Seismic reservoir monitoring with simultaneous sources

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ABSTRACT

Hydrocarbon reservoirs can be efficiently monitored with simultaneous-source seismic data sets. Because simultaneous-source acquisition reduces time and cost requirements, seismic data sets can be recorded cheaply at short regular intervals, thereby allowing for near real-time monitoring. Although, in many cases, the recorded multiplexed data can be separated into independent records, we choose to leverage the efficiency of direct imaging of such data sets. However, direct imaging with a migration algorithm introduces cross-talk artifacts and does not account for differences in acquisition geometry and relative shot-timing between surveys. To attenuate cross-talk artifacts and acquisition discrepancies between data sets, we propose a joint least-squares migration/inversion method. By incorporating spatio-temporal and sparseness constraints in our inversion algorithm, we ensure that the resulting time-lapse images are geologically plausible. Using a 2D numerical model, we show that our method can give results of comparable quality to migrated single-source data sets.

INTRODUCTION

Conventional seismic data acquisition involves a single seismic source and a recording array of receivers. Although not a new idea (Womack et al., 1990), recent advances in acquisition technology enables seismic acquisition with multiple sources (Hampson et al., 2008; Beasley, 2008). This acquisition approach, also called simultaneous-shooting (or multi-shooting, or blended acquisition), can be used to achieve longer offsets, better shot-sampling, and improved time and cost efficiency (van Mastrigt et al., 2002; Berkhout et al., 2008; Howe et al., 2009). The recorded data can be separated into independent shot records and then imaged with conventional methods (Hampson et al., 2008; Spitz et al., 2008), or they can be imaged directly (Berkhout et al., 2008; Tang and Biondi, 2009).

Although time-lapse (4D) seismic is an established technology for monitoring hydrocarbon reservoirs (Rickett and Lumley, 2001; Whitcombe et al., 2004; Zou et al., 2006; Ebaid et al., 2009), it still has several limitations. First, because of the high cost of conventional (single-source) acquisition, it is impractical to acquire seismic data sets at short time intervals. Therefore, typical monitoring survey intervals may be too large to measure production-related, short-period variations in reservoir properties. Because of the large time intervals between seismic surveys, it may be difficult to match time-lapse seismic signatures to reservoir property changes derived from well-sampled sources (e.g. production history matching). Secondly, in many time-lapse seismic applications, inaccuracies in the replication of acquisition geometries for different surveys (*geometry non-repeatability*) are a recurring problem. Although modern acquisition techniques can improve repeatability of shot-receiver geometries, field conditions usually prevent perfect repetition. In order to isolate differences caused by changes in reservoir properties, non-repeatability effects must be removed from time-lapse data sets. Furthermore, because of operational, climatic, and other limitations, the acquisition time-window may be too small for conventional seismic data acquisition. In such cases, it would be difficult to acquire conventional seismic data sets at desirable intervals.

Some limitations in current and conceptual time-lapse seismic applications can be overcome by simultaneous-shooting. First, by acquiring time-lapse data sets with multiple seismic sources, we can limit acquisition time and cost, and therefore acquire more data sets at shorter time intervals. Sufficiently small survey intervals will enable *quasi-continuous* monitoring of changes in reservoir properties. Other methods for quasi-continuous monitoring have been suggested (Arogunmati and Harris, 2009). Secondly, because we can account for differences in survey geometries during imaging, repetition of survey geometries is unnecessary. Furthermore, because of its high efficiency, simultaneous-shooting can be used for seasonal time-lapse seismic data acquisition in areas with short acquisition time-windows (Berkhout, 2008). Depending on operational limitations, an arbitrary number of seismic sources can be used for each survey. Figure 1 illustrates some scenarios where simultaneous-shooting concepts can be utilized.

There are two discrepancies in time-lapse seismic data sets recorded with multiple sources, namely, geometry and shot-timing non-repeatabilities (Ayeni et al., 2009). As mentioned above, geometry non-repeatability is a result of differences in acquisition geometries for different surveys. Shot-timing non-repeatability between different surveys is a result of mismatches in their relative shooting times. Neglecting survey geometry and shot-timing repeatability during acquisition ensures time and cost efficiency. However, if not accounted for, these two discrepancies will degrade the resulting time-lapse seismic images. Because conventional imaging and time-lapse processing methods are inadequate to account for such discrepancies, we propose a joint (global) least-squares imaging approach.

Least-squares migration/inversion can improve structural and amplitude information in seismic images (Nemeth et al., 1999; Kühl and Sacchi, 2003; Plessix and Mulder, 2004). Direct imaging of simultaneous-source data sets using least-squares migration/inversion methods has been discussed by previous authors (Ayeni et al., 2009; Dai and Schuster, 2009; Tang and Biondi, 2009). In this paper, we formulate time-lapse imaging of simultaneous-source data sets as a regularized joint least-squares problem. By avoiding separation of the recorded data into independent records, we reduce the data volume and processing cost. For each survey, we model the acquisition experiment with a phase encoding operator and the recorded shot-receiver geometries and relative shot-timings. We assume that the velocity and structural dips are known and that they change linearly between surveys. In addition, we assume that for each survey, the shot-receiver positions and relative shot timings are known. Finally, by including structural and temporal constraints in the inversion, we obtain geologically plausible time-lapse seismic images.

First, we consider the phase-encoding representation of simultaneous-shooting. We then introduce a joint inversion framework for simultaneous-source time-lapse data sets. Finally, using fifteen data sets from a 2D numerical model, we show that our method can give high quality images of reservoir property changes.

LINEAR PHASE-ENCODED MODELING AND SIMULTANEOUS-SHOOTING

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 time-delay function, depends on the delay time t_s at shot $\mathbf{s}$.

For acquisition efficiency, it is unnecessary to repeat either the acquisition geometry or the relative shot timings for different surveys. By eliminating the cost associated with repeatability between surveys, we can significantly reduce the total acquisition cost. Because acquisition cost is usually several times higher than the processing cost, a reduction in acquisition cost will significantly reduce the total seismic monitoring cost. In addition, we achieve further cost reduction by imaging all the data sets directly. Figure 2 shows examples of wavefields from two configurations of simultaneous-shooting. In both figures, the third dimension represents the survey time, while the orthogonal lines indicate positions of the displayed slices within the cube.

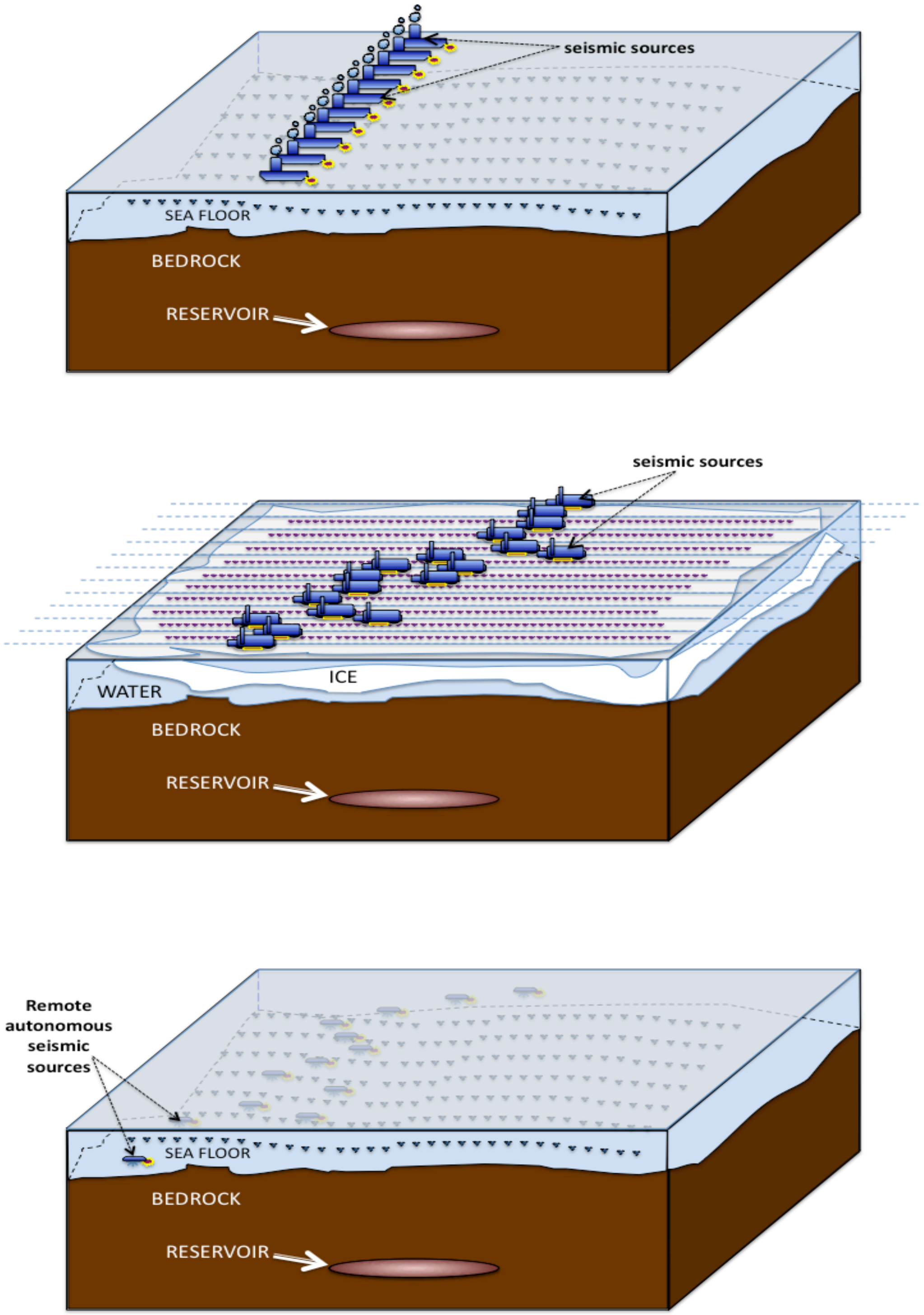
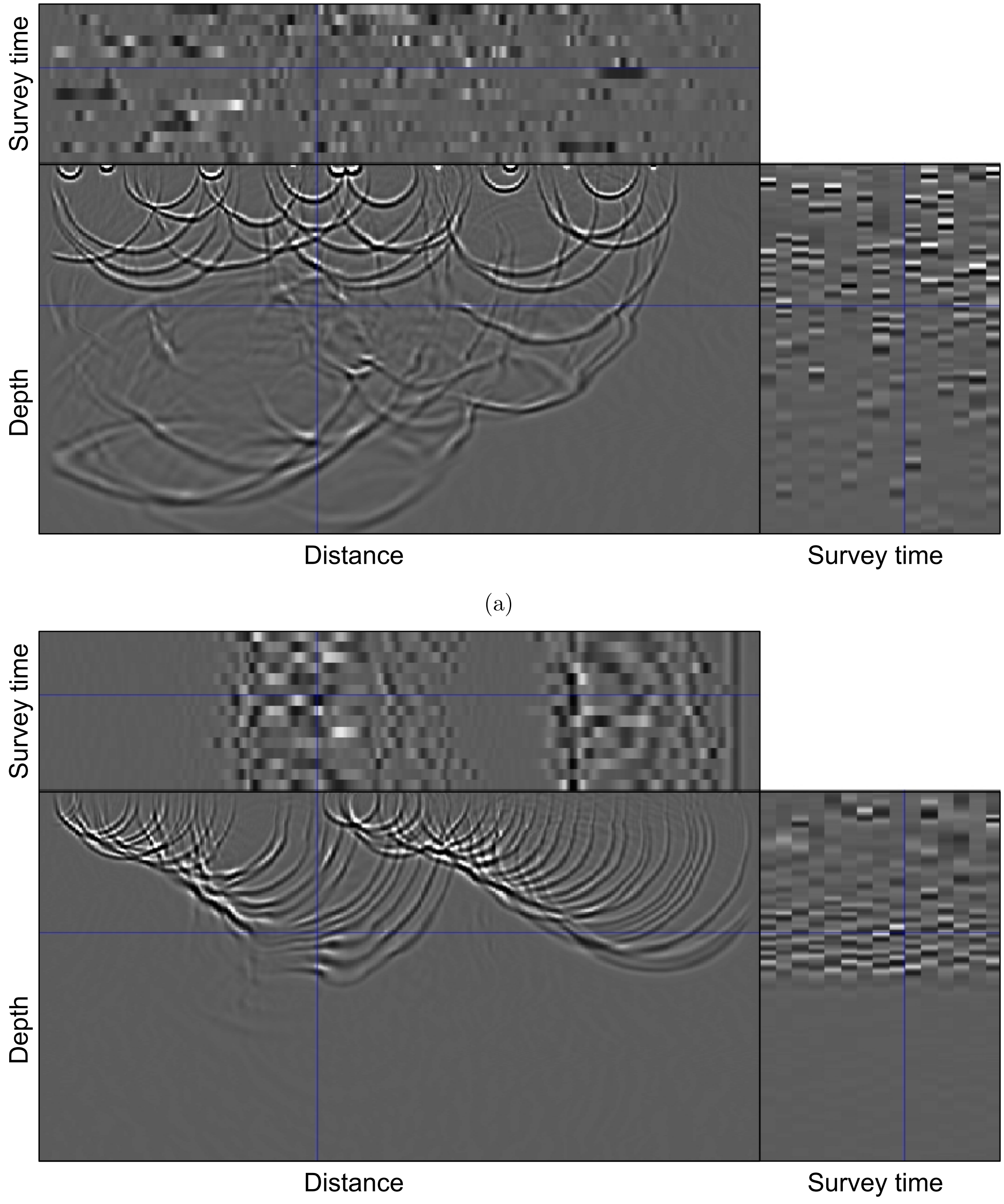


Figure 1: Some conceptual applications of simultaneous-shooting for ocean bottom cable/seismometer acquisition (top), Frontier (e.g. Arctic) data acquisition (middle), and remote autonomous data acquisition (bottom). [**NR**].



(a)

(b)

Figure 2: Wavefields from multiple randomized simultaneous sources (a), and from two continuously shooting seismic sources (b). In each figure, the blue line indicates intersecting positions of the the three slices that are displayed. In Panel (a), the geometry and relative shot-timing are different for all surveys, whereas in Panel (b), only the acquisition geometry differs between surveys. The third dimension denotes survey/recording time. [**CR**].

REGULARIZED JOINT INVERSION

For an arbitrary survey i, we can simplify the modeling equation into the form

$$\widetilde{\mathbf{d}}_i = \mathbf{B}_i \mathbf{L}_i \mathbf{m}_i = \widetilde{\mathbf{L}}_i \mathbf{m}_i, \tag{4}$$

where $\widetilde{\mathbf{d}}$ is the recorded data, $\mathbf{B}$ is the encoding operator, $\mathbf{L}$ is the modeling operator, $\mathbf{m}$ is the earth reflectivity, and $\widetilde{\mathbf{L}} = \mathbf{BL}$. The migrated image, computed by applying the adjoint operator $\widetilde{\mathbf{L}}^T$ to $\widetilde{\mathbf{d}}$, will contain cross-term artifacts generated by cross-correlation between incongruous source and receiver wavefields (Romero et al., 2000; Tang and Biondi, 2009). In addition, because of the associated geometry and relative shot-time non-repeatability, different surveys have unique cross-term artifacts. To attenuate these artifacts, for N surveys, we minimize a joint (global) cost function S given by

$$\begin{aligned} S(\mathbf{m}_0, .., \mathbf{m}_N) = & \sum_{i=0}^{N} \left|\left| \widetilde{\mathbf{L}}_i \mathbf{m}_i - \widetilde{\mathbf{d}}_i \right|\right|^2 + \sum_{i=0}^{N} \left|\left| \epsilon_i \mathbf{R}_i \mathbf{m}_i \right|\right|^2 + \\ & \sum_{i=1}^{N} \left|\left| \zeta_i \mathbf{\Lambda}_i \left(\mathbf{m}_{i-1}, \mathbf{m}_i \right) \right|\right|^2 + \sum_{i=1}^{N} \left|\left| \beta_i \mathbf{\Gamma}_i \left(\Delta m_i \right) \right|\right|_{hb}, \end{aligned} \tag{5}$$

where the parameters ϵ_i and ζ_i determine the strengths of the spatial and temporal regularization operators, $\mathbf{R}_i$ and $\mathbf{\Lambda}_i$ respectively. Because only a small region in the model space contain desired in time-lapse signal, a sparseness requirement is desirable. Parameter β_i determines the strength of the sparseness operator $\mathbf{\Gamma}_i$. Related formulations have been applied to other time-lapse imaging problems (Ajo-Franklin et al., 2005). We compute the time-lapse image as the difference between the migrated or inverted image at time t and that at time 0. Because several shots are encoded and directly imaged, the computational cost of this approach is considerably reduced compared to non-encoded data sets.

In this paper, the spatial regularization operator is a system of non-stationary dip-filters, whereas the temporal regularization operator is a gradient between surveys. We compute dips using the plane-wave destruction method (Fomel, 2002), and we compute dip-filters using factorized directional Laplacians (Hale, 2007). To ensure stable transitions at sharp boundaries, the filter corresponding to any image point is scaled according to a dip-contrast-dependent variance. We estimate the spatial and temporal regularization parameters by scaling the maximum amplitude in each data set. Finally, we minimize the objective function using an iterative hybrid conjugate direction algorithm (Li et al., 2010) which enforces desired spareness on the time-lapse images.

NUMERICAL EXAMPLE

The proposed method was applied to a modified 2D Marmousi model (Bourgeois et al., 1991). For simplicity, we neglect overburden geomechanical changes and assume no change in reflectivity, except within the reservoir (Figure 3(a)). Using a

Born modeling algorithm, we simulated 15 data sets representing different production stages (Figure 4). Each data set comprises 56 randomly encoded shot records with unique shot positions and unique relative shot-timings (Figure 5). We estimated the dip-field and dip-contrast (Figures 3b and c) from the migrated baseline image. For data modeling and migration, we use a phase-encoding one-way wave-equation operator. For comparison, using the same number of shots and receivers and perfect repeatability, we modeled and migrated 15 conventional data sets. The migrated and inverted images, together with the corresponding time-lapse images, are shown in Figures 6 to 8.

DISCUSSION

If the temporal spacing between seismic surveys is small, we see that a near-continuous image of reservoir property change can be obtained (Figure 6). We can reduce the acquisition cost for these conventional seismic surveys by using multiple seismic sources. Instead of separating the recorded data from such an experiment, they can be imaged directly with a phase-encoding operator. However, direct imaging causes cross-talk artifacts that degrade the quality of migrated images (Figure 7(a)). In addition, if the the acquisition geometries and relative shot-timings are not repeated, the cross-term artifacts will degrade the quality of the time-lapse images (Figure 7(b)). Regularized joint inversion attenuates these artifacts (Figure 8(a)). Furthermore, inversion also produces high-quality time-lapse images (Figure 8(b)) that are of comparable quality but better resolution than perfectly repeated single-source data sets (Figure 6(b)). A careful choice of the regularization parameters ensures that the objective function is well behaved for all components of the global cost function. This leads to a gradual reduction in the cross-term and non-repeatability artifacts with iteration (Figures 9 and 10).

CONCLUSIONS

We have proposed an efficient scheme for acquiring and processing time-lapse seismic data sets. This method can reduce the overall data acquisition and processing cost for seismic reservoir monitoring. We have shown that even if the survey geometries and relative shot timing are not repeated, our joint inversion method gives high-quality time-lapse images. These acquisition and processing approaches provide a realistic framework for efficient seismic reservoir monitoring in many scenarios. It can make several conceptual seismic monitoring technologies (e.g. autonomous seismic acquisition, Arctic seismic reservoir monitoring) possible. In the near future, we will incorporate a scheme to compensate for geomechanical reservoir changes.

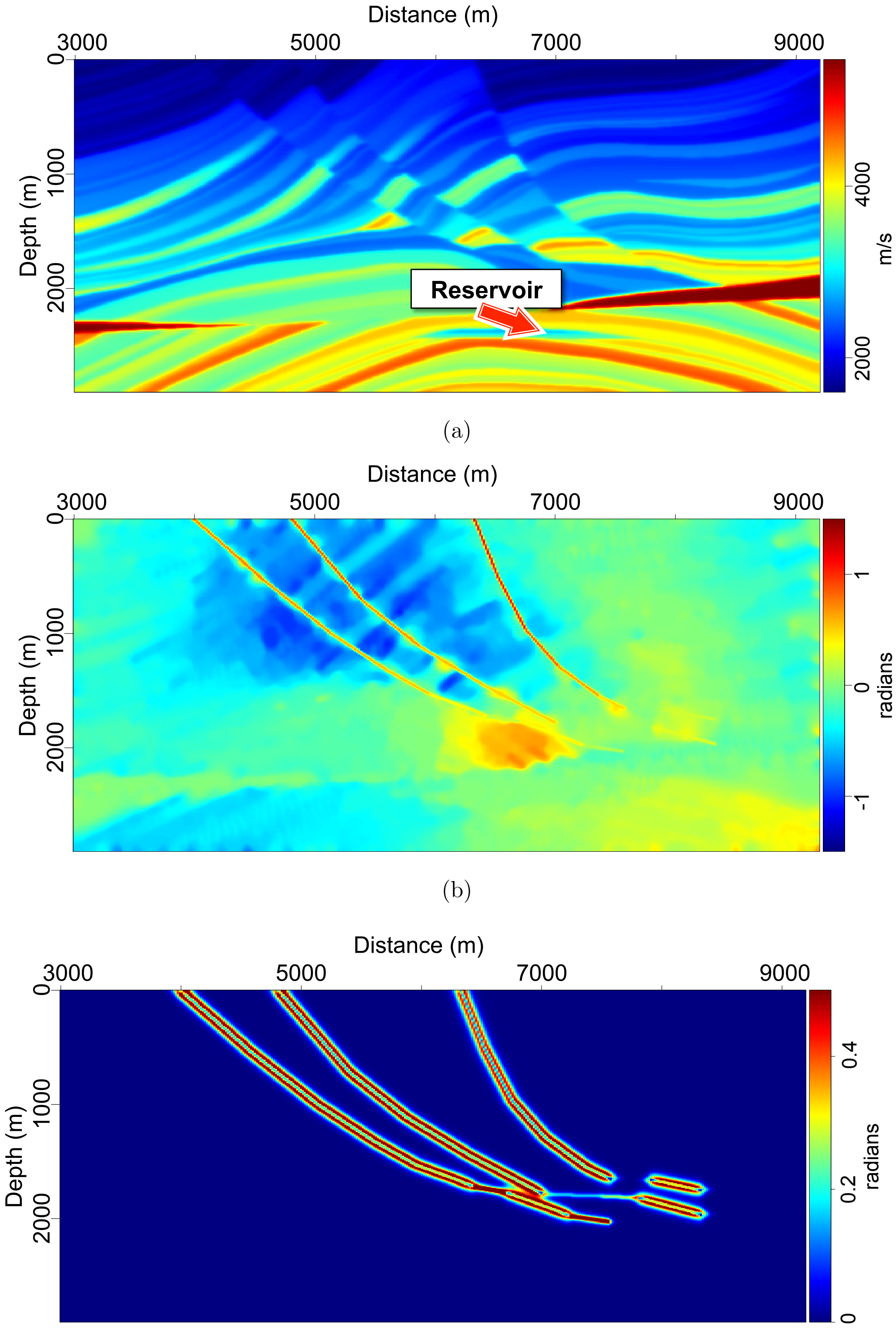


Figure 3: Baseline velocity model (a), dip-field computed from the migrated baseline image (b), and dip-variance estimated as a function of dip contrast (c). [**CR**].

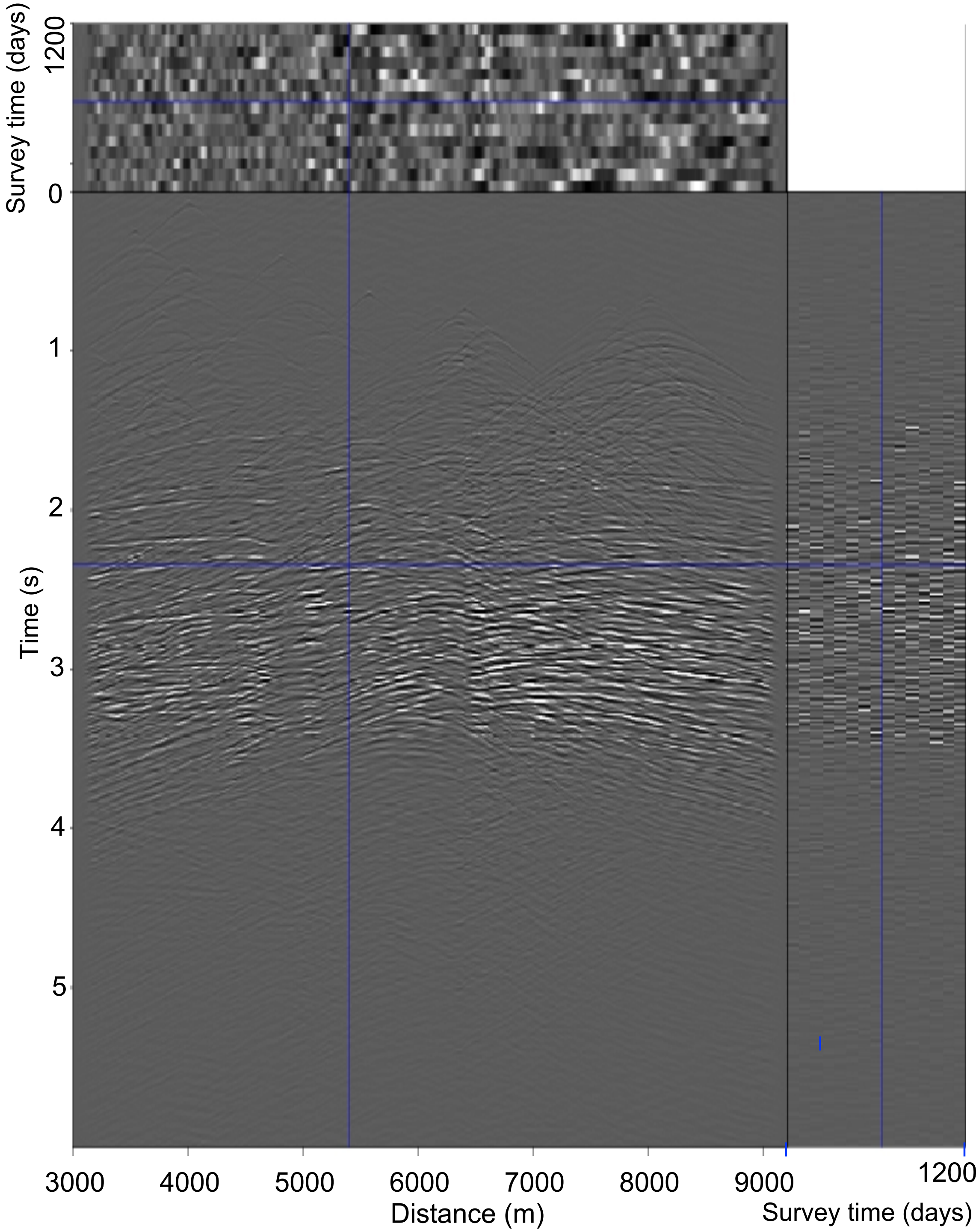


Figure 4: Synthetic data from multiple asynchronous sources. The third dimension denotes survey/recording time. [**CR**].

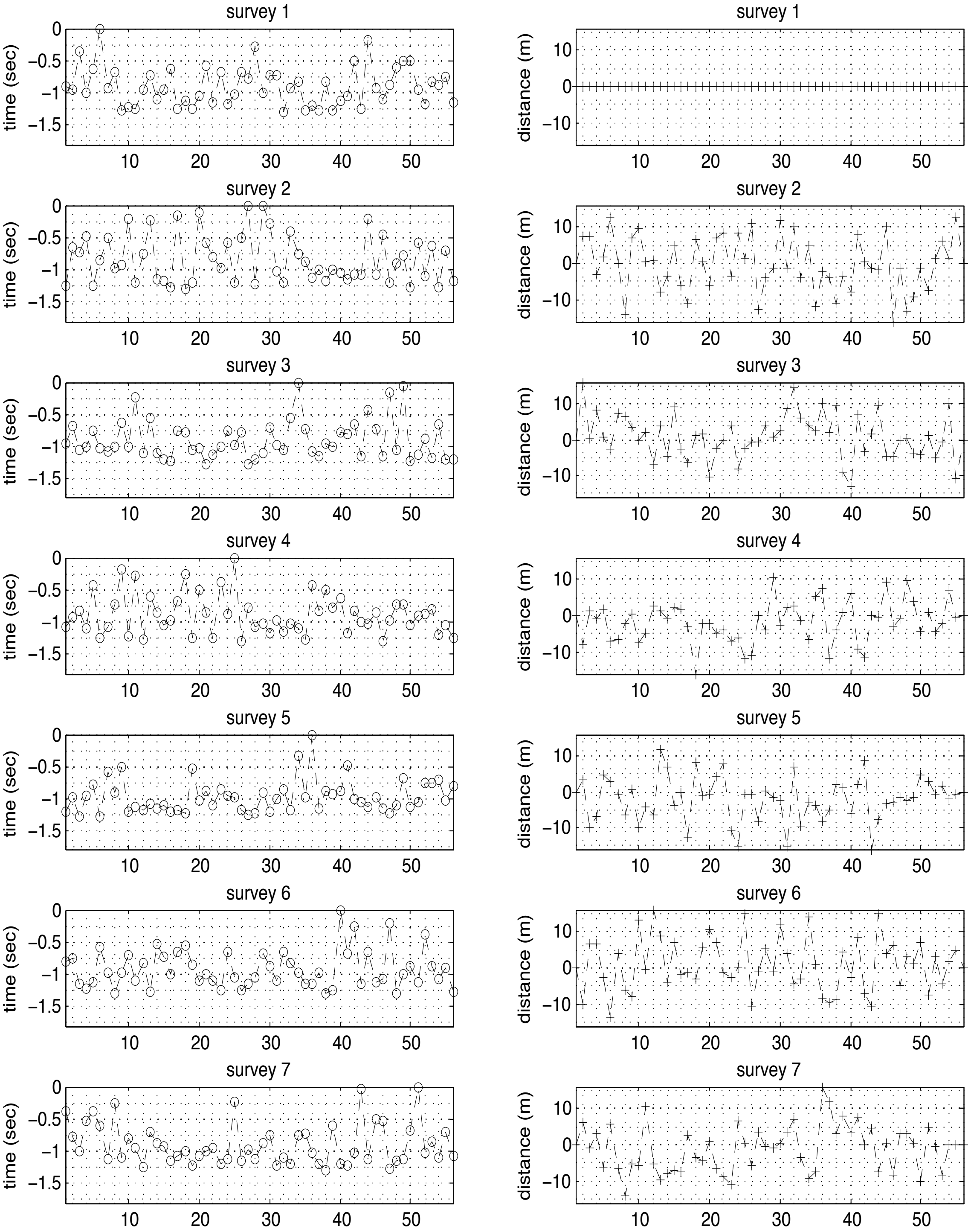
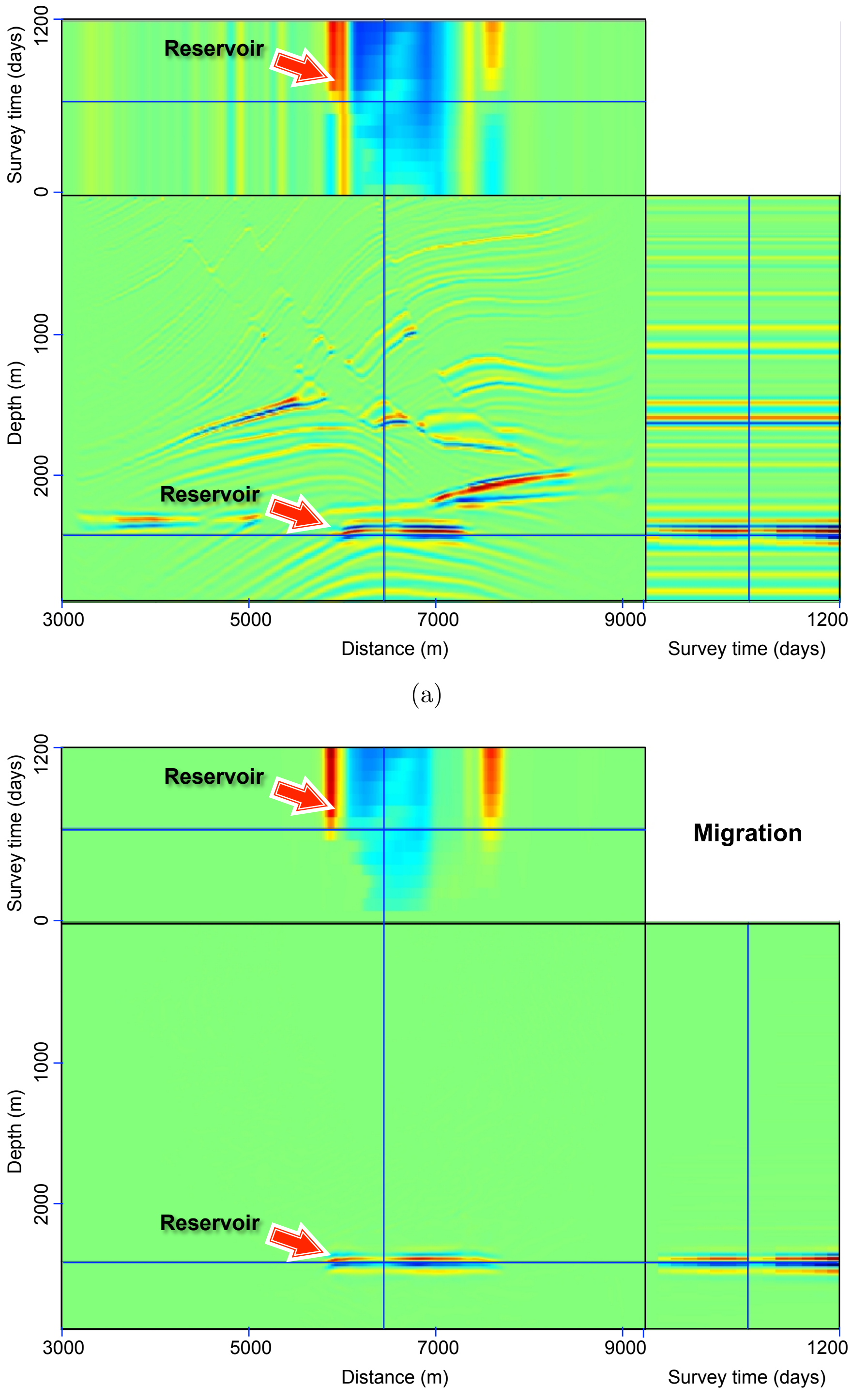


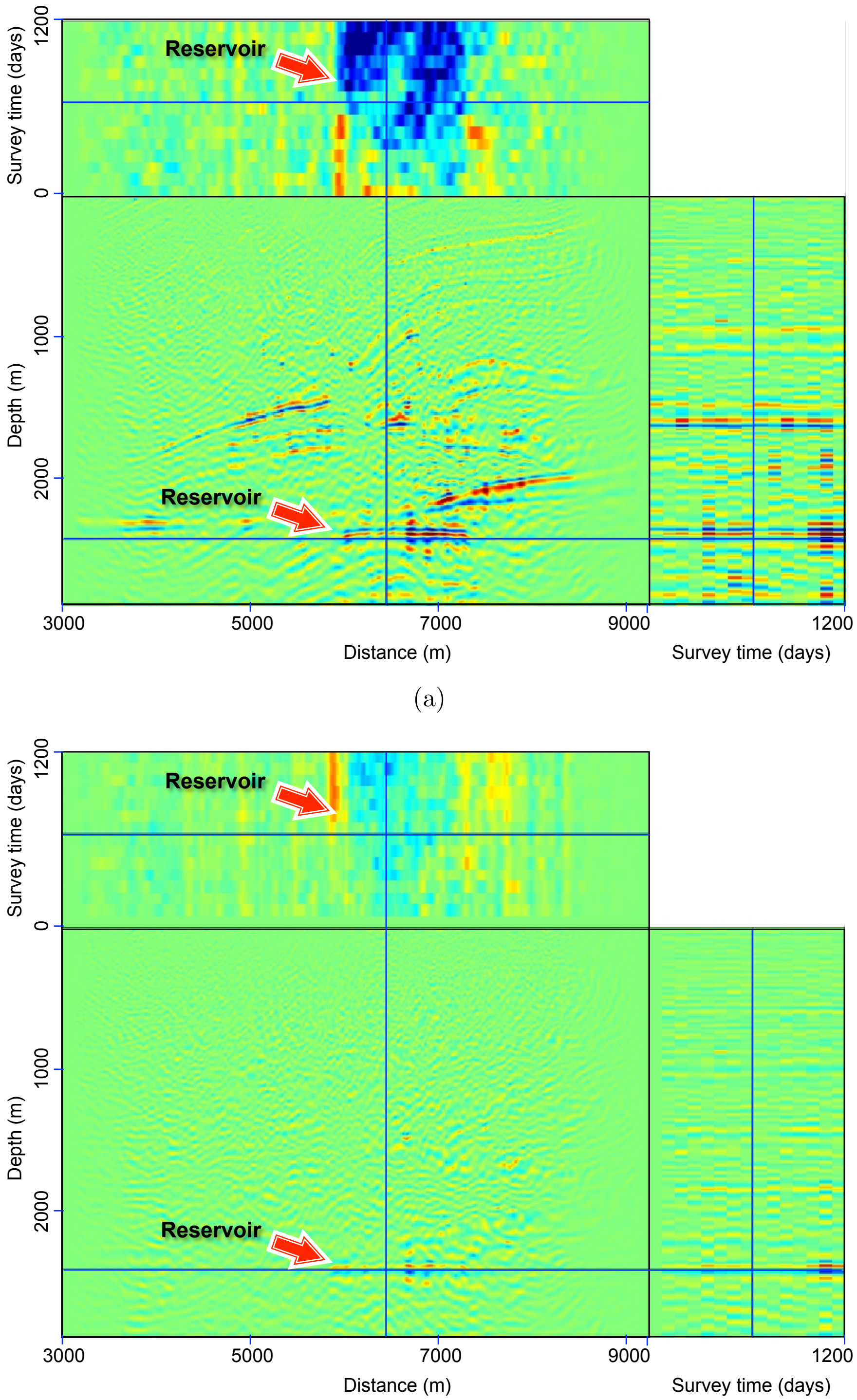
Figure 5: Plots of relative time-delays (left) and shot-displacements for seven out of the fifteen numerical models that were used to generate the data in Figure 4. In all plots, the horizontal axis indicates shot position. The relative shooting times are referenced to the earliest shot in each survey, whereas shot-displacements are referenced to the baseline shot positions. [**NR**].



(a)

(b)

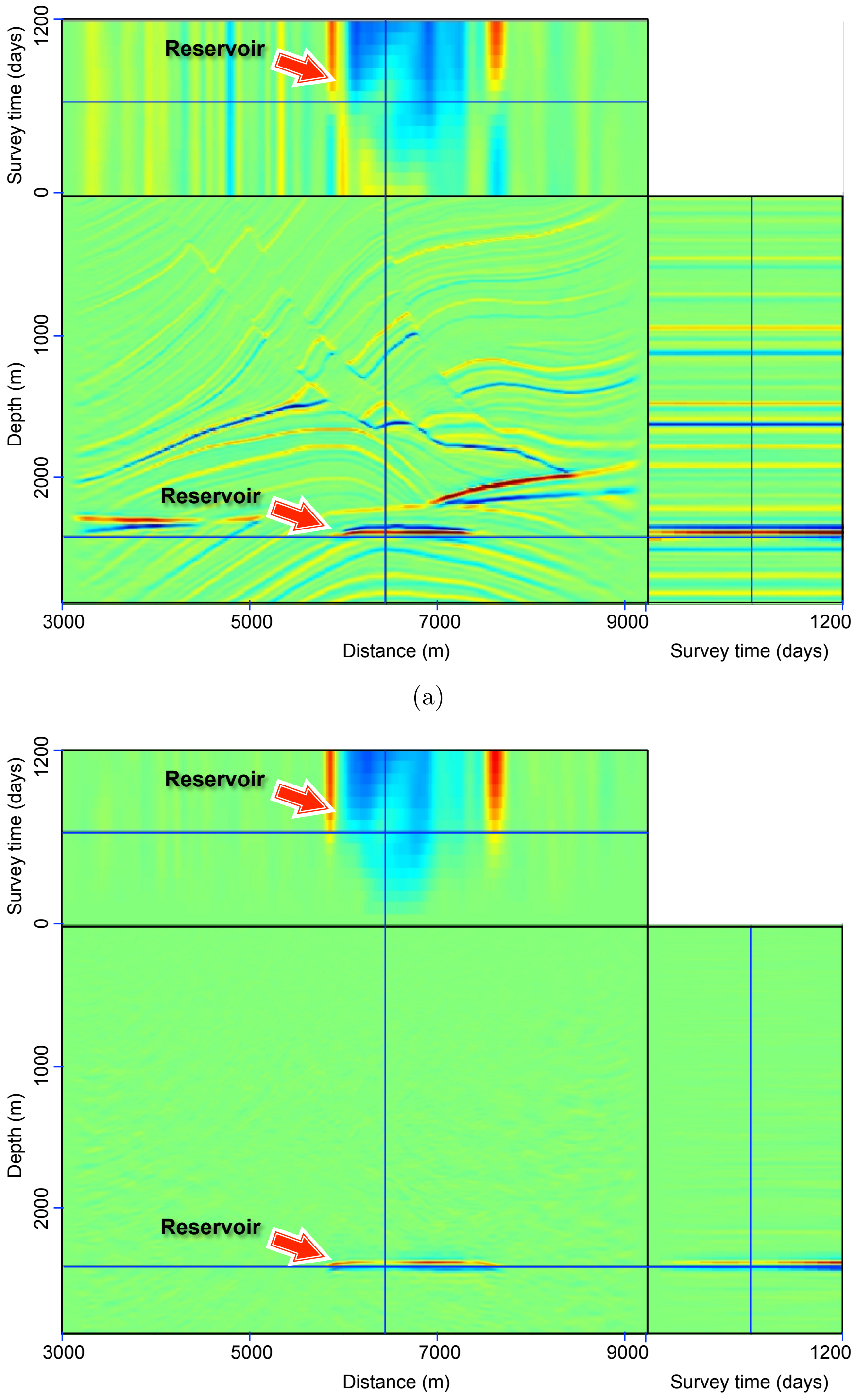
Figure 6: Images (a) and corresponding time-lapse estimates (b) obtained from migrating perfectly repeated conventional (single-source) data sets. In this (and in similar) Figures, the side panel (third axis) shows the seismic properties (a) and time-lapse changes (b) at a fixed spatial position, whereas the top panel shows the spatial-temporal distribution seismic properties. [**CR**].



(a)

(b)

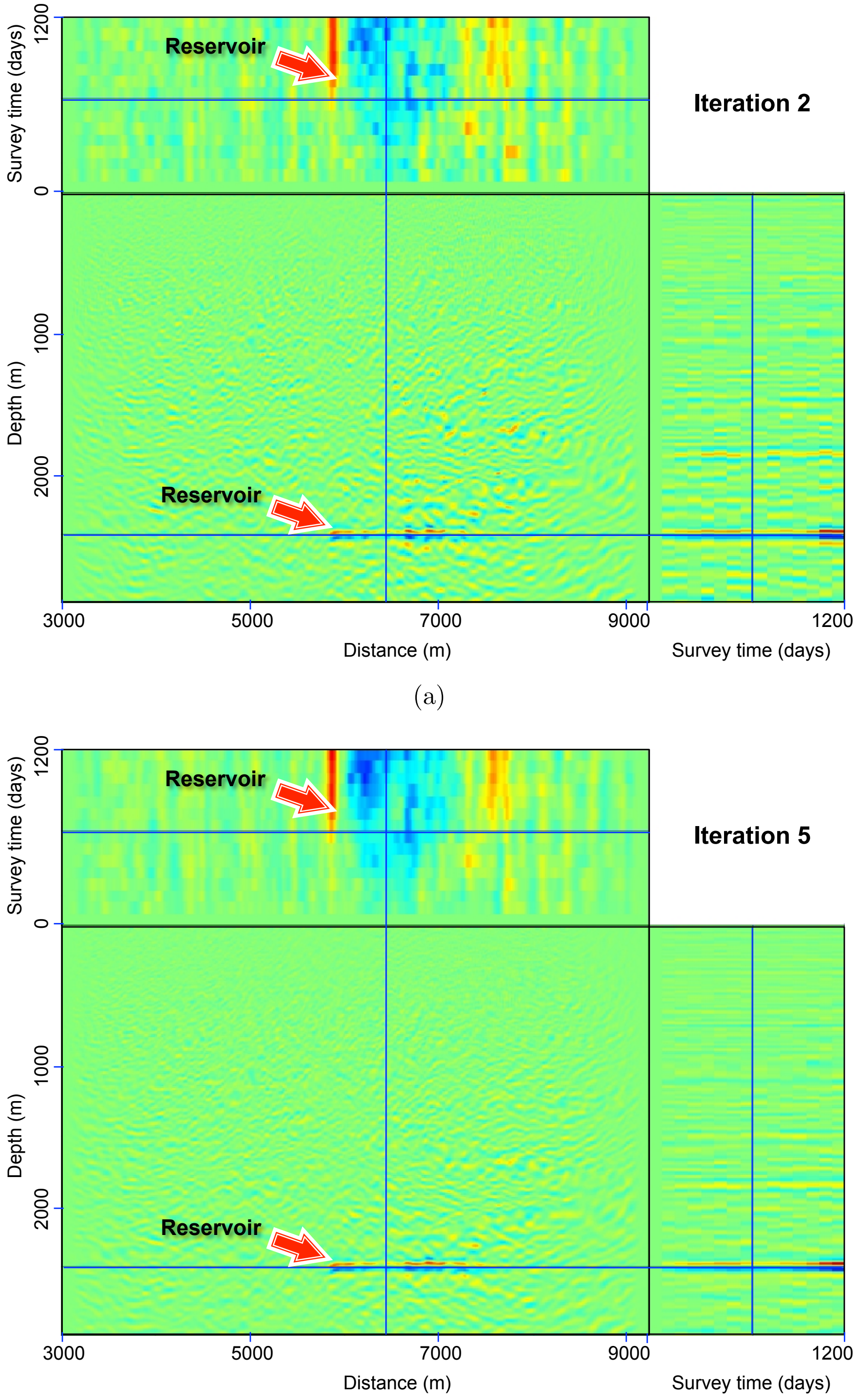
Figure 7: Images (a) and corresponding time-lapse estimates (b) obtained from migrating the data sets in Figure 4. In both Figures, note the numerous artifacts caused by geometry and shot-timing non-repeatability and cross-term artifacts. Without attenuating these artifacts, it would be difficult to accurately interpret the time-lapse information. [**CR**].



(a)

(b)

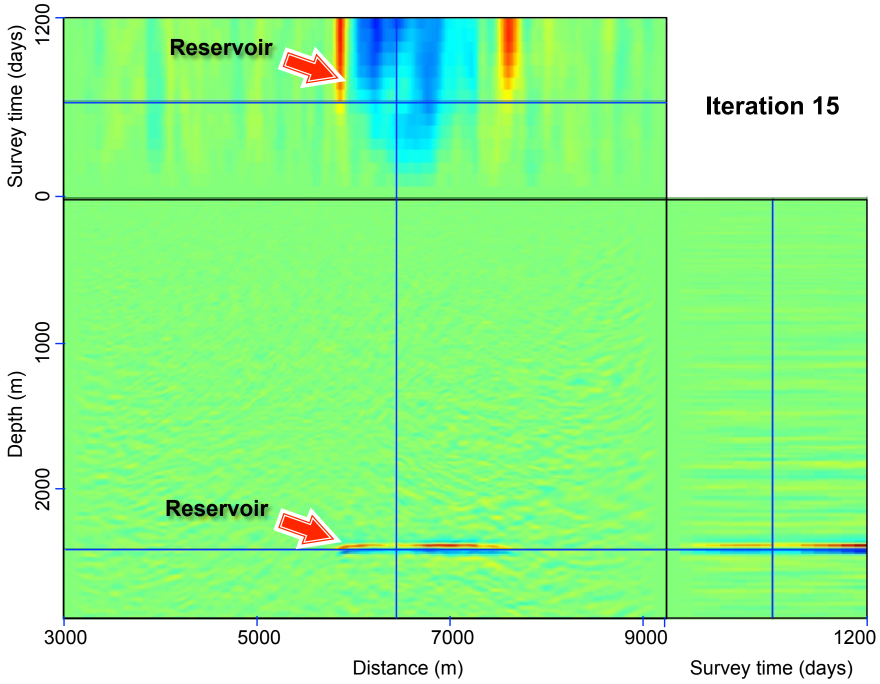
Figure 8: Images (a) and corresponding time-lapse estimates (b) obtained from inverting the simultaneous-source data sets in Figure 4. Note that the non-repeatability and cross-talk artifacts in the migrated images (Figure 7) have been attenuated by inversion. Also, note the better resolution of the inverted images compared to the migrated single-source data (Figure 6).



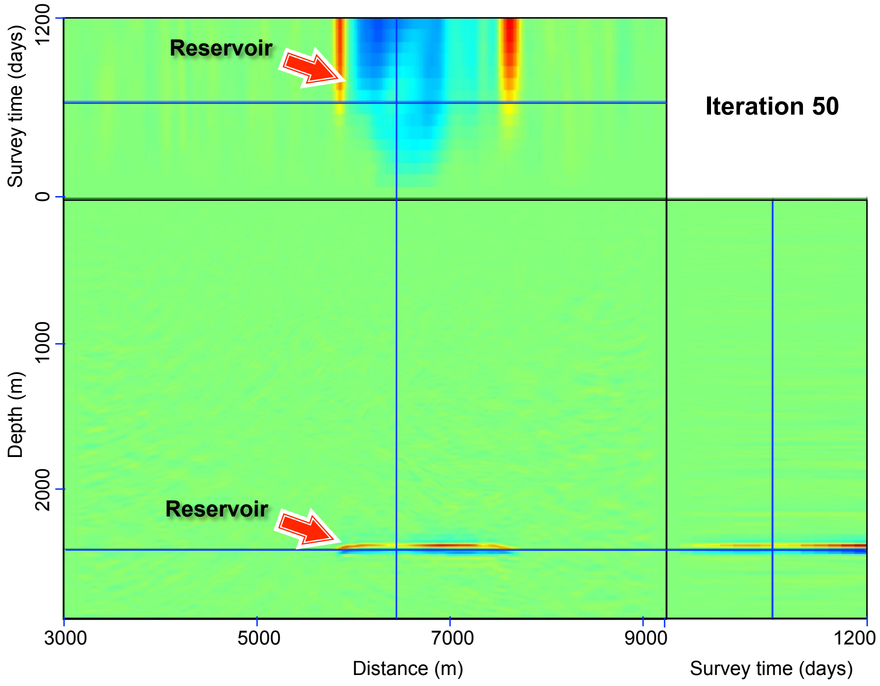
(a)

(b)

Figure 9: Time-lapse seismic images obtained after 2 and 5 conjugate gradient iterations (a) and (b) respectively. Note the gradual reduction in the artifacts compared to the time-lapse images from migration (Figure 7(b)). [**CR**].



(a)



(b)

Figure 10: Time-lapse seismic images obtained after 15 and 50 conjugate gradient iterations (a) and (b) respectively. Note the reduction in the artifacts compared to the time-lapse images from migration (Figure 7(b)). [**CR**].

REFERENCES

Ajo-Franklin, J. B., J. Urban, and J. M. Harris, 2005, Temporal integration of seismic traveltime tomography: SEG Technical Program Expanded Abstracts, **24**, 2468–2471.

Arogunmati, A. and J. M. Harris, 2009, An approach for quasi-continuous time-lapse seismic monitoring with sparse data: SEG Technical Program Expanded Abstracts, **28**, 3899–3903.

Ayeni, G., Y. Tang, and B. Biondi, 2009, Joint preconditioned least-squares inversion of simultaneous source time-lapse seismic data sets: SEG Technical Program Expanded Abstracts, **28**, 3914–3918.

Beasley, C. J., 2008, Simultaneous sources: A technology whose time has come: SEG Technical Program Expanded Abstracts, **27**, 2796–2800.

Berkhout, A. J. G., 2008, Changing the mindset in seismic data acquisition: The Leading Edge, **27**, 924–938.

Berkhout, A. J. G., G. Blacquière, and E. Verschuur, 2008, From simultaneous shooting to blended acquisition: SEG Technical Program Expanded Abstracts, **27**, 2831–2838.

Bourgeois, A., M. Bourget, P. Lailly, M. Poulet, P. Ricarte, and R. Versteeg, 1991, Marmousi, model and data:: Proceedings of 1990 EAEG workshop on practical aspects of seismic data inversion.

Dai, W. and J. Schuster, 2009, Least-squares migration of simultaneous sources data with a deblurring filter: SEG Technical Program Expanded Abstracts, **28**, 2990–2994.

Ebaid, H., M. Nasser, P. Hatchell, and D. Stanley, 2009, Time-lapse seismic makes a significant business impact at Holstein: SEG, Expanded Abstracts, **28**, 3810–3814.

Fomel, S., 2002, Applications of plane-wave destruction filters: Geophysics, **67**, 1946–1960.

Hale, D., 2007, Local dip filtering with directional laplacians: CWP Project Reiew, **567**, 91–102.

Hampson, G., J. Stefani, and F. Herkenhoff, 2008, Acquisition using simultaneous sources: SEG Technical Program Expanded Abstracts, **27**, 2816–2820.

Howe, D., M. Foster, T. Allen, I. Jack, D. Buddery, A. Choi, R. Abma, T. Manning, and M. Pfister, 2009, Independent simultaneous sweeping in Libya-full scale implementation and new developments: SEG Technical Program Expanded Abstracts, **28**, 109–111.

Kühl, H. and M. D. Sacchi, 2003, Least-squares wave-equation migration for avp/ava inversion: Geophysics, **68**, 262–273.

Li, Y., Y. Zhang, and J. Claerbout, 2010, Geophysical applications of a novel and robust l1 solver: SEP Report, **140**.

Nemeth, T., C. Wu, and G. T. Schuster, 1999, Least-squares migration of incomplete reflection data: Geophysics, **64**, 208–221.

Plessix, R.-E. and W. Mulder, 2004, Frequency-domain finite-frequency amplitude-preserving migration: Geophysical Journal International, **157**, 975–985.

Rickett, J. E. and D. E. Lumley, 2001, Cross-equalization data processing for time-lapse seismic reservoir monitoring: A case study from the Gulf of Mexico: Geophysics, **66**, 1015–1025.

Romero, L. A., D. C. Ghiglia, C. C. Ober, and S. A. Morton, 2000, Phase encoding of shot records in prestack migration: Geophysics, **65**, 426–436.

Spitz, S., G. Hampson, and A. Pica, 2008, Simultaneous source separation: A prediction-subtraction approach: SEG Technical Program Expanded Abstracts, **27**, 2811–2815.

Tang, Y. and B. Biondi, 2009, Least-squares migration/inversion of blended data: SEG Technical Program Expanded Abstracts, **28**, 2859–2863.

van Mastrigt, P., S. Vaage, M. Dunn, and B. Pramik, 2002, Improvements in 3-D marine acquisition using continuous long offset (CLO): The Leading Edge, **21**, 394–.

Whitcombe, D. N., J. M. Marsh, P. J. Clifford, M. Dyce, C. J. S. McKenzie, S. Campbell, A. J. Hill, R. S. Parr, C. Pearse, T. A. Ricketts, C. P. Slater, and O. L. Barkved, 2004, The systematic application of 4D in BP's North-West Europe operations — 5 years on: SEG Technical Program Expanded Abstracts, **23**, 2251–2254.

Womack, J. E., J. R. Cruz, H. K. Rigdon, and G. M. Hoover, 1990, Encoding techniques for multiple source point seismic data acquisition: Geophysics, **55**, 1389–1396.

Zou, Y., L. R. Bentley, L. R. Lines, and D. Coombe, 2006, Integration of seismic methods with reservoir simulation, Pikes Peak heavy-oil field, Saskatchewan: The Leading Edge, **25**, 764–781.