Elastic velocity analysis and time-lapse full-waveform inversion

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Abstract

Until recently, a majority of seismic-processing and seismic-imaging techniques has to a large extent ignored amplitude effects and has been designed to use the information contained in the kinematic part of seismic waves. With the introduction of inversion techniques designed to use the amplitude properties of seismic data also, such as full-waveform inversion, one can no longer use the simple acoustic approximation to describe seismic waves but has to employ the full elastic formulation, possibly also including anisotropy. Reverse time migration can be modified easily to take elastic waves into account. This also leads directly to elastic migration velocity analysis, in which the effect of anisotropy can be taken into account in a straightforward way. Full-waveform inversion using the full elastic wave equation gives more accurate results compared with acoustic full-waveform inversion and is capable of exploiting information contained in reflected waves. Time-lapse elastic full-waveform inversion is capable of recovering compressional- and shear-wave velocity changes caused by fluid effects on synthetic data. Real data results are more uncertain but seem to indicate that the elastic approach leads to better results than the conventional acoustic method.

Introduction

Traditionally, seismic processing has been preoccupied with the acoustic approximation, i.e., the earth has been regarded as a fluid with no shear forces. This has been a remarkably successful approach considering the fact that the subsurface is far from being purely acoustic. Elastic phenomena such as surface waves and shear waves play a significant role and are easily observed on industrial seismic data. The main reason for the success of the acoustic approximation is that almost all industrial seismic-processing schemes ignore amplitude effects and are designed to use only the kinematic part of seismic waves. One exception to this rule is the widely used amplitude-variation-with-offset (AVO) inversion techniques in which amplitude information is exploited.

In recent years, an inversion technique designed to use the amplitude properties of seismic wavefields, the full-waveform inversion approach (FWI), has become popular and has seen some success (Sirgue et al., 2009; Virieux and Operto, 2009). FWI has been implemented by the seismic industry through the acoustic approximation, using mainly the properties of diving waves and refracted waves. Although acoustic FWI is relatively easy to implement and provides promising results, the time has probably arrived for breaking out of the acoustic "comfort zone" and starting to consider the more realistic elastic description. Mora (1987) implements an elastic inversion scheme, and several followers have implemented similar schemes; see Virieux and Operto (2009) for an overview.

Using elastic full-waveform inversion (EFWI) should in principle provide better results than acoustic FWI, which is illustrated by the example in Figure 1. Figure 1a shows a compressional-wave velocity model constructed using EFWI, whereas Figure 1b shows the velocity model resulting from FWI using the acoustic approximation. As observed, a much better result with higher resolution is achieved when the full elastic methodology is used.

An important limitation with FWI is that a starting model with correct kinematic properties is required. In the following section, we show that this problem can be solved by using wave-equation migration velocity analysis (WEMVA) to provide a smooth but kinematically correct initial model. In the two subsequent sections, we show how EFWI can be applied to time-lapse (4D) data, both real and synthetic.

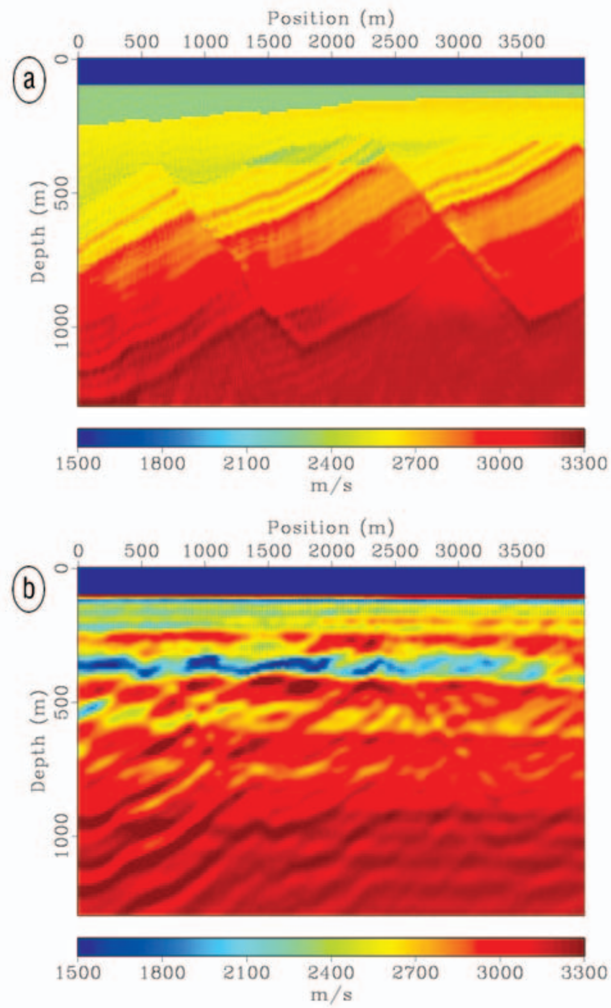

Figure 1. (a) Elastic full-waveform inversion of compressional velocity on synthetic data. (b) Acoustic full-waveform inversion using the same elastic synthetic data as in (a). Comparing (a) and (b), it is clear that acoustic inversion produces velocity artifacts which are caused by inability of the acoustic approximation to properly explain the amplitudes in the observed data.

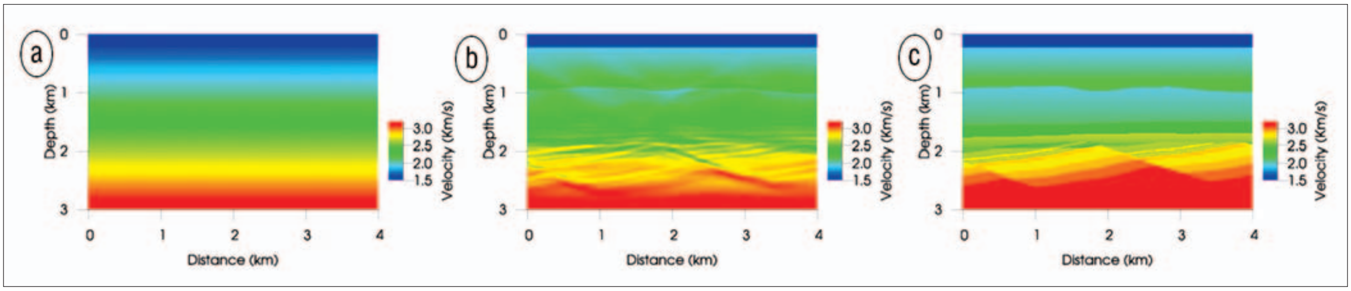

Figure 2. (a) Initial compressional-velocity model for full-waveform inversion. Velocity is laterally invariant but has a constant vertical gradient. (b) FWI using the model in (a) as the starting model. Comparison with the true model in (c) shows that the result is incorrect and far from the true model. This is because the initial model in (a) is not kinematically correct.

Elastic wave-equation migration velocity analysis (EWEMVA)

FWI is sensitive to the initial model and requires a starting model which can explain the observed traveltimes. If an incorrect kinematic model is used, the inverted model will contain errors, as illustrated in Figure 2.

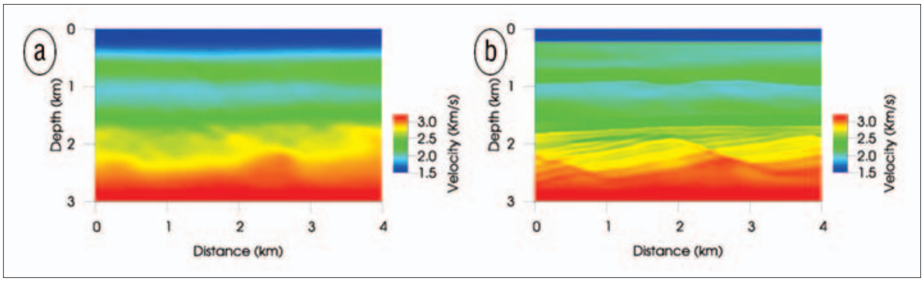

Figure 3. (a) Initial compressional-velocity model created using WEMVA. (b) Full-waveform inversion with the initial model shown in (a). Comparison with Figure 2c shows that the result is correct and not far from the true model. This is because the initial model in (a) is kinematically correct.

A useful technique for computing kinematically correct initial models is wave-equation migration velocity analysis (WEMVA). Figure 3 shows the inverted velocity model using the same data as in Figure 2, in which the starting model has been obtained using WEMVA. For comparison, the exact model is shown in Figure 2.

The fundamental idea in EWEMVA is to estimate the velocity model by optimizing the focusing of the reflectivity. Here, we use reverse time migration (RTM) to compute reflectivity. RTM back-propagates recorded data by solving the elastic wave equation starting with the largest recorded time samples and focusing waves toward earlier times. The wavefield created by the seismic source is also computed, and the reflectivity is formed by crosscorrelation of these two wavefields according to the extended imaging condition (Rickett and Sava, 2002)

$$R(x, h) = \int dt\, W^{S}(x-h, t, s)\, W^{r}(x+h, T-t, S),$$

where R is reflectivity, t is time, W^S is the forward-simulated source wavefield, W^r is the back-propagated data, x is the position, h is the subsurface offset, s is the source position, and T is the record length. These wavefields are computed by solving the full anisotropic elastodynamic differential equations.

Optimizing the focusing of the reflectivity is done mathematically by minimizing an object function given by (Weibull and Arntsen, 2014)

$$J = \int \left\| h \frac{dR(x, z, h)}{dz} \right\|^2,$$

where z is the vertical coordinate. This object function is known as differential semblance, and minimizing J is equivalent to flattening classical angle gathers.

The object function depends nonlinearly on the velocity model, and an iterative numerical procedure is required to find the velocity model which minimizes J. The simplest approach is to use a gradient-based search algorithm which computes in each iteration an update, Δc, of the velocity model according to

$$\Delta c = \alpha \nabla J,$$

where α is a step length and ∇J is the gradient of J with respect to the velocity model.

Usually a more sophisticated approach is used in which curvature of the object function is taken into account. In addition, this is an inverse problem which is nonunique and ill posed. In practice, this requires regularization in the form of additional terms added to the object function. The actual computation of the gradient requires the computation of two wavefields, similar to the computation of reflectivity. This procedure requires an initial velocity function which in most cases is reasonably simple, typically a linear gradient with depth, as shown in Figure 2.

Because we are using a full anisotropic elastic wave equation, we also can easily optimize other elastic parameters such as shear-wave velocity and anisotropic parameters. In Figure 4, we show an example of the initial and inverted compressional-wave velocity model using EWEMVA, along with inverted models for the anisotropic Thomsen parameters epsilon and delta.

Figure 5 shows the corresponding depth-migrated images of the initial and inverted models. We note that the depth section created by the optimized velocity model in Figure 5b is better focused than the section shown in Figure 5a using the initial velocity model.

The models obtained using EWEMVA are smooth and well suited for depth imaging. Lack of details in the models is counteracted by the fact that the models are kinematically correct and can explain traveltimes for reflected events, which makes these models ideal as initial models for elastic full-waveform inversion.

Elastic 3D full-waveform inversion (EFWI)

Full-waveform inversion is based on minimizing the error between observed seismic data, $p(x,t)^{obs}$, and forward-modeled synthetic data $p(x, t)$ with respect to one or more seismic parameters such as compressional-wave velocity, shear-wave velocity, and density. Several error measures have been proposed. The least-squares error is the most common and is defined by

$$e = ||p(x_r^{obs},t;x_s) - p(x_r,t;x_s)||^2,$$

where s and r are source and receiver indices, and t is time. We can use the same numerical technique as for EWEMVA to minimize the error and obtain an estimate of seismic parameters.

Estimating density, shear-wave velocity, and compressional-wave velocity is in practice quite challenging because those parameters have different sensitivities with respect to measured data. For conventional marine seismic data consisting of pressure measurements, sensitivity of compressional-wave velocity is much larger than sensitivity of shear-wave velocity and density, implying that only the compressional-wave velocity model can be estimated with some confidence. For other types of data, the situation might be different. In the case of ocean-bottom seismic, shear-wave velocity also can be estimated because of the presence of pure shear waves and converted waves.

Conventionally, pure acoustic wave propagation has been used for forward-modeling and computation of the model update. This makes some sense because an important contribution to the error is diving waves propagating from source to receiver without reflections. However, traditional seismic-imaging techniques are based on reflected waves, and in fact, diving waves usually are excluded. Because reflected energy penetrates deeper for the same offset as diving waves, reflected waves provide more information about deeper structures.

It thus makes sense to include reflected waves in the inversion process. However, attempting to use the acoustic approximation to also describe reflected waves will fail because the acoustic reflection coefficient is usually different from the elastic reflection coefficient and has a different AVO behavior. To include both diving waves and reflected waves in the inversion, the full elastic description has to be used. This is clearly demonstrated in Figure 1, in which data contain mostly reflected energy, and we see that the acoustic approach fails miserably.

EFWI requires considerably more computer resources than acoustic full-waveform inversion. This is because of the larger number of differential equations to solve, but also because the numerical grid needs to be fine enough to resolve the short wavelengths of the shear waves. We have implemented a fully shot-parallelized code for 3D elastic inversion capable of running efficiently on a multicore computer cluster. In the following section, we show application of this code to time-lapse seismic data, both real and synthetic.

Elastic time-lapse full-waveform inversion (ETLFWI)

The time-lapse, or 4D, technique has seen increased use in the last decade, particularly for mature provinces where maximizing the recovery rate is economically important.

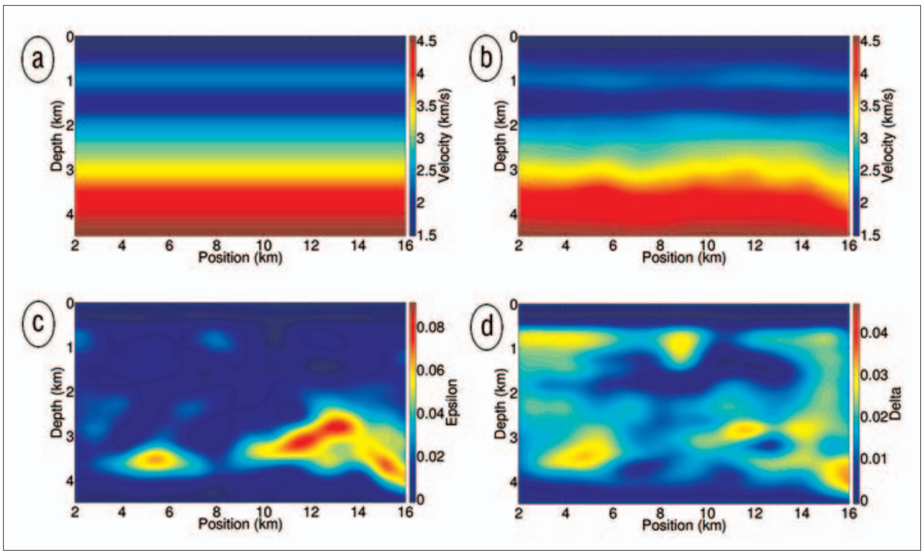

Figure 4. (a) Initial compressional-velocity model. (b) Velocity model estimated by EWEMVA using the initial model in (a). Note that the inverted velocity model is smooth and contains few details but is kinematically correct. Parts (c) and (d) show Thomsen parameters epsilon and delta estimated by EWEMVA.

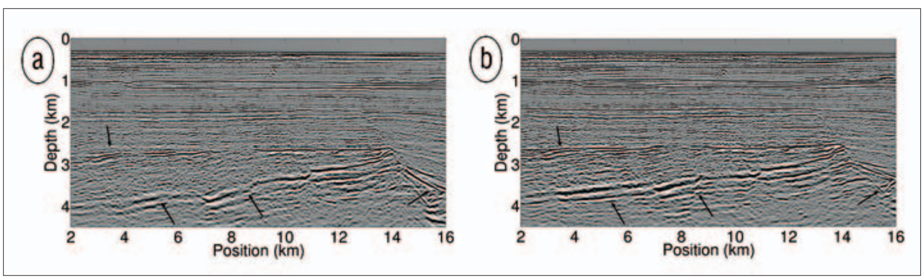

Figure 5. (a) Depth-migrated image using the initial velocity model shown in Figure 4. (b) Depth-migrated image using the velocity model and anisotropic parameters inverted by EWEMVA shown in Figure 4. Arrows mark areas where the section is improved.

Conventionally, the 4D technique has been based on using poststack data to infer changes in seismic parameters. Use of full-waveform technology offers the possibility of obtaining a direct estimate of the difference between pre- and postproduction seismic parameters (Raknes and Arntsen, 2014). To do this successfully, the complete seismic wavefield, including the reflected part, has to be used, which in practice implies that a full elastic inversion approach is necessary.

As an example, synthetic ocean-bottom-cable time-lapse data were computed for a part of the SEG/EAGE overthrust model and then were inverted for compressional- and shear-wave velocity. Figure 6 show horizontal slices through the channels of the inverted compressional- and shear-wave models and the corresponding exact models.

The velocity in sand channels was changed slightly to simulate a production effect. Figure 7a shows the velocity change. Synthetic data were generated for the changed model and were inverted for compressional- and shear-wave velocities. Figures 7b and 7c shows the difference between the inverted results shown in Figure 6 and the inverted results for the changed model in a 3D view. It is clear that full-waveform inversion is capable of reproducing the true time-lapse effect.

Two-dimensional elastic time-lapse full-waveform inversion was applied to a North Sea data set in which the initial compressional-velocity model was estimated using EWEMVA. Conventional streamer data are sensitive to shear-wave velocity mainly through angle dependence of reflection coefficients. Although this effect is important for matching observed and modeled data in the inversion, estimating the shear-wave velocity is difficult. Instead, the shear-wave velocity model and density model were obtained from the compressional-velocity model using empirical relationships. This ensures that the elastic effect on the amplitudes is approximately accounted for. The source pulse was inverted using direct arrivals.

Very little preprocessing was performed on the data except for applying a band-pass filter with cutoff at 20 Hz and a time-variant scaling factor to account for the difference between 2D and 3D geometric spreading.

Figure 8a shows the inverted time-lapse velocity model. A velocity anomaly is expected at a depth of approximately 450 m because of an underground blowout and is clearly visible. The largest offset used in the inversion was 1200 m,

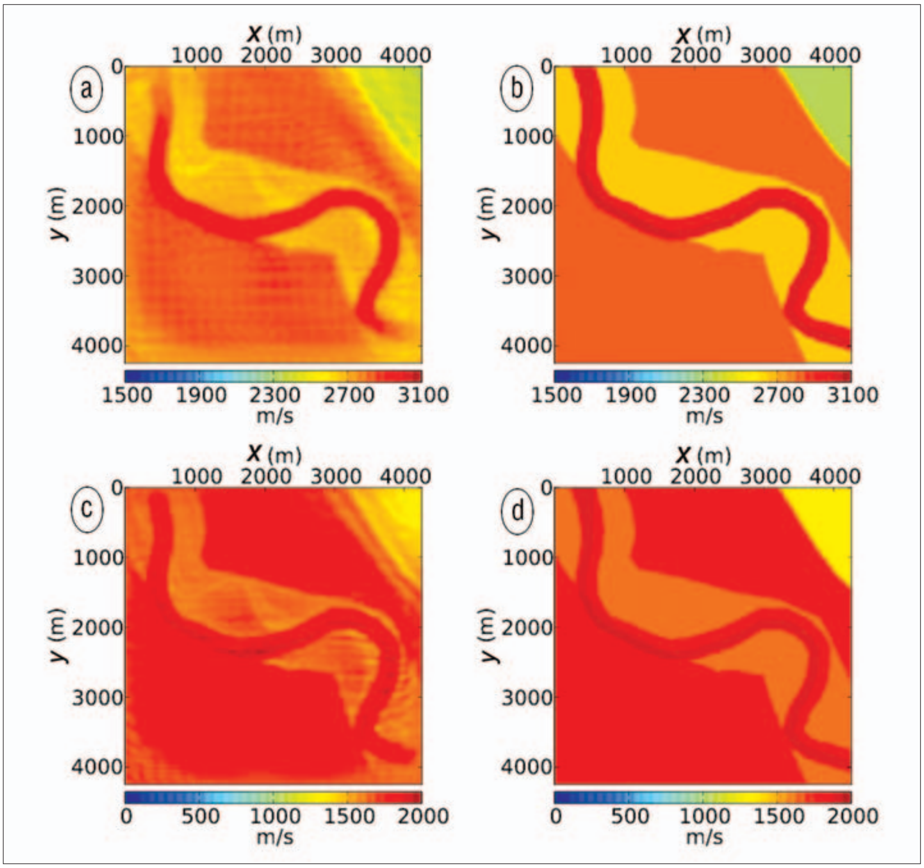

Figure 6. (a) Depth slice of compressional-wave velocity inverted by EFWI for the SEG/EAGE overthrust model. (b) Exact compressional-wave velocity. (c) Depth slice of shear-wave velocity inverted by EFWI. (d) Exact shear-wave velocity.

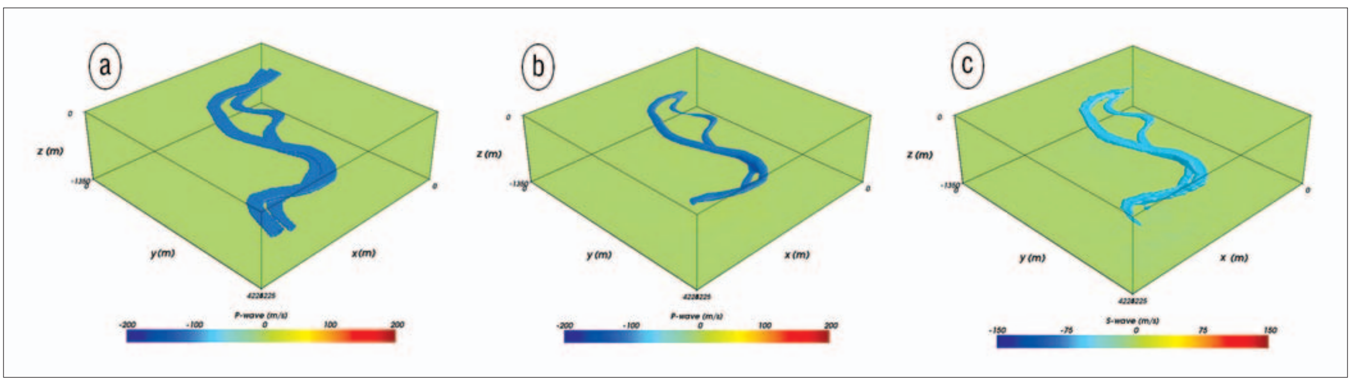

Figure 7. (a) Difference between base and monitor model for compressional-wave velocity showing the true time-lapse effect. (b) Compressional-wave velocity time-lapse effect inverted by EFWI. (c) Corresponding shear-wave time-lapse effect.

which implies that reflected energy contributes significantly to the inverted result. The large-scale trends in the velocity model are hard to obtain from reflection arrivals; these will be provided mostly by the initial model. The combination of WEMVA and EFWI thus provides a velocity model containing both large-scale trend and small-scale details.

Because the main contribution to the inversion is reflected energy, one would expect that full-waveform inversion using the acoustic approach would fail because the acoustic and elastic reflection coefficients are different. This is indeed the case, as shown in Figure 8b. The acoustic inversion shows anomalies in the shallow part of the section that are not present in the elastic result.

Conclusions

Seismic data are fundamentally elastic. Although the acoustic approximation has turned out to be useful, the elastic approach should be used to take full advantage of the information in the seismic wavefield. However, there are difficulties still to be overcome. For conventional streamer data, estimating shear-wave velocity directly seems to be difficult. Although the elastic reflection coefficient does contain shear-wave information, the present formulation of full-waveform inversion seems not to exploit this. In addition, multiply converted waves usually have very low amplitudes, thus not contributing to the inversion. However, for OBC data, the situation is different because the presence of converted waves provides kinematic shear-wave information which can be used easily.

Applying elastic full-waveform inversion to 4D seismic data seems in principle to be possible, at least for data types that contain converted-wave arrivals. For streamer time-lapse data, the situation is more undecided, but experience with real data seems to indicate that this should be possible if additional information such as rock-physics models is available.

To obtain a complete solution to the problem of estimating subsurface velocity models containing both long- and short-wavelength information, full-waveform inversion in its present incarnation is not enough. Kinematically correct initial velocity models have to be provided, which we have demonstrated can be done by elastic wave-equation migration velocity analysis. The initial model estimation and the full-waveform inversion thus are performed in a consistent way, avoiding the ray approximation present in traditional tomography. TLE

References

Mora, P., 1987, Nonlinear two-dimensional elastic inversion of multioffset seismic data: Geophysics, **52**, no. 9, 1211–1228, http://dx.doi.org/10.1190/1.1442384.

Raknes, E. B., and B. Arntsen, 2014, Time-lapse full-waveform inversion of limited-offset seismic data using a local migration regularization: Geophysics, **79**, no. 3, WA117–WA128, http://dx.doi.org/10.1190/geo2013-0369.1.

Rickett, J., and P. C. Sava, 2002, Offset and angle-domain common image point gathers for shot-profile migration: Geophysics, **67**, no. 3, 883–889, http://dx.doi.org/10.1190/1.1484531.

Sirgue, L., O. I. Barkved, J. P. Van Gestel, O. J. Askim, and J. H. Kommedal, 2009, 3D waveform inversion on Valhall wide-azimuth OBC: 71st Conference and Exhibition, EAGE, Extended Abstracts.

Virieux, J., and S. Operto, 2009, An overview of full-waveform inversion in exploration geophysics: Geophysics, **74**, no. 6, WCC1–WCC26, http://dx.doi.org/10.1190/1.3238367.

Weibull, W. W., and B. Arntsen, 2014, Anisotropic migration velocity analysis using reverse-time migration: Geophysics, **79**, no. 1, R13–R25, http://dx.doi.org/10.1190/geo2013-0108.1.

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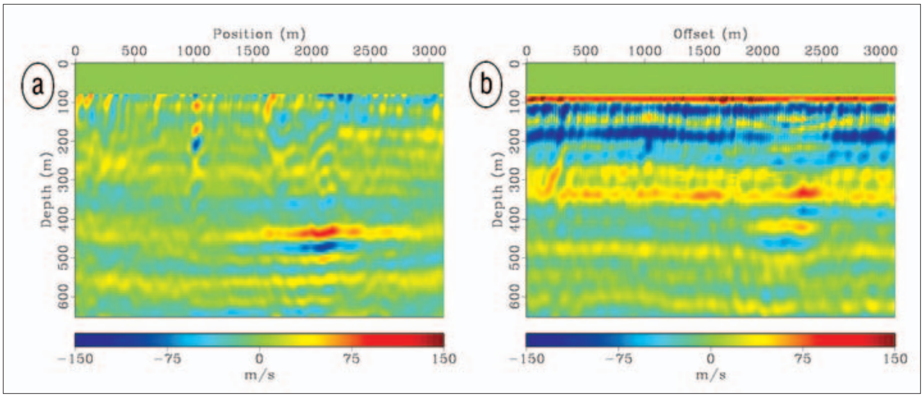

Figure 8. (a) Compressional-wave time-lapse effect using elastic FWI of a North Sea time-lapse survey. (b) Corresponding result using conventional acoustic FWI.