Acoustic full waveform inversion in time domain using blended data

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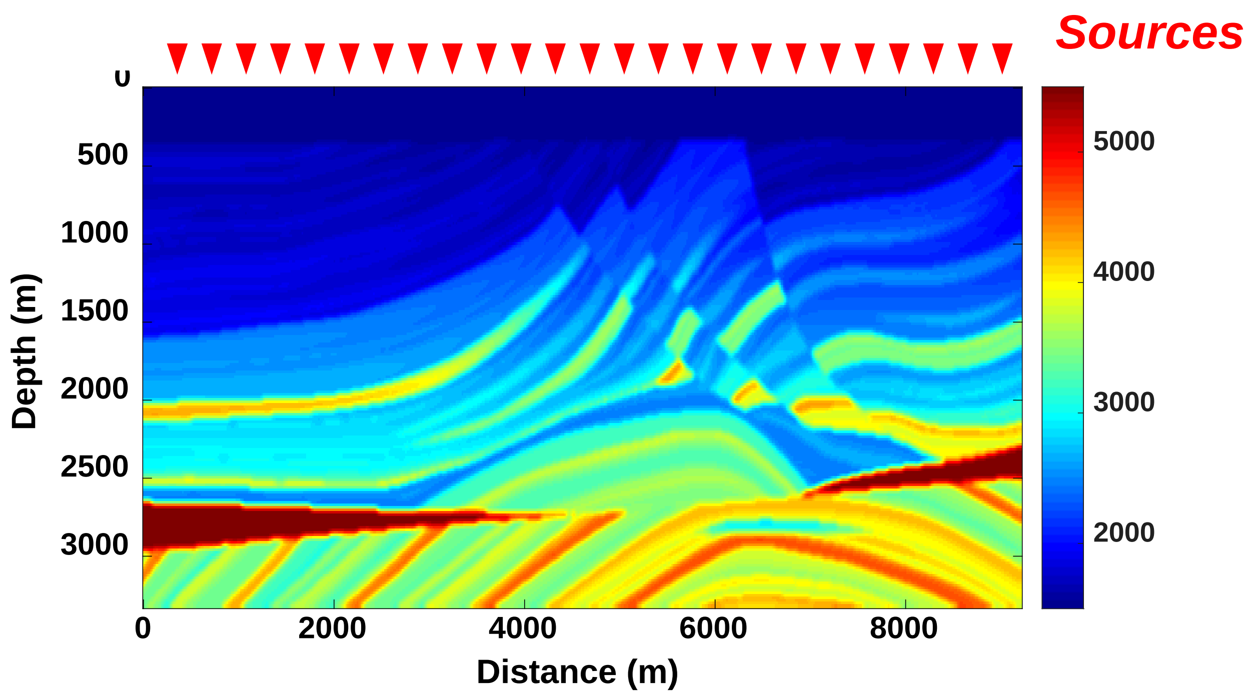
Outline

- Motivation
- Acoustic FWI using blended data
- Synthetic examples
- Conclusions

Motivation

- Super-shot or blended data strategy has been used in marine and land seismic surveys to reduce acquisition costs by reducing the number of recording times.



- To reduce the costs of both data acquisition and processing, FWI using blended data has been recognized very promising in future oil exploration.

Conventional acoustic FWI in time domain

In the case of constant density, the acoustic wave equation is described by

$$\frac{1}{v^2(x)}\frac{\partial^2 p(x,t;x_s)}{\partial t^2} - \nabla^2 p(x,t;x_s) = f_s(x,t;x_s) \qquad (1)$$

where $f_s(x,t;x_s) = f(t')\delta(x-x_s)\delta(t-t')$

The objective function (data misfit function) taking the least-squares norm of the misfit vector δp is given by

$$E(m) = \frac{1}{2}\delta p^{\dagger}\delta p = \frac{1}{2}\| p_{cal} - p_{obs} \|^2 \qquad (2)$$

where † denotes the adjoint operator (conjugate transpose).

Acoustic FWI using blended data

The encoding matrix is defined as

$$\mathbf{B} = \begin{bmatrix} b^{1,1} & b^{2,1} & . & b^{N_{ig},1} \\ b^{1,2} & b^{2,2} & . & b^{N_{sig},2} \\ . & . & . & . \\ b^{1,N_{sup}} & b^{2,N_{sup}} & . & b^{N_{sig}\cdot N_{sup}} \end{bmatrix} \tag{3}$$

where *Nsup* is the number of the super-shots and *Nsig* is the number of the individual shots.

The *Nsig* single shots are blended into *Nsup* super shots by

$$\begin{aligned} p_{cal}^{sup} &= \mathbf{B}p_{cal} \\ p_{obs}^{sup} &= \mathbf{B}p_{obs} \end{aligned} \tag{4}$$

The objective function is redefined by:

$$\begin{aligned} E(\mathbf{m}) &= \frac{1}{2}\left\|p_{cal}^{sup} - p_{obs}^{sup}\right\|^2 = \frac{1}{2}\left\|\mathbf{B}p_{cal} - \mathbf{B}p_{obs}\right\|^2 \\ &= \frac{1}{2}\left(p_{cal} - p_{obs}\right)\boxed{\mathbf{B}^T\mathbf{B}}\left(p_{cal} - p_{obs}\right) \end{aligned} \tag{5}$$

Source-encoding strategies

Source-encoding strategies are first introduced into pre-stack migration in frequency domain (Romero et al., 2000).

Random time delay: compose multi-source shot gather of a sum of single shot gathers with random time delays (Zhan et al., 2009; Florez et al., 2016).

Random polarity: multiply the source wavelet with random polarity of +1 or -1 and then blend all the shot gathers into one super-shot at each iteration (Krebs et al. , 2009).

Combined strategy: use both random time delay and random polarity as the encoding function in LSRTM (Dai et al., 2012).

Amplitude encoding: apply different amplitude weights to all the individual shot gathers and then blend them into super-shots for wave migration (Godwin and Sava, 2013; Hu et al., 2016).

Synthetic model

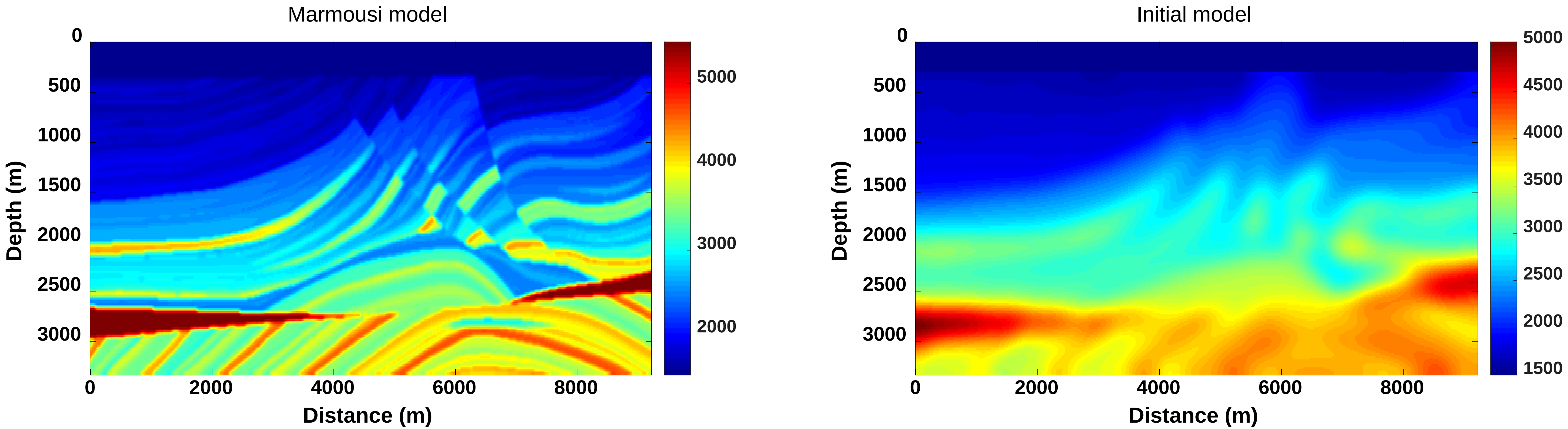


Fig 1. (a) The original Marmousi is down sampled along depth and lateral direction. The shots are generated according to the Marmousi model. (b) The initial model of FWI for Marmousi model, which is obtained by smoothing the original model.

Acquisition geometry

140 sources evenly distributed near the surface of the model with a spatial interval of 64 m (4 grids).

576 receivers deployed beneath the sources with a spatial interval of 16 m (1 grid).

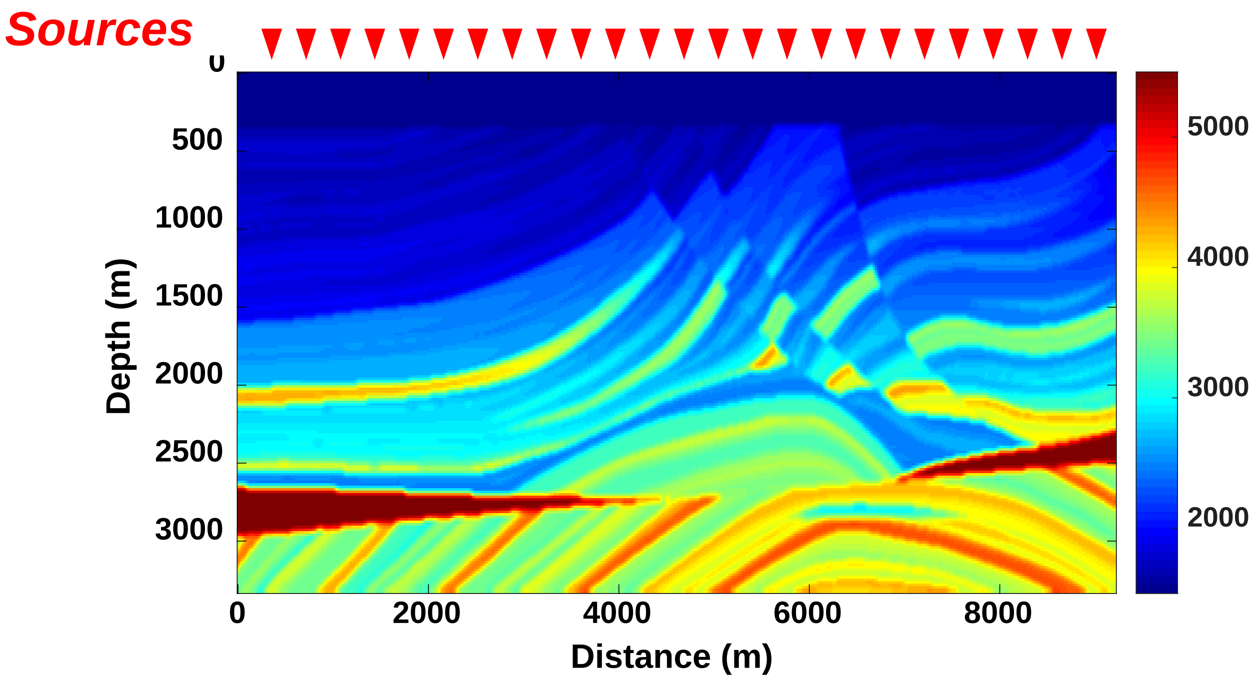


Fig 2. Acquisition geometry

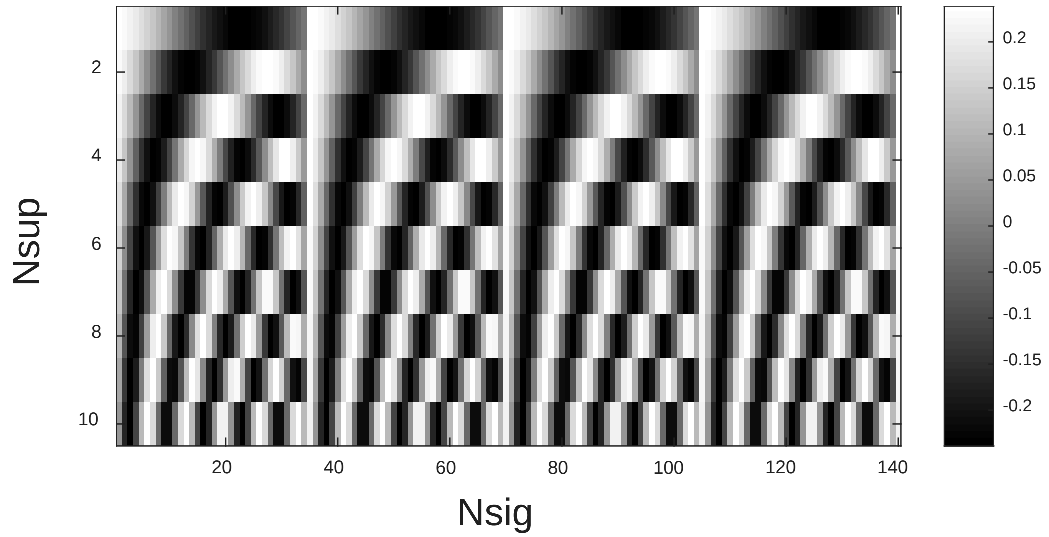
Instead of blending all the shots into one super-shot, we blend them into 10 super-shots that contain all the shot records.

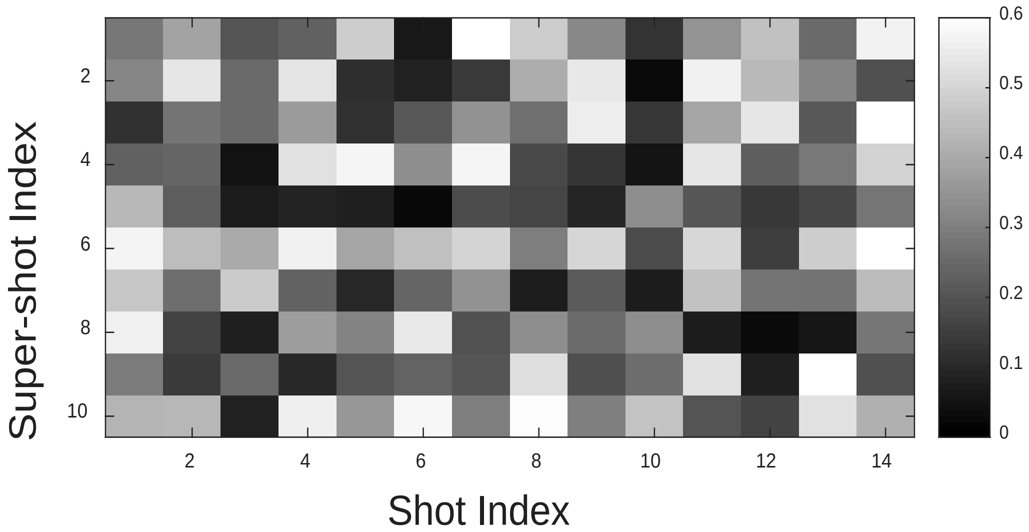
Source-encoding matrices

For amplitude source-encoding using cosine basis , the encoding matrix element is defined as (Hu et al., 2016):

$$b = \sqrt{\frac{2}{n_{\mathrm{sig}}}} \cos\left(\frac{\pi}{n_{\mathrm{sig}}} \frac{(2iss+1)(2ik+1)}{4}\right) \quad (6)$$

where iss=j%nsig, j is the shot index, ik is the super-shot index, nsig is the number of the single shots in a reference distance.





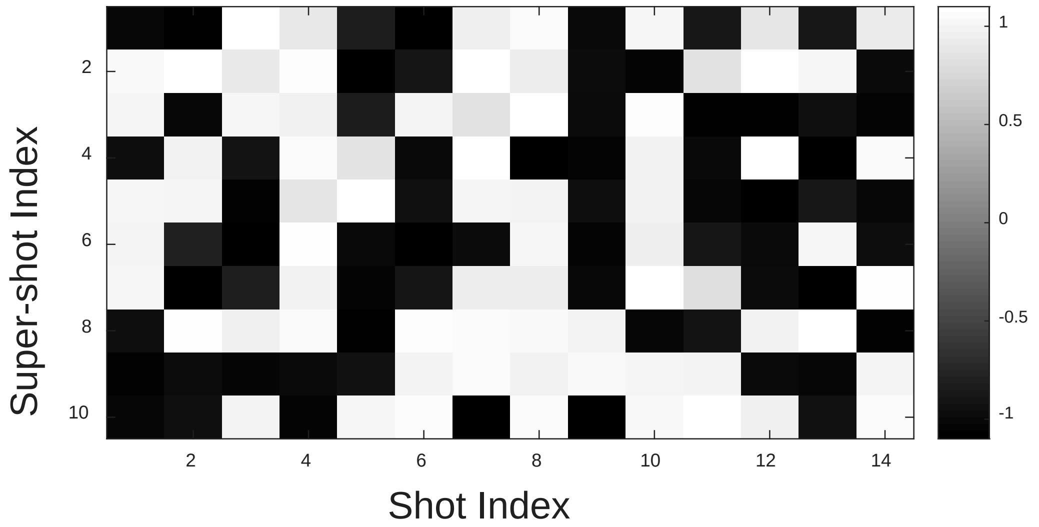


Fig 3. Encoding matrix: (a) amplitude encoding; (b) random time delay encoding; (c) random polarity encoding

Synthetic acoustic data

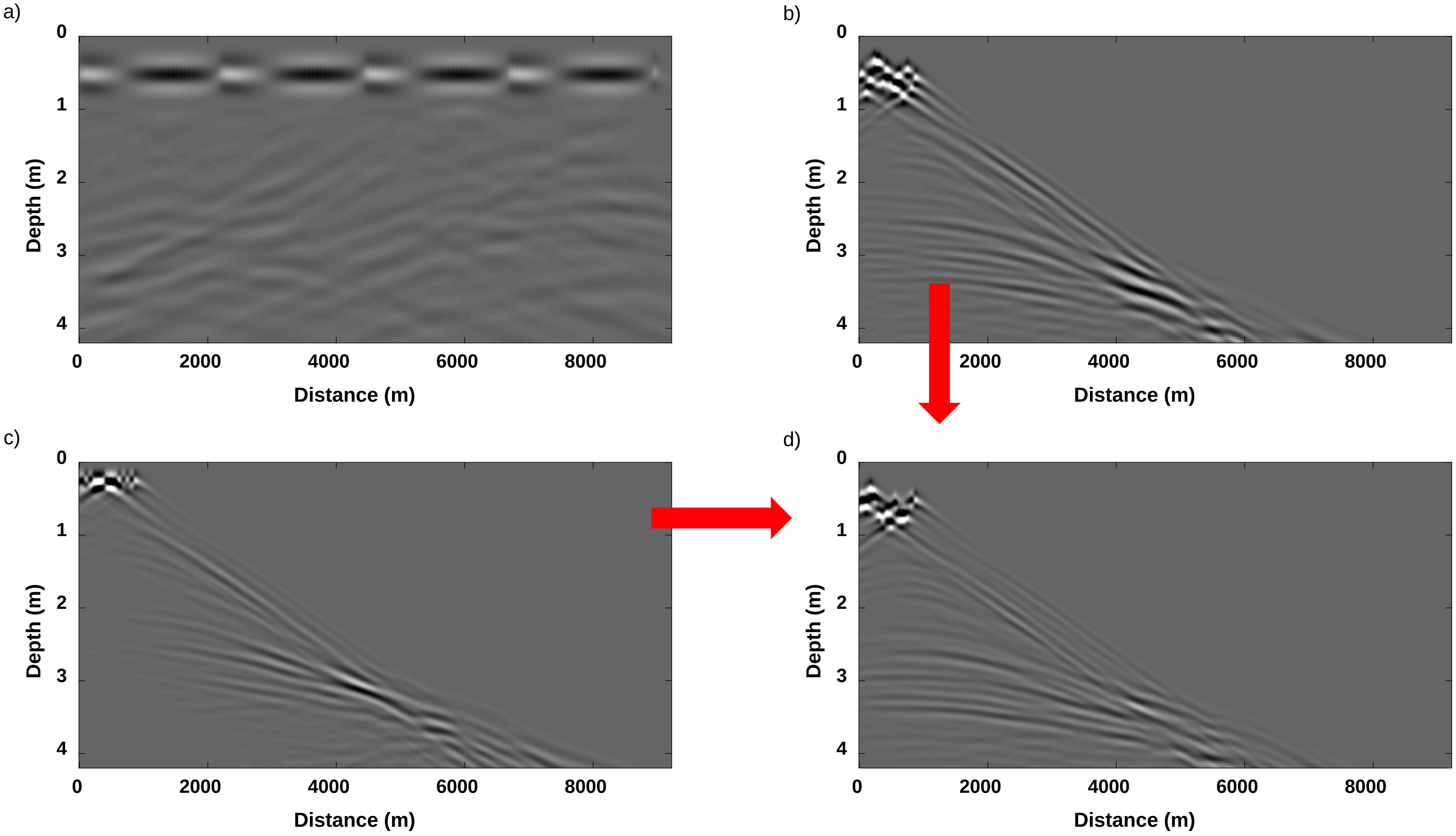


Fig 4. Synthetic first super-shot for acoustic FWI using blended data: (a) the first super-shot encoded with amplitude matrix; (b) the first super-shot encoded with random time delay; (c) the first super-shot encoded with random polarity; (d) the first super-shot encoded with both of random time delay and random polarity.

Comparison of updated velocity model

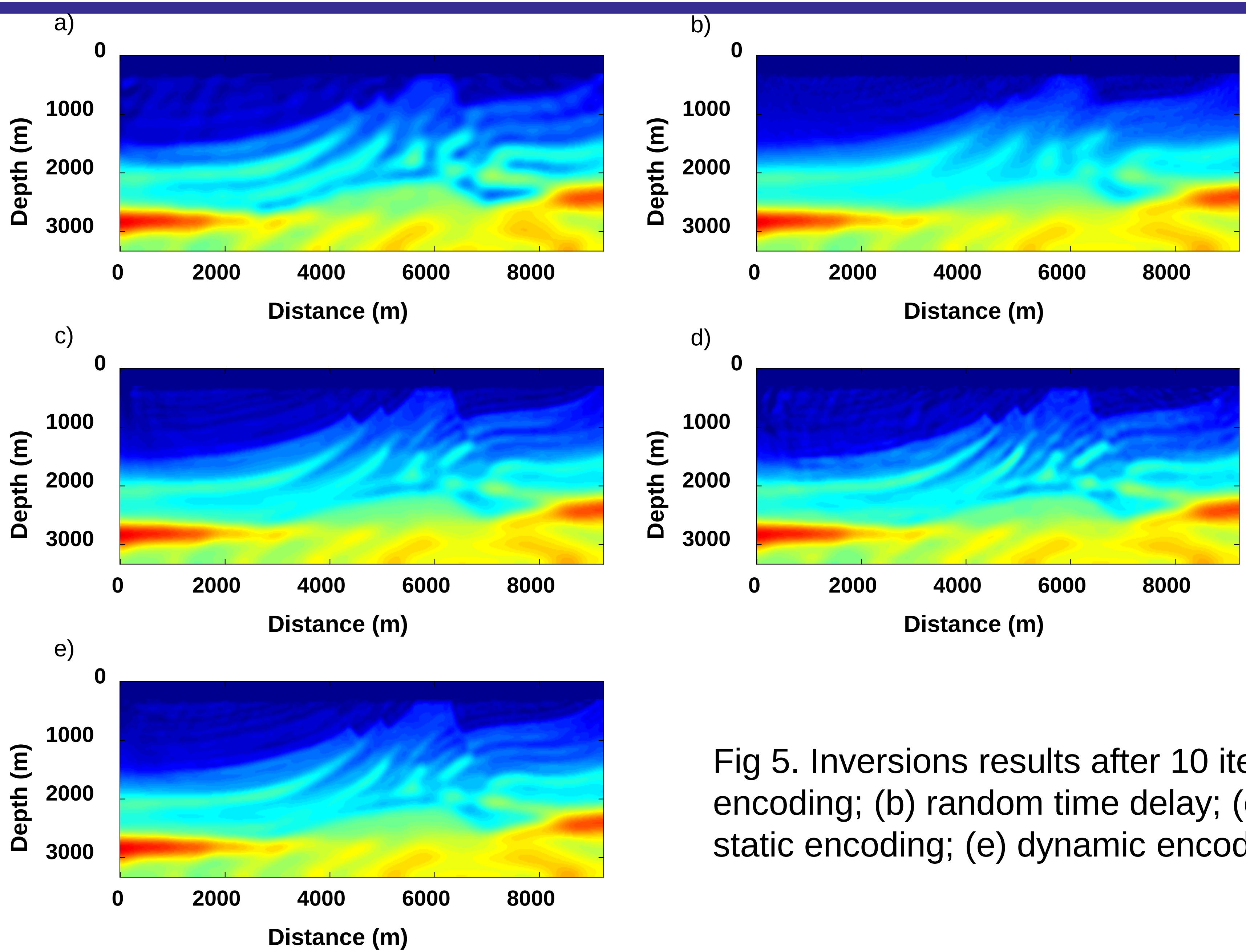


Fig 5. Inversions results after 10 iterations: (a) amplitude encoding; (b) random time delay; (c) random polarity; (d) static encoding; (e) dynamic encoding.

Comparison of updated velocity model

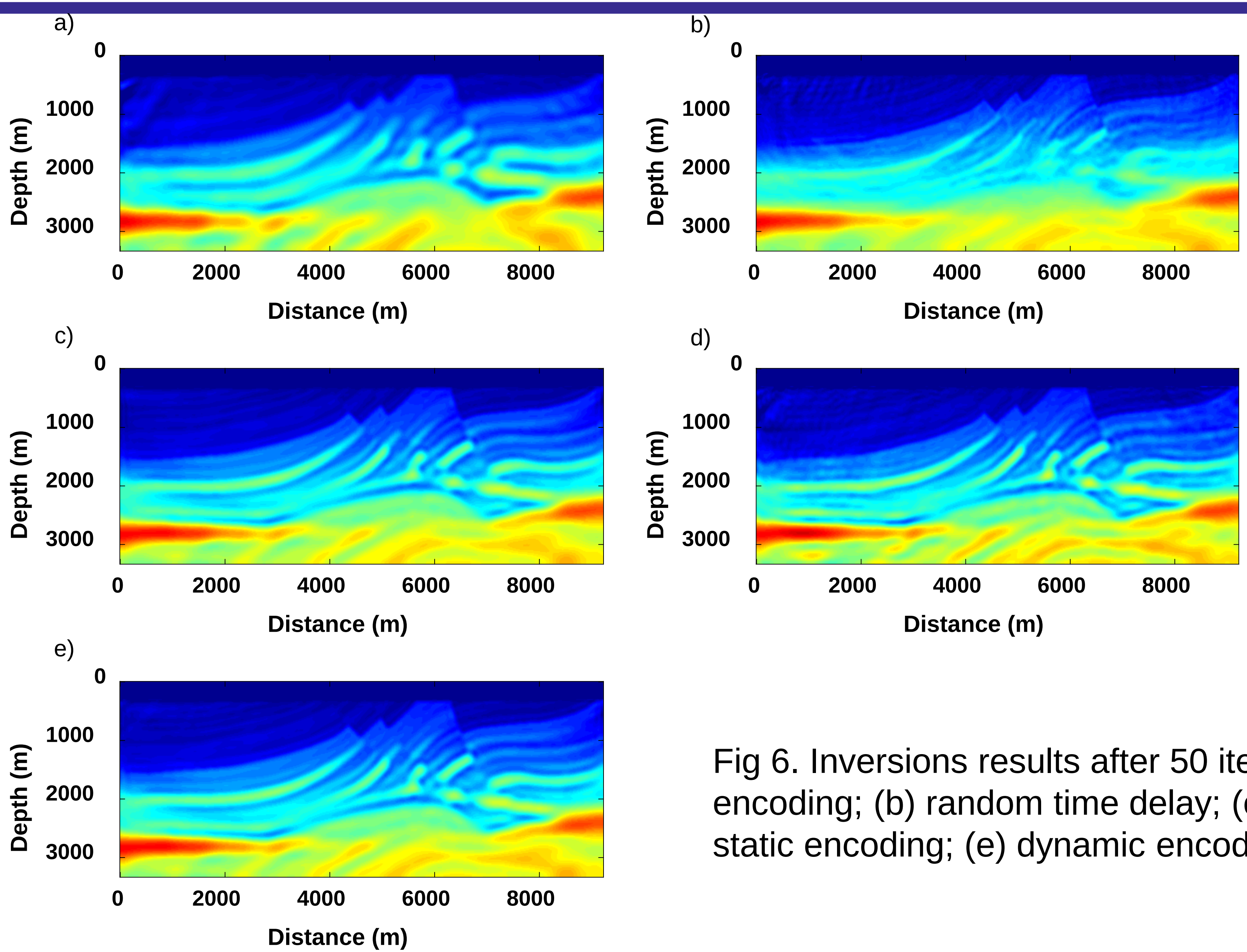


Fig 6. Inversions results after 50 iterations: (a) amplitude encoding; (b) random time delay; (c) random polarity; (d) static encoding; (e) dynamic encoding.

Comparison of updated velocity model

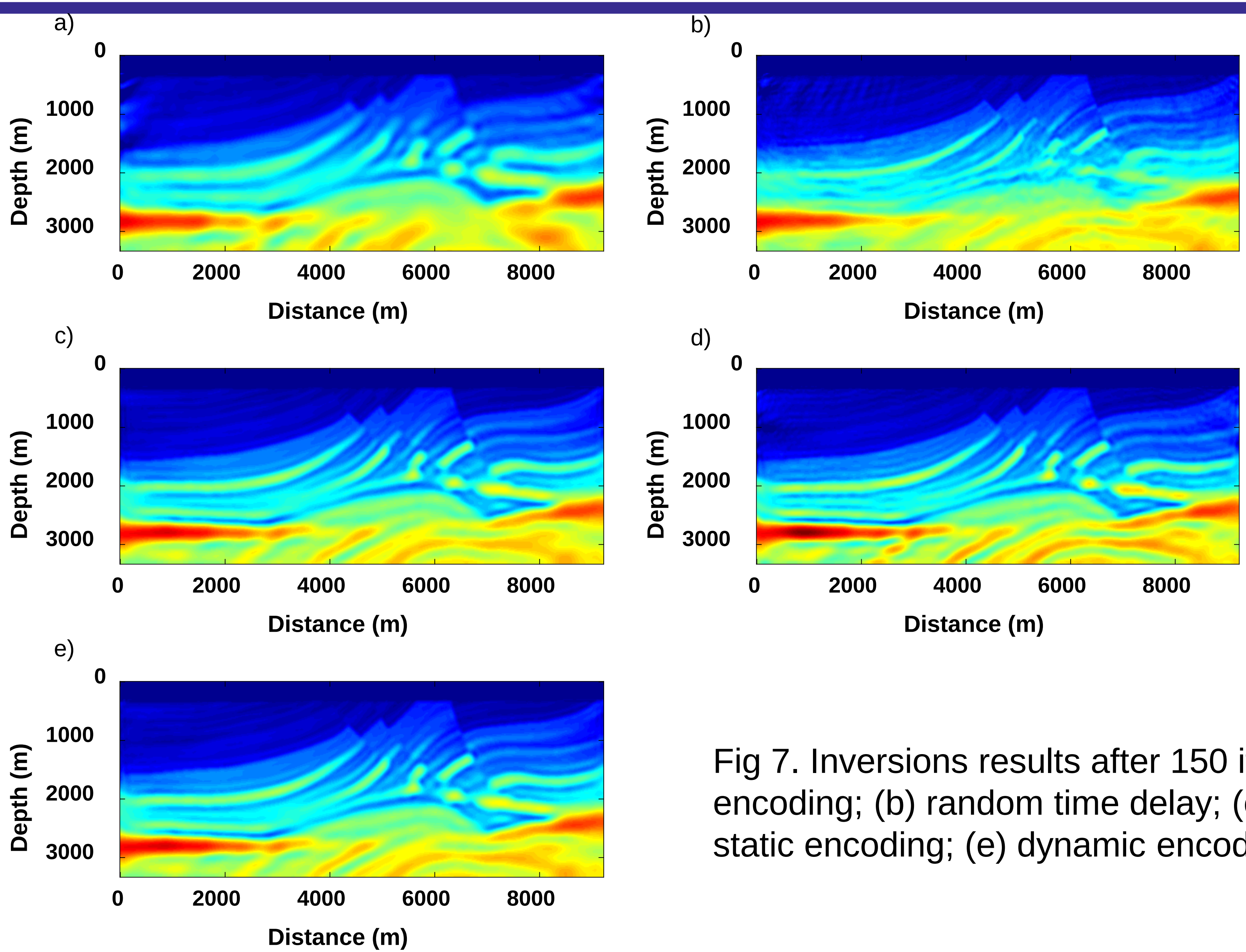
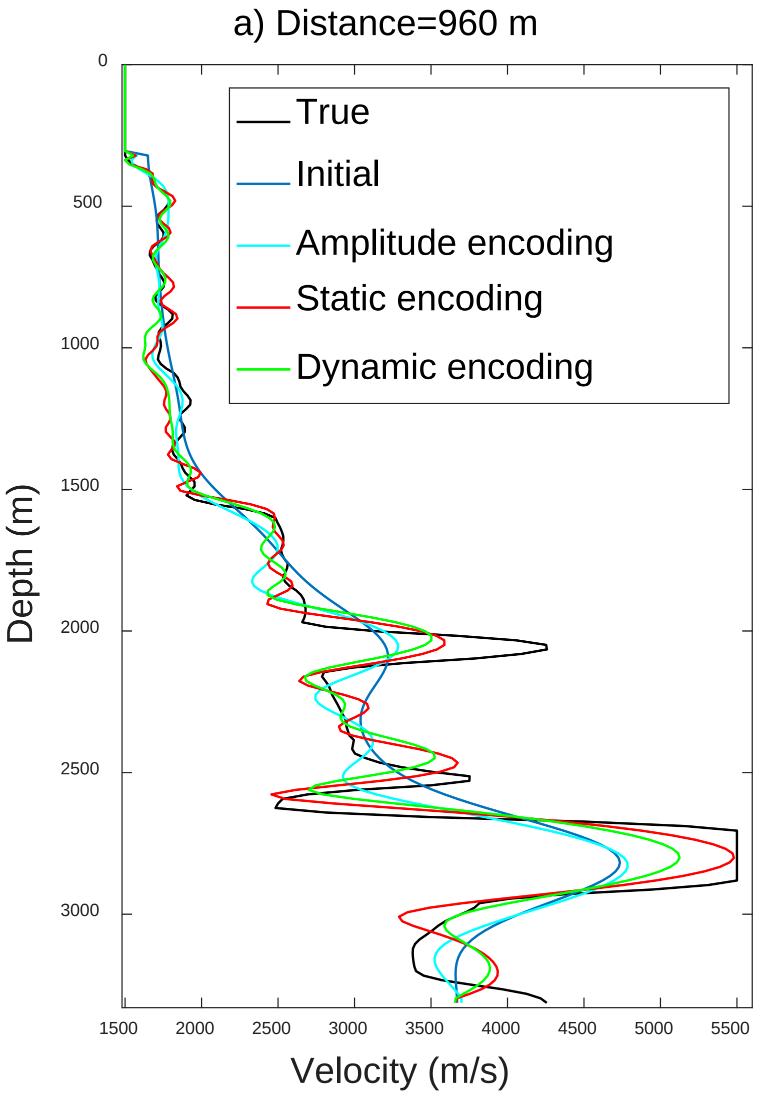


Fig 7. Inversions results after 150 iterations: (a) amplitude encoding; (b) random time delay; (c) random polarity; (d) static encoding; (e) dynamic encoding.

Comparison of vertical profiles



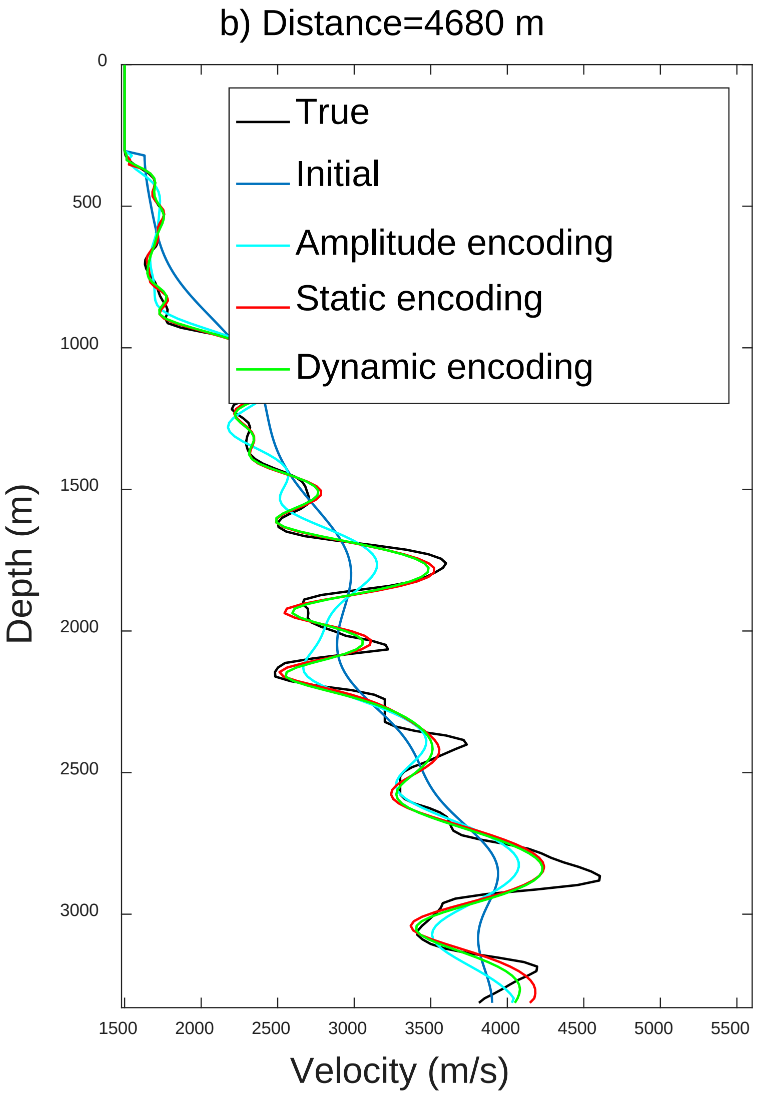


Fig 8. Comparison of vertical profiles between the true, initial and inverted velocity models using static and dynamic encoding at different locations.

Comparison of model misfit

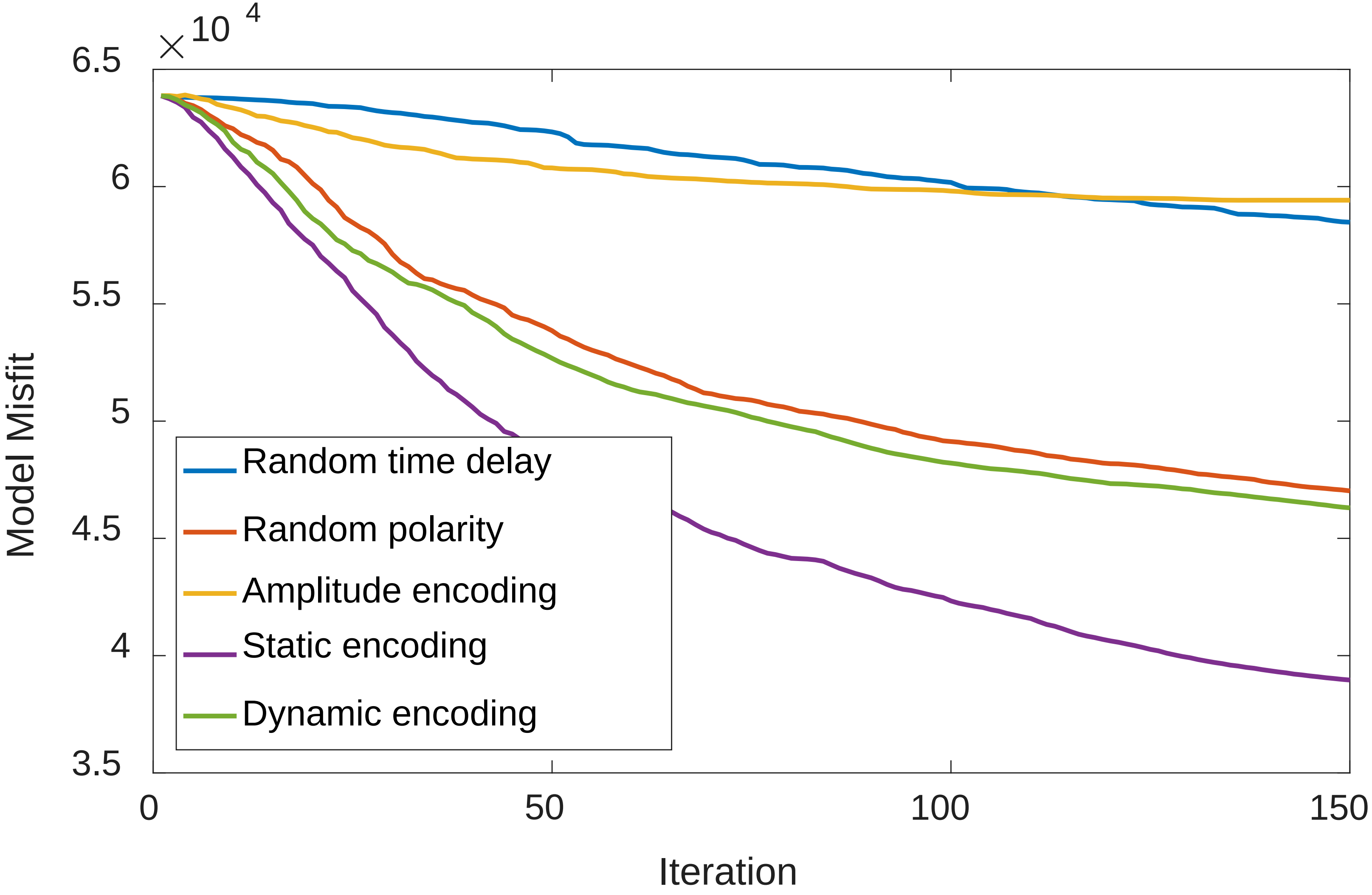


Fig 9. Comparison of model misfit versus iteration for FWI using different source-encoding strategies: random time delay, random polarity, amplitude encoding, static encoding and dynamic encoding.

Conclusions

1. In this work, we present acoustic FWI in time domain using blended data with different source-encoding strategies, which avoids the de-blending stage and reduces both of field data acquisition and computational cost.
2. In our experiments, amplitude and random time delay encoding provide slow convergence rate and less satisfactory updated velocity models.
3. FWI using the static combined source-encoding strategy provides the fastest convergence rate and satisfactory updated velocity model, even though there still remains minor artifacts.
4. For FWI using the dynamic combined source-encoding strategy, it also converges fast and provides updated velocity model with ignorable artifacts. However, considering the calculation efficiency, it requires extra computational cost of forward modelling and I/O cost with a factor directly associated with the number of blended data and iteration times.

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