Seismic reservoir monitoring with encoded permanent seismic arrays

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ABSTRACT

Hydrocarbon reservoirs can be efficiently monitored with encoded data recorded by permanent seismic arrays. Permanent seismic sources and receivers can yield a vast amount of data that may enable near–real-time monitoring. I propose an encoding approach that may overcome some of the operational, storage and processing challenges posed by these vast data volumes. Although data encoding introduces cross-talk artifacts, permanent arrays allow for good repeatability of such artifacts, thereby aiding time-lapse seismic cross-equalization. Because the proposed method utilize low-energy intermittent seismic sweeps, data must be recorded for longer durations compared to conventional data recording. Direct migration of these long-duration data is efficient and gives good-quality time-lapse images. Using a 2D numerical model, I show that this method can produce reliable time-lapse images of comparable quality to those from conventional seismic sources.

INTRODUCTION

Time-lapse seismic reservoir monitoring is an established technology. By repeating the seismic experiment over an evolving reservoir, changes in reservoir properties can be estimated from seismic amplitude and travel-time changes. Many successful case studies demonstrate the technical considerations and business impact of time-lapse seismic (Rickett and Lumley, 2001; Whitcombe et al., 2004; Ebaid et al., 2009).

By enabling seismic recordings at small time intervals, permanent seismic arrays can make near–real-time reservoir monitoring possible. Lumley (2001, 2004) discusses important business and technical drivers for permanent seismic arrays. Several field experiments have been published (Meunier et al., 2001; Smit et al., 2005; Forgues et al., 2006). Because permanent arrays do not suffer from positioning errors, seismic experiments can be repeated with high accuracy. However, in addition to the high operation and storage costs of the recorded data volumes, conventional processing cost of the recorded data can be high. Although, under certain conditions, simple (e.g. NMO) processing can give satisfactory results (Forgues et al., 2006), such methods are inadequate in many geological environments. In this paper, I show that direct wave-equation migration of encoded data sets from such permanent recording systems can provide high-quality time-lapse images at relatively low cost.

Encoded seismic data recording with permanent seismic arrays straddles conventional and passive data recording. Although our understanding of passive data imaging has improved over the past decade, several limitations still exist. Direct imaging of passive data suffers several pitfalls (Artman, 2006), and interferometric Green's function retrieval is computationally expensive (de Ridder, 2009). In many scenarios, seismic reservoir monitoring with interferometric Green's function from surface passive seismic arrays is difficult (Lu et al., 2009). However, reservoir monitoring with active (virtual) source and ambient-noise interferometric Green's functions have been shown for borehole sensors (Bakulin and Calvert, 2004; Lu et al., 2009). Furthermore, it has been demonstrated that interferometric Green's functions from borehole systems may give satisfactory time-lapse responses in the well vicinity (Bakulin and Calvert, 2004; Lu et al., 2009). The proposed recording approach may overcome some of the current limitations in reservoir monitoring with pure passive data or well-bore virtual source methods.

Although encoded seismic recording is not new (Womack et al., 1990), recent advances in acquisition and processing technology have increased interest in the subject (Hampson et al., 2008; Beasley, 2008; Berkhout et al., 2008; Howe et al., 2009). Direct imaging of such encoded data is possible but suffers from *cross-talk* between data sets from different shots (Romero et al., 2000; Artman, 2006). To directly image field-encoded time-lapse data sets from non-permanent seismic arrays, a linearized inversion method can be used to attenuate artifacts caused by non-repeatable geometry and relative shot delays (Ayeni et al., 2009). Because permanent seismic arrays enable excellent repeatability of the geometry and encoding function, cross-term artifacts are similar between consecutive surveys, and linearized inversion is unnecessary.

To ensure good repeatability over the monitoring period, to limit operational cost, and to limit environmental impact, low-energy, low-footprint seismic sources are desirable. Each source waveform may be a long-duration sweep (Forgues et al., 2006), or intermittent sweeps from an idealized source. By stacking data from several low-energy sources, the signal-to-noise (S/N) ratio is increased and sufficiently high-quality data and images can be obtained. Encoding is important, because it reduces the total recording time for several shots, each requiring a long recording duration. In this paper, it is assumed that these conceptual low-energy sources are randomly and intermittently ignited over a long time period.

Using a phase-encoding migration operator and the relative time-delays between sources, the encoded data are migrated without any separation or interferometric Green's function retrieval. Because all the data are migrated with a baseline velocity model, images from different vintages are not aligned and must be cross-equalized. In this paper, the data are cross-equalized using a cyclic 1D correlation algorithm and an optimized local-matching method (Ayeni, 2010).

First, we give a conceptual description of the proposed data recording and imaging methods. Next, we summarize the cross-equalization methodology that is applied. Finally, using five data sets from a 2D numerical model, we show that the proposed method gives good-quality time-lapse images.

DATA RECORDING AND IMAGING

From the linearized Born approximation of the acoustic wave equation, the seismic data d recorded by a receiver at $\mathbf{x_r}$ due to a shot at $\mathbf{x_s}$ is given by

$$d(\mathbf{x_s}, \mathbf{x_r}, \omega) = \omega^2 \sum_{\mathbf{x}} f_{\mathbf{s}}(\omega) G(\mathbf{x_s}, \mathbf{x}, \omega) G(\mathbf{x}, \mathbf{x_r}, \omega) m(\mathbf{x}), \tag{1}$$

where ω is frequency, $m(\mathbf{x})$ is the *reflectivity* at image points $\mathbf{x}$, $f_s(\omega)$ is the source wavelet, and $G(\mathbf{x_s}, \mathbf{x}, \omega)$ and $G(\mathbf{x}, \mathbf{x_r}, \omega)$ are the Green's functions from $\mathbf{x_s}$ to $\mathbf{x}$ and from $\mathbf{x}$ to $\mathbf{x_r}$, respectively. When there are multiple seismic sources, the recorded seismic data is due to a concatenation of phase-shifted sources. For example, the recorded data due to shots starting from $\mathbf{s} = \mathbf{q}$ to $\mathbf{s} = \mathbf{p}$, is given by

$$d(\mathbf{x_{s_{pq}}}, \mathbf{x_r}, \omega) = \sum_{s=p}^{q} a(\gamma_{\mathbf{s}}) \omega^2 \sum_{\mathbf{x}} f_{\mathbf{s}}(\omega) G(\mathbf{x_s}, \mathbf{x}, \omega) G(\mathbf{x}, \mathbf{x_r}, \omega) m(\mathbf{x}), \tag{2}$$

where $a(\gamma_{\mathbf{s}})$ is given by

$$a(\gamma_{\mathbf{s}}) = e^{i\gamma_{\mathbf{s}}} = e^{i\omega t_{\mathbf{s}}}, \tag{3}$$

and γ_s, the phase-shift function, depends on the delay time t_s.

Randomized intermittent shooting of several shots is equivalent to repetition of equation 2 with a spatially and temporally varying encoding function. The recorded data are similar to passive data, except that all shot positions and timings are known. Therefore, the recording experiment can be regarded as a controlled-source continuous-recording experiment. Figures 1 and 2 show examples of idealized source waveforms at six shot positions. It is assumed that these sources are orders of magnitude weaker than conventional seismic sources and that data from a single sweep is insufficient to create a good-quality image.

Direct imaging of the recorded data, the adjoint to equation 2, is a linear phase-encoding migration operator (Romero et al., 2000). This is equivalent to a single shot-profile migration of the recorded data with an areal source-function derived by concatenating delayed source waveforms from all shot positions.

CROSS-EQUALIZATION

Cross-equalization processing removes unwanted differences between the imaged data sets. Such differences may be caused by uncorrelated noise or geomechanical changes. The post-imaging procedure can be divided into two steps. First, because direct velocity analysis with the recorded data is difficult, we assume that a baseline velocity model built from conventional seismic data will be used to image all data sets. This leads to image misalignment due to reservoir compaction and velocity changes between surveys. To align the monitor and baseline images, a cyclic 1D correlation method is used to estimate vertical and horizontal displacement components (Hale,

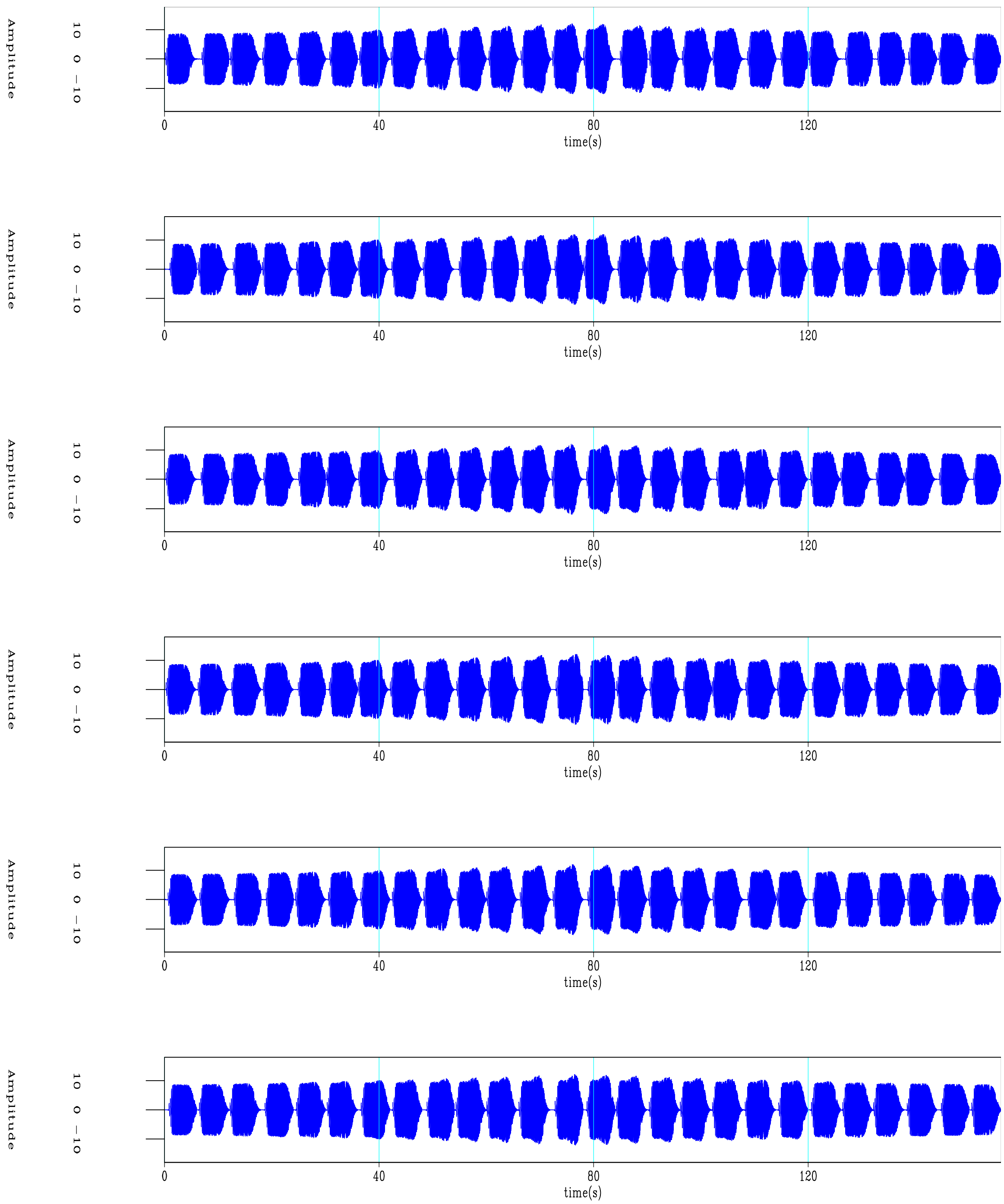

Figure 1: First 150 seconds of the 320 seconds long source waveforms at six source positions. Note that the relative delays between intermittent sweeps from different sources are determined by the encoding function in equation 3. [**ER**]

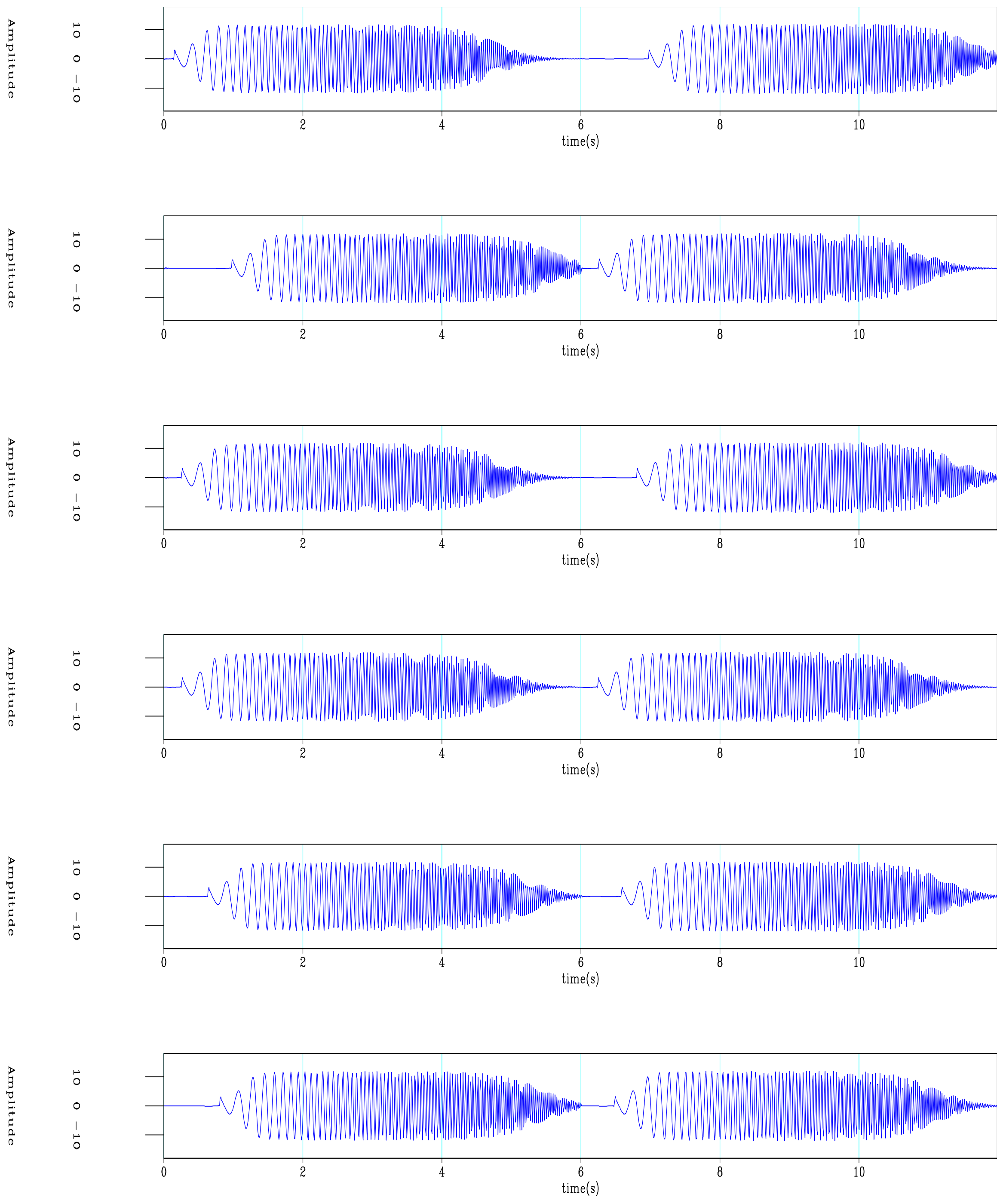

Figure 2: First 12 seconds of the source waveforms shown in Figure 1. Note that there are temporal and spatial differences in the starting times of the seismic sweep at all shot positions. [**ER**]

2009). The aligned images are then matched using an optimized matching procedure. Match filters estimated in non-reservoir regions are applied to the monitor data on a trace-by-trace basis. These cross-equalization steps are discussed in detail by Ayeni (2010).

NUMERICAL EXAMPLE

Five data sets were modeled over a modified section of the 2D Marmousi model (Figure 3). The objective is to image seismic amplitude and geomechanical changes around the reservoir using encoded data sets from permanent arrays. Non-linear, discontinuous changes in the reservoir were modeled by velocity changes within the reservoir. Geomechanical changes due to reservoir compaction were modeled by a morphed expanding gaussian anomaly above the reservoir.

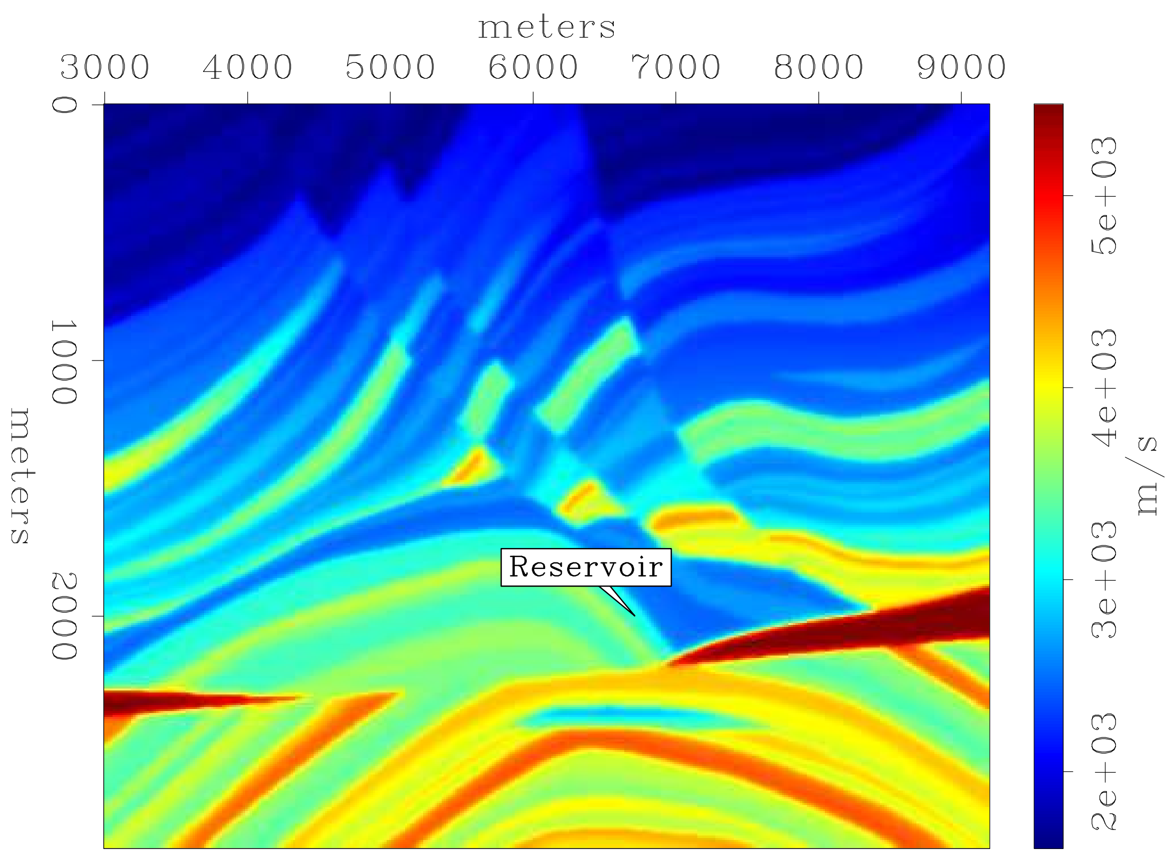

Figure 3: 2D Marmousi velocity model. [**ER**]

Each surface seismic source generates an intermittent sweep within a six-second window with unique random zero- to three-second delays between sources. 320 seconds of data from 388 seismic sources were recorded by surface receivers (Figure 4). Although it was not essential, because this method allows for perfect repeatability, the same encoding function was used for all surveys. However, different amounts of ambient noise (coherent plane-wave and uniform-distribution random noise) were introduced for each survey to produce data at S/N of 4:1. For each survey, using a strongly smoothed version of the baseline modeling velocity, all data were imaged directly with a phase-encoding one-way wave equation algorithm. For comparison, images from noise-free conventional data and processing are shown in Figure 5, those from only 6 seconds of data are shown in Figure 6, and those from the full 320 seconds of data are shown in Figure 7. Note that the longer data records (Figure 7) produce cleaner images than the shorter data records (Figure 6). Note that in the encoded data examples, only a single phase encoded shot-profile migration was required for each survey.

Time-lapse images computed from the migrated images show significant misalignments (Figure 8). Results obtained after alignment and after match filtering are shown in Figures 9 and 10. Note that time-lapse images obtained after matching are comparable to those obtained from the conventional example (Figure 11). In addition, note that apparent displacements—which carry geomechanical information—estimated from the proposed method (Figure 12) and from conventional methods (Figure 13) are similar.

DISCUSSION

Data from permanent encoded low-energy seismic sources have the form of passive data recording (Figure 4). However, because the shot locations and timings are known and can be perfectly repeated, a strong limitation of passive data is eliminated. Furthermore, because the seismic array is permanent, data recording can be repeated perfectly. If these data sets are recorded for long enough, direct imaging of these randomly encoded data can give images of comparable quality to conventional data recording and processing (Figures 5 to 7). The poor resolution of these images in Figure 7 is due to the fact that these data were imaged with the original seismic sweeps without any source designature. These results and it's derivatives can be imporved significantly by first deconvolving the source wavelet before migration. Even then, during imaging wavefield correlations, ambient noise and cross-talk artifacts from different seismic sweeps destructively interfere, whereas the true reflections constructively interfere. Whereas, the images from the short-duration data (Figure 6) are not clean enough to generate reliable time-lapse images, those from the long-duration data (Figure 7) are clean enough to generate interpretable time-lapse images.

It is important that the time-lapse images obtained from this type of recording can provide information similar to that provided by conventional recordings. The time-lapse images computed prior to cross-equalization (Figure 8) are similar to those from conventional data recording and processing (not shown). After cross-equalization, time-lapse images from the proposed method and from conventional methods are similar (Figures 10 and 11). Even when all the data recorded using the proposed method are imaged with a strongly smoothed baseline velocity model, interpretable geomechanical information can still be obtained (Figure 12). These apparent dis-

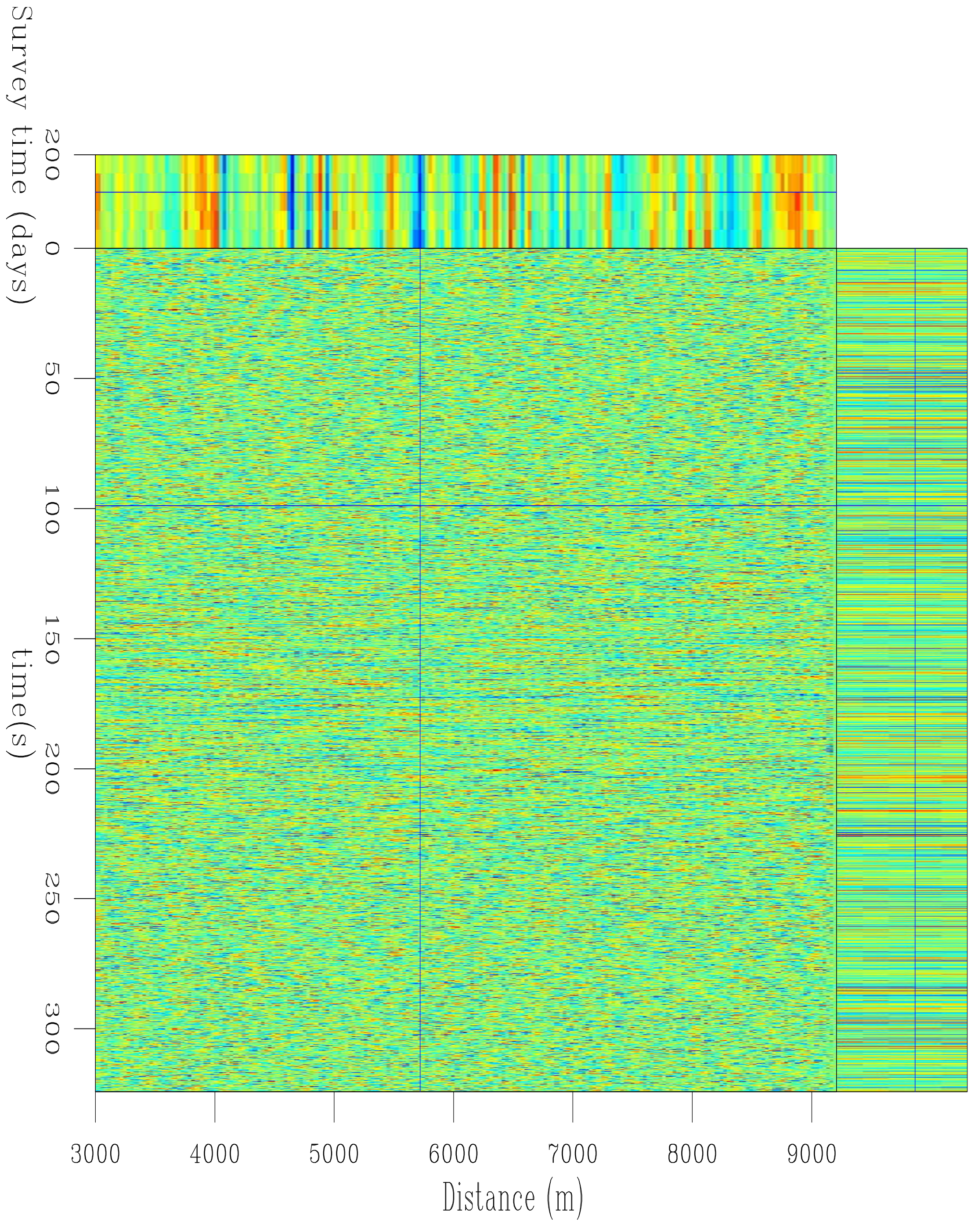

Figure 4: Five seismic data sets from intermittent seismic sweeps over the model in Figure 3. The intersecting lines indicate positions of the three panels within the data volume. [**CR**]

placement components are similar to those from conventional time-lapse seismic data (Figure 13).

With this approach, there can be significant cost-savings in both data acquisition and processing. Encoding eliminates the need for long waiting periods that would be otherwise required for low-energy seismic sources that require data stacking. In addition, encoding reduces the data storage requirements. Furthermore, independent of the number of encoded sources, direct imaging can be posed as a single phase-encoding shot-profile migration.

CONCLUSIONS

A method for reservoir monitoring with encoded data from permanent seismic arrays has been proposed. Encoding randomly delayed intermittent sweeps from low-energy sources reduces the total recording time for each seismic experiment. Direct imaging of such data give good-quality images that can be used for near-continuous reservoir monitoring. The numerical experiment shows that seismic amplitude and geomechanical changes from the proposed method are similar to those from conventional seismic data.

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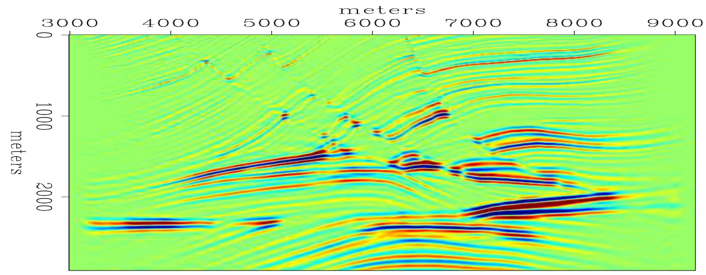

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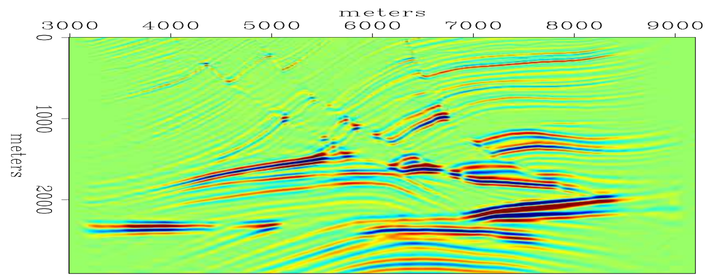

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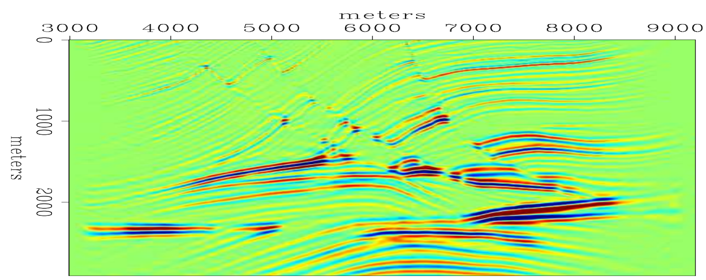

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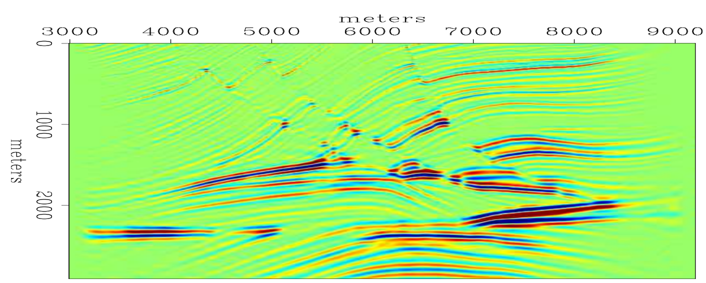

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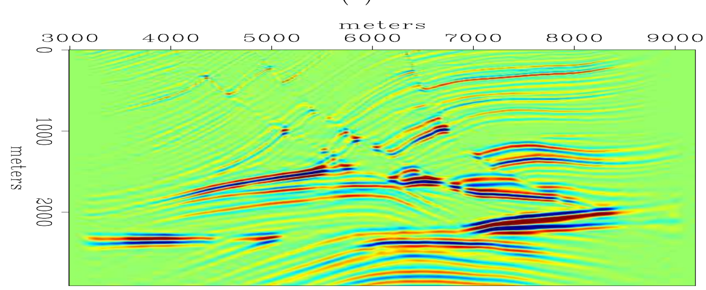

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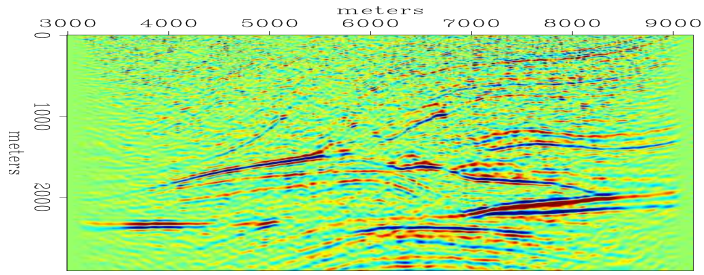
Figure 5: Images from shot-profile imaging of noise-free conventional data over five models modified from Figure 3. [**CR**]



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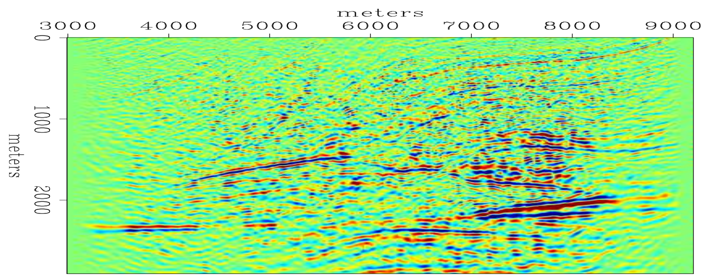

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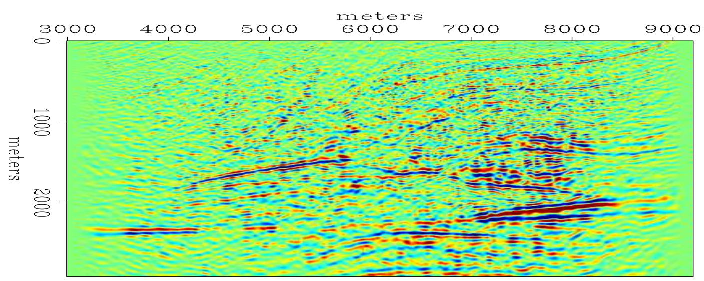

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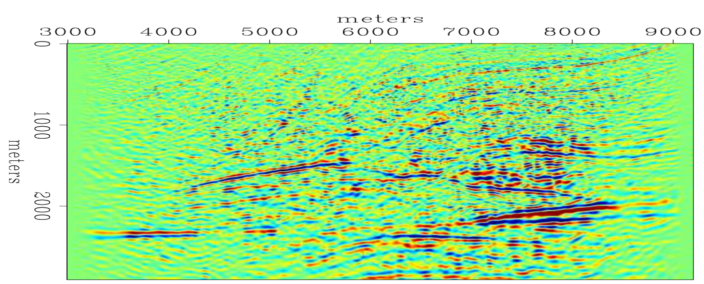

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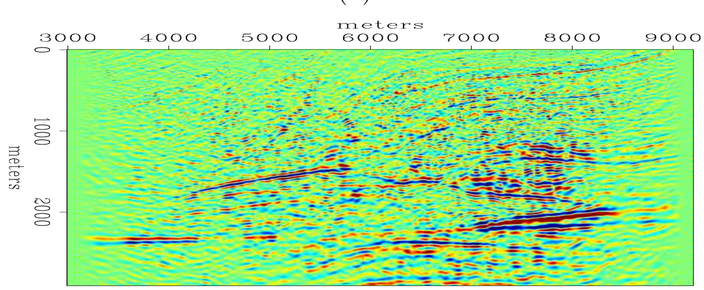

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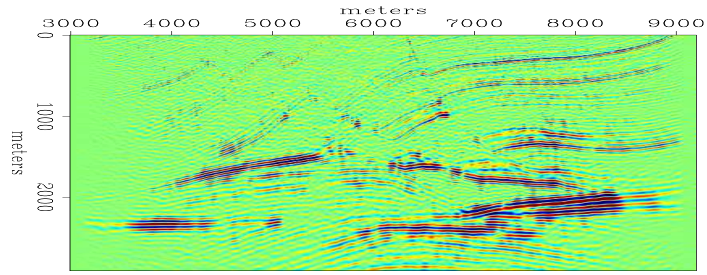
Figure 6: Images from direct imaging of 6 seconds encoded intermittent source data (Figure 4). Note the presence of numerous crosstalk and ambient noise artifacts. [**CR**]



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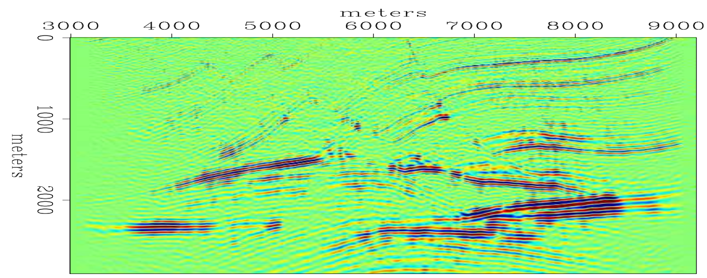

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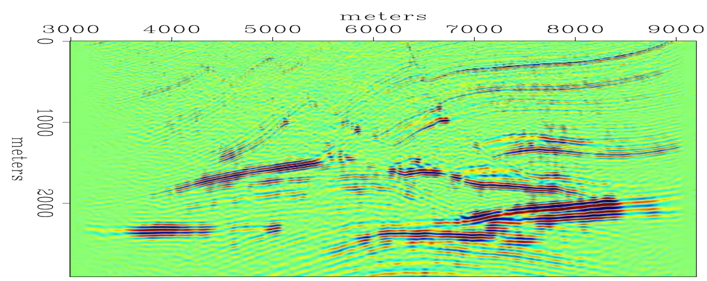

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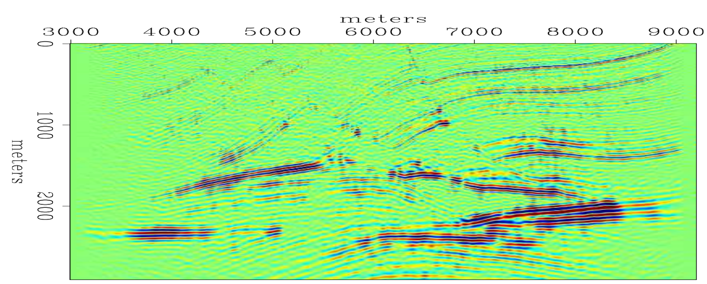

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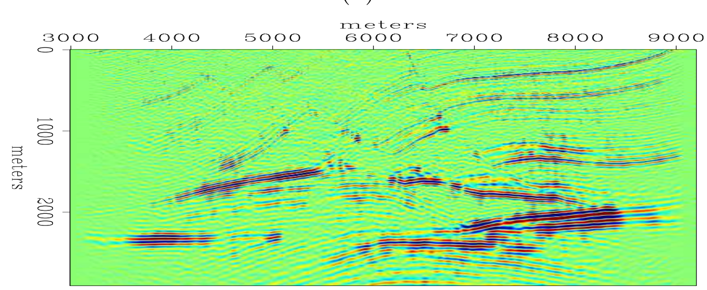

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Figure 7: Images from direct imaging of 320 seconds of encoded intermittent sweep data (Figure 4). Note that the crosstalk and ambient noise artifacts in Figure 6 have been attenuated. Note that these images are comparable to those in Figure 5. [**CR**]

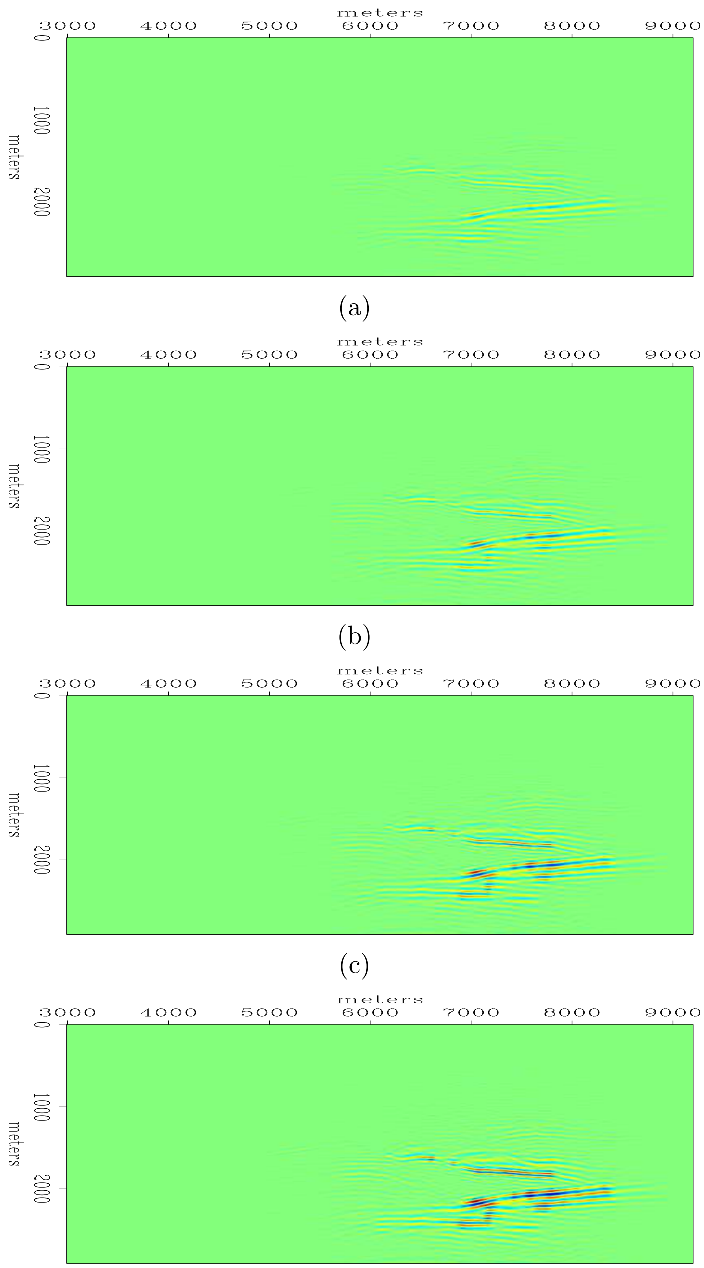

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Figure 8: Time-lapse images from direct imaging of encoded intermittent source data (Figure 4). Note that the seismic amplitude changes at the reservoir are masked by the strong misalignment of the images which result from migration with a wrong *baseline* velocity. Reservoir change increases non-linearly from top to bottom. [**CR**]

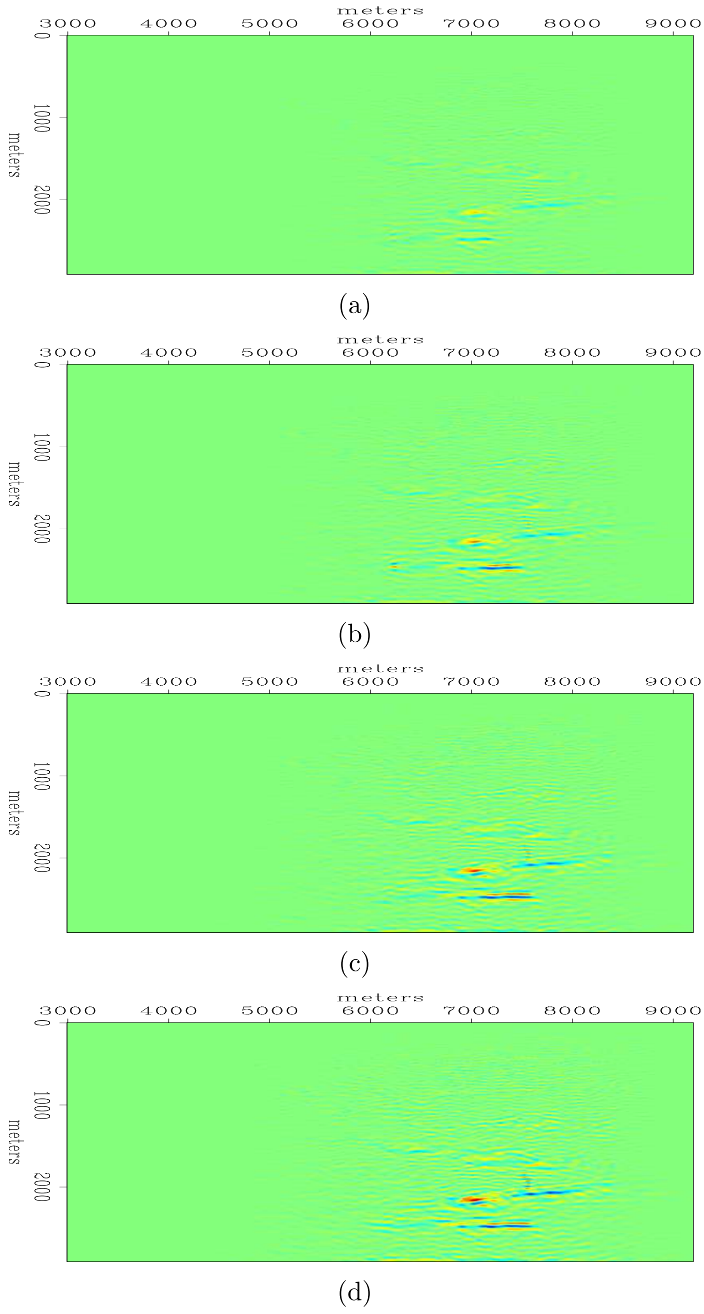
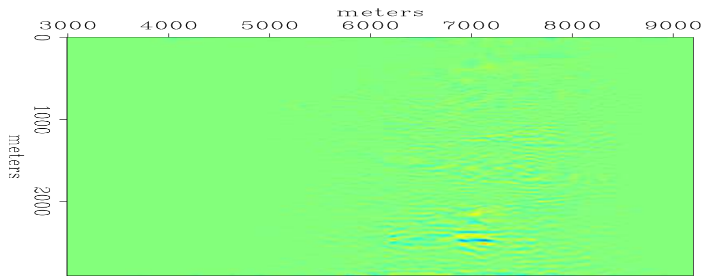


Figure 9: Time-lapse images from direct imaging of encoded intermittent source data (Figure 4) after cyclic 1D warping to remove image misalignments. Note that the seismic amplitude changes at the reservoir are better clearly defined than in Figure 8. However some artifacts (e.g. from the over-hanging salt wedge) persist. [**CR**]



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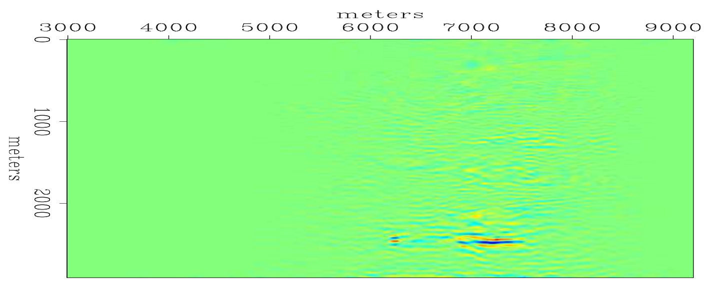

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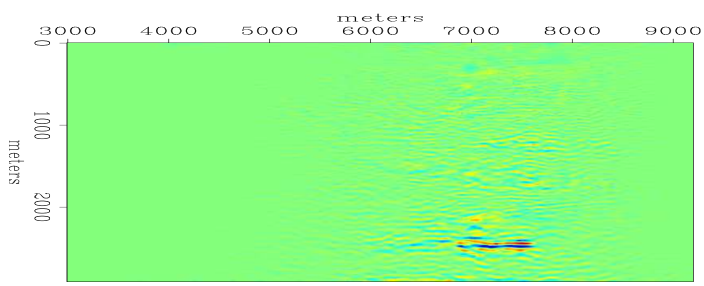

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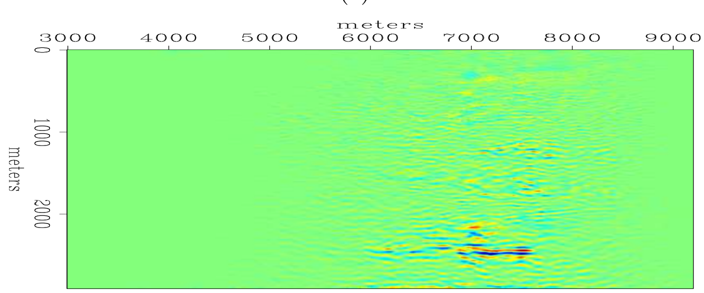

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Figure 10: Time-lapse images from direct imaging of encoded intermittent source data (Figure 8) after match-filtering to remove residual artifacts. Compare this to Figures 8 and 9. Note that the seismic amplitude change (and discontinuities) are accurately imaged by the proposed method. [**CR**]

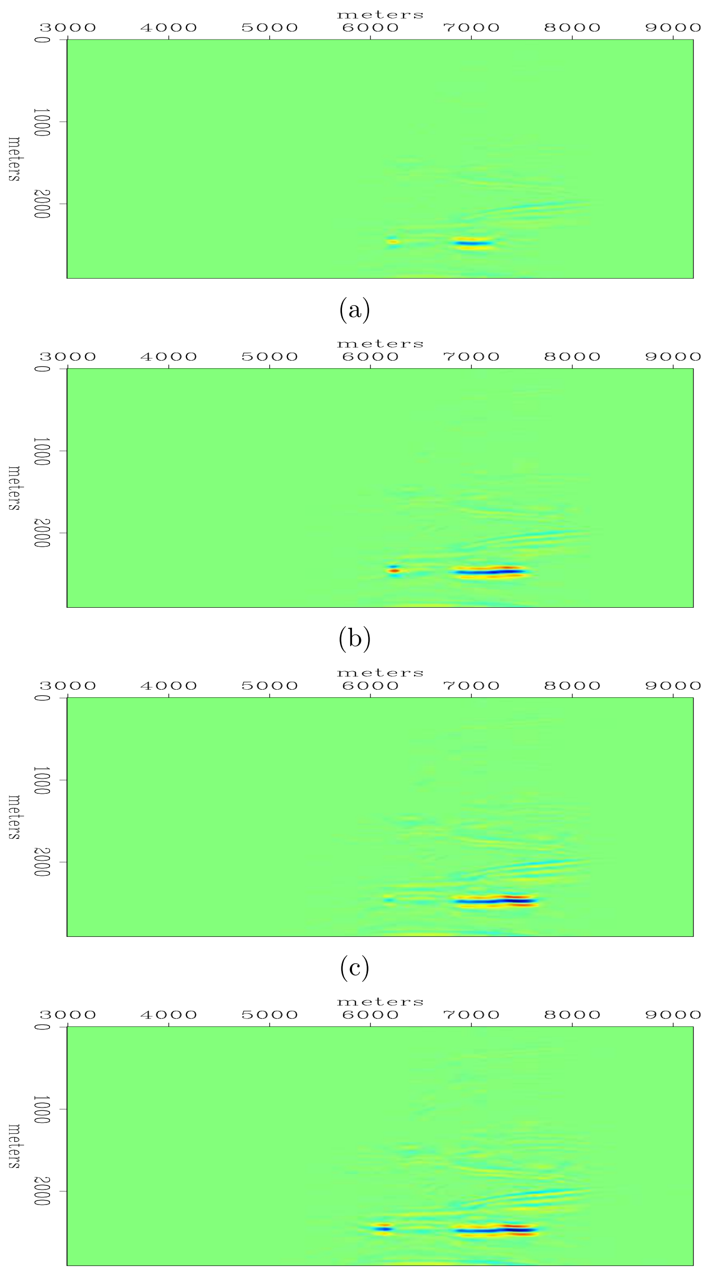

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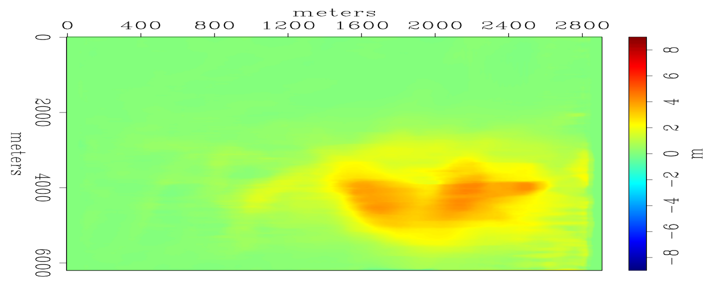
Figure 11: Time-lapse images from from conventional (single-source, high-energy, shot-period) seismic data after warping and match-filtering. These results were obtained using the same models as in the intermittent-source case. Note that these results are similar to those from the proposed method (Figure 10). [**CR**]



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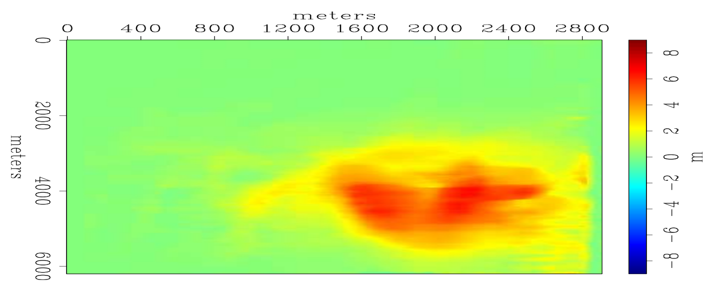

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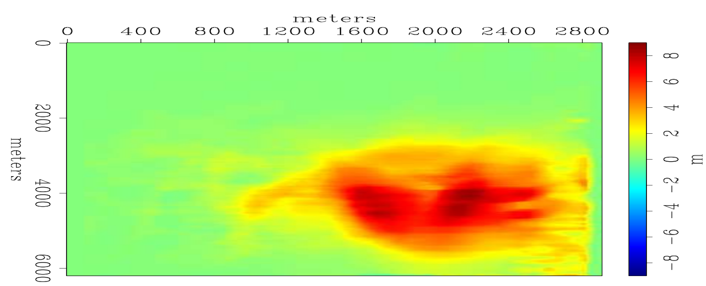

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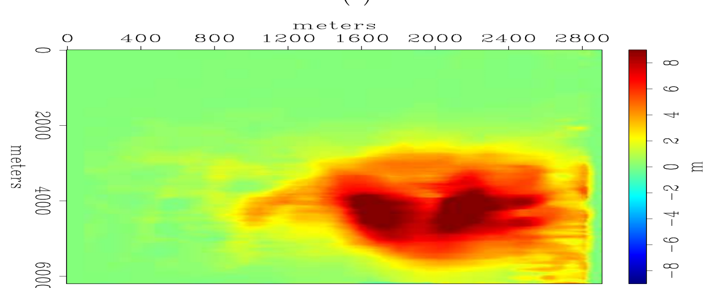

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Figure 12: Vertical components of the apparent displacement vectors computed by warping the monitor images in Figure 7 to the Baseline (Figure 7(a)). Note that these are similar to those from conventional data recording/processing (Figure 13). [**CR**]

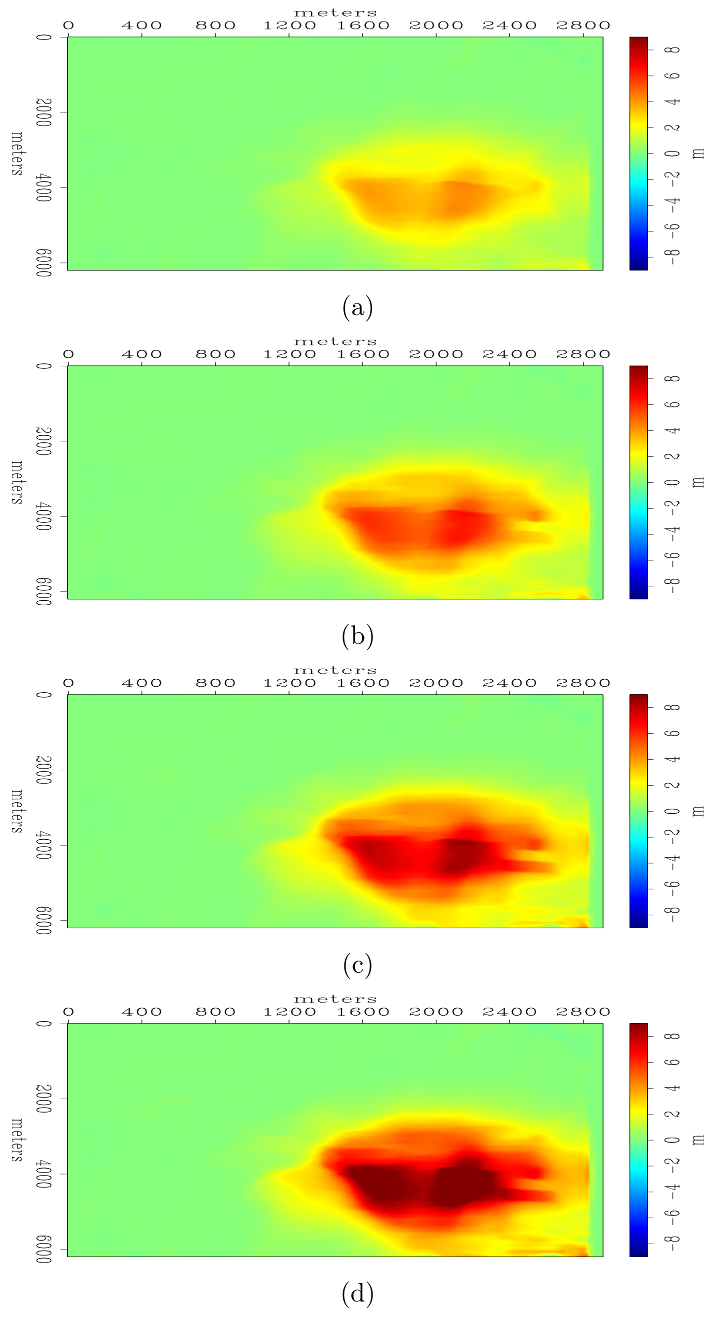

Figure 13: Vertical components of the apparent displacement vectors computed by warping the monitor images in Figure 5 to the Baseline (Figure 5(a)). Note that, in general, these are similar to those from the proposed method (Figure 12). [**CR**]

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