]

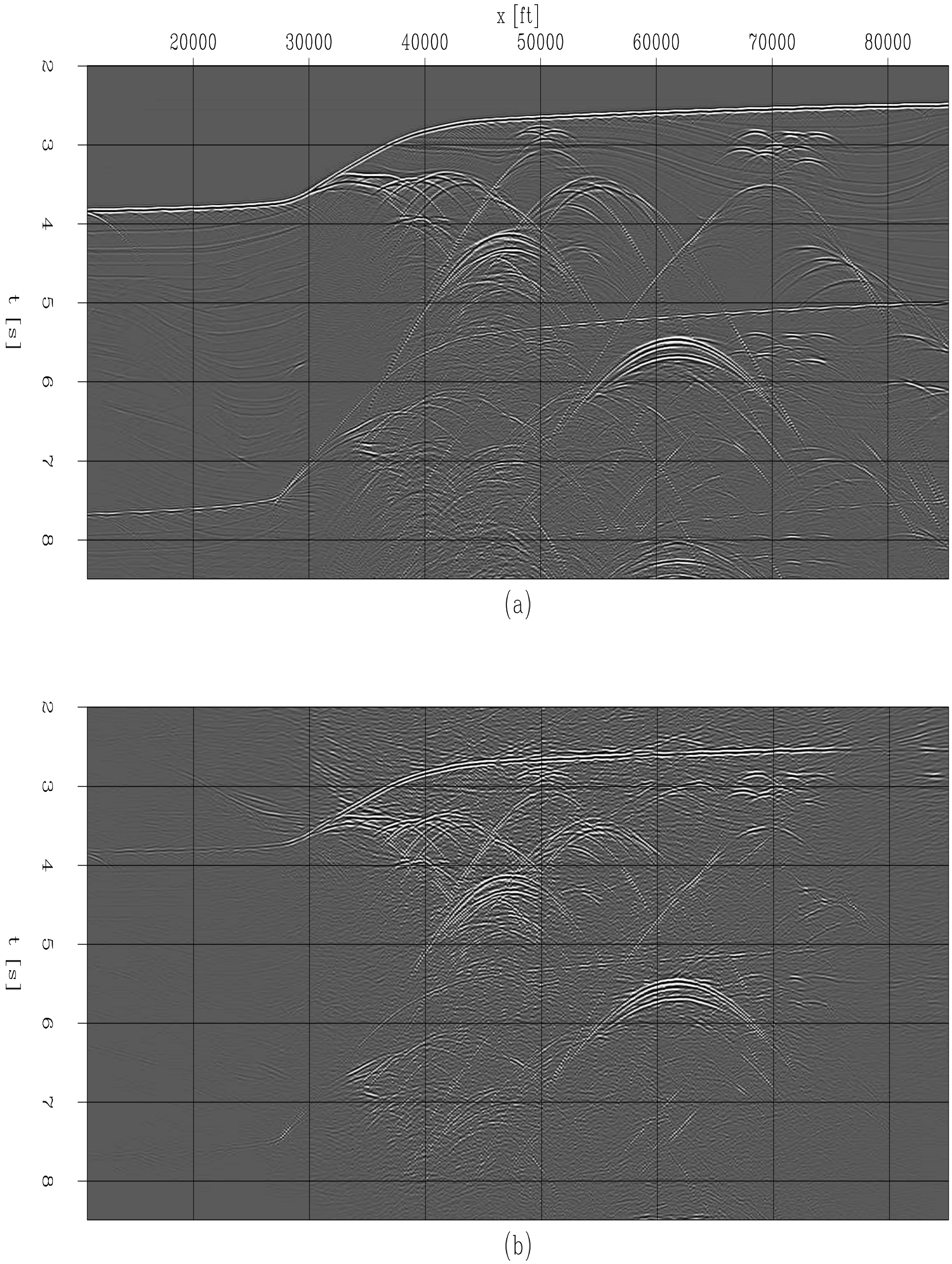

Figure 5: Comparison of zero-offset datasets for (a) the original data (primaries+multiples) and (b) the pseudo-primary, generated by cross-correlating the original dataset with the multiple dataset without near and far offsets. guojian2-zerooffset [CR]

MIGRATION OF THE PSEUDO-PRIMARY DATASET

As illustrated in Figure 4, shot gathers of the pseudo-primaries are similar to those of the original dataset. We now migrate the pseudo-primary dataset by shot-profile, downward-continuation migration. We use Fourier finite difference (Ristow and Ruhl, 1994) as our wavefield extrapolation operator for the migration. Figure 6 compares the image from the primary-only dataset (NFS), the image from the original dataset (FS), and the image from the pseudo-primaries, which consists of primaries (from first-order multiples) and multiples (from higher-order multiples). Figure 6a shows the migration result of primaries, Figure 6b shows the migration result of the original dataset and Figure 6c shows the migration result of pseudo-primaries. The pseudo-primary image is noisier than the images from the primaries only and the original dataset. This is caused by the noise from the cross-correlation and first-order multiples in the pseudo-primary gathers. In the image obtained by migrating the pseudo-primaries (Figure 6c), the salt body is clearly imaged, and reflectors below the salt are also well imaged. However the reflectors below $20,000$ ft are contaminated by first-order multiples in the pseudo-primaries, which are similar to those in the original-dataset image (Figure 6b).

CONCLUSIONS

In this paper, we show how multiples can be transformed into primaries (i.e., pseudo-primaries) by being cross-correlated with the original dataset (primaries+multiples). Pseudo-primaries can recover missing near-offset data as well as some far-offset events that are not recorded. The comparison between images from the primary dataset and from the pseudo-primary dataset on the Sigsbee2B model demonstrates that multiple migration can be used to image complex geological structures.

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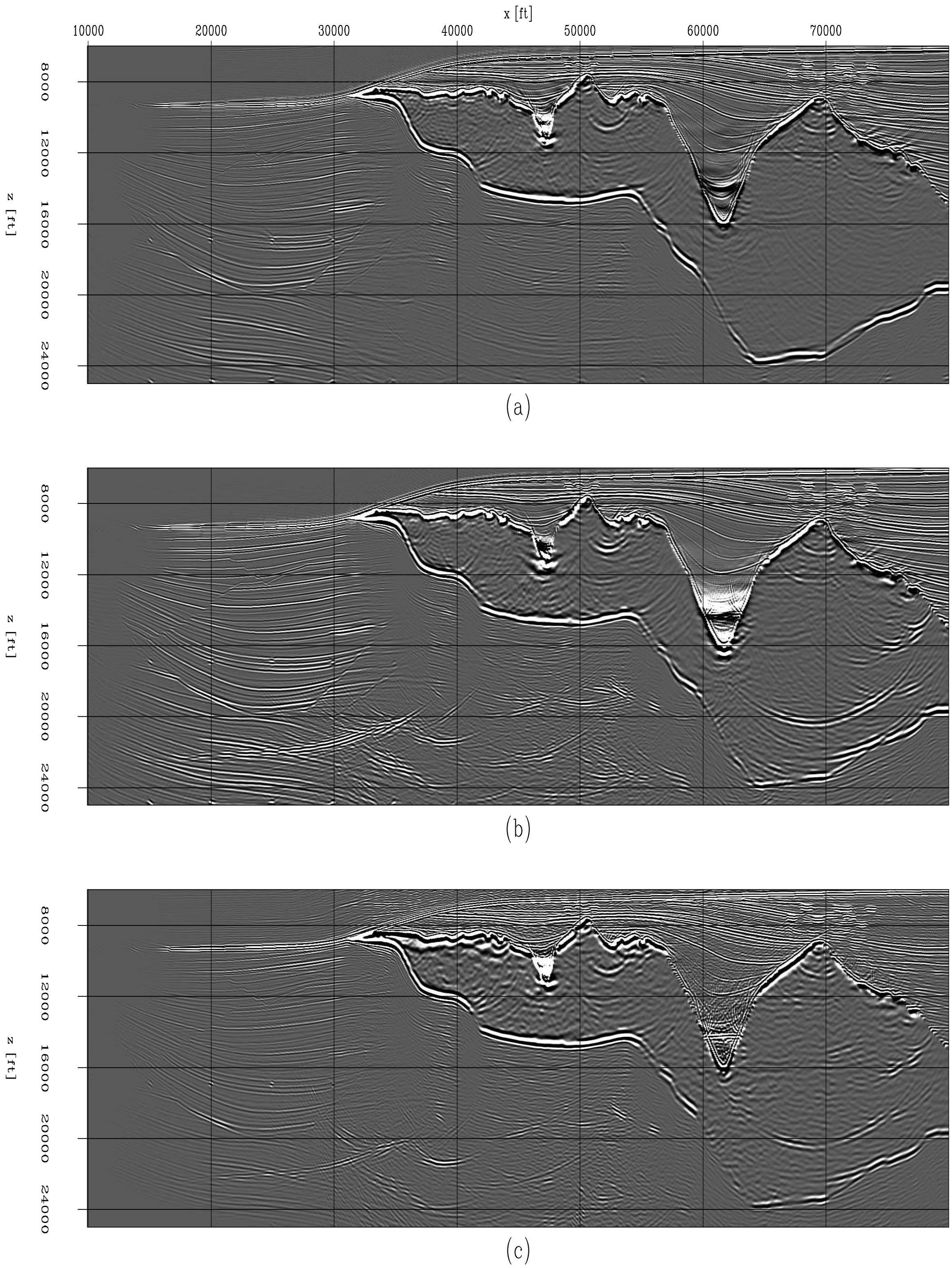

Figure 6: Comparison of migration results for (a) the primaries only, (b) the original dataset (primaries+multiples) and (c) the pseudo-primary dataset. guojian2-image [CR]

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