

**Figure 13.** Field and modelled data for the hydrophone channel of OBS 32, for (a) the same five traces as shown in Fig. 7 and (b) the same trace as shown in Fig. 9. Predicted data are generated using the smooth starting model in Fig. 6(b) and the final FWI model shown in Fig. 10. The location of the peaks and troughs for the data predicted by the FWI model are closer to the observed data overall, and the relative amplitudes of the peaks and troughs are much better matched for traces 1–3 in panel (a).

velocity model, respectively. Data from longer offsets are included in this plot as data out to 15 km offset were input to inversions at this frequency. The match between predicted and observed phase is clearly significantly better for the final velocity model. In summary, the phase plots show no evidence of cycle-skipping and suggest that FWI is moving the velocity model towards a global not a local minimum.

Fig. 13(a) shows the same five traces as in Fig. 7. The observed traces are examples of data input to the inversion with the 750 ms window applied. The predicted data are generated from the starting and final FWI velocity models. The FWI model produces data that better match the observed: the travel times to individual peaks and troughs are closer overall, and there is significant improvement in the waveform match. For example, the amplitudes of the peaks and troughs in the later arrivals in traces 1–3 are all closer to the observed. Fig. 13(b) shows the same trace as in Fig. 9; here the traveltimes fit is much better for the FWI model and the amplitude match is about the same. Note that the starting model is the smoothed velocity model shown in Fig. 6(b), for which the predicted data is shown in Fig. 9(b).

Fig. 14 shows the change in misfit for each iteration for the final inversion strategy. The misfit is reduced by ~14 per cent for the first 10 iterations at 3 Hz and then, thereafter, reduces by ~5 per cent every 10 iterations. This relatively small reduction in misfit is in accordance with the observed improvement in match for individual traces (Fig. 13): the initial fit is quite good and the improvement is clear but often quite small.

While testing different inversion strategies for the field data, the same strategies (smoothing, window lengths, iteration sequence) were also applied to recover checkerboards of various sizes and depths within the velocity model. These checkerboard tests were run to verify that the adopted inversion strategy could recover the anomalies seen in the inverted velocity models. Fig. 15 shows depth slices (where depth is bsl) through checkerboards that were all recovered using the inversion strategy adopted in the final FWI models shown in Fig. 10. Fig. 15(a) shows the successful recovery of a  $1.5 \times 1.5 \times 1.0$ -km sized checkerboard that was placed between 2.8 and 3.8 km bsl. Below this depth only larger checkerboards could be recovered. Fig. 15(b) shows the recovery of a checkerboard that was 2.5-km wide and 2-km deep and placed between 3 and 5 km bsl; Figs 15(c)–(d) show the recovery of the same checkerboard located between 4.5 and 6.5 km bsl. The smaller checks are well recovered down to about 3.5 km bsl, and the larger checks are well recovered down to about 4.5 km bsl. Below this, the checks are partially recovered down to about 6 km bsl, by which we mean

that the velocity perturbations are at the correct location and have the correct sign, but the absolute size of the perturbation is not recovered. Hence, it can be concluded that, away from the model edges, the velocity structure in the final inversions is likely to be real, but the magnitude of the recovered anomalies is probably too small in deeper parts of the model.

To explore further whether the final inversions are robust and produce consistent results, two additional tests were performed. In the first, the final velocity model shown in Fig. 10 was used to generate synthetic data, which was then treated as the observed data and inverted using the original inversion strategy and starting model. Fig. 16 shows the results of this test above the original FWI model. Each of the depth slices have the same structural features and all the areas of high and low velocity are matched. The re-recovered velocity model is slightly smoother, and only about 80 per cent of the original velocity perturbation has been recovered. In this test, unlike for the field data, the observed data are noise free. Hence, the results shown in Fig. 16 suggest that the velocity anomalies obtained from inverting the field data are recoverable using the selected inversion strategy, and are not artefacts produced by noise within the field data. This test also suggests that our final inversion strategy will not fully recover the magnitude of the real velocity anomalies.

In the second test, a new starting model was generated by taking the velocity perturbations recovered by FWI, multiplying them by 1.5 and adding them to the original starting velocity model (Figs 17a–c). The inversion was performed again using the same input field data and with the original inversion strategy, but substituting this model as the starting model. Such an approach is useful in FWI since the inversion tends to head in the right direction but may take many iterations to get there. The process of multiplying the recovered perturbations by 1.5 can move the inversion more rapidly towards the global minimum. Figs 17(d)–(f) show that the inversion moves the recovered anomalies back towards the original FWI model (Figs 17g–i). The results of this test, together with the other quality assurance procedures that have been applied, lead us to the conclude that the velocity structure in our final velocity model is robust. The recovered features in the FWI model shown in Fig. 10 consistently appear in the inverted velocity models.

## DISCUSSION

The checkerboard tests shown in Fig. 15 indicate that FWI can improve the model resolution by 2–4 times over traveltime tomography. A suite of checkerboard tests were performed by Weekly *et al.* (2014), and these showed that traveltime tomography could recover  $2.5 \times 2.5 \times 1$ -km sized checks in the uppermost 2 km of the crust, and  $5 \times 5 \times 2$ -km checkerboards down to 3 km below the seafloor. The recovery of finer-scale structure in the FWI model shown in Figs 10(b), (d) and (f) is encouraging and suggests that the approach adopted here could be successfully applied to other relatively sparse data sets. The theoretical resolution for FWI is half the seismic wavelength (Pratt *et al.* 1996) which, for the final inversion frequency of 5.1 Hz, corresponds to ~300 m in the uppermost crust and ~750 m in the lower crust at the Endeavour ridge. The resolution of the FWI velocity models presented here, which correspond to about 1.5 km in the upper crust and 2.5 km in the lower crust (Fig. 15), indicate that we have only obtained about 1/3–1/5 of the potential resolution of this technology. A suite of additional inversions were attempted to improve the resolution, including many

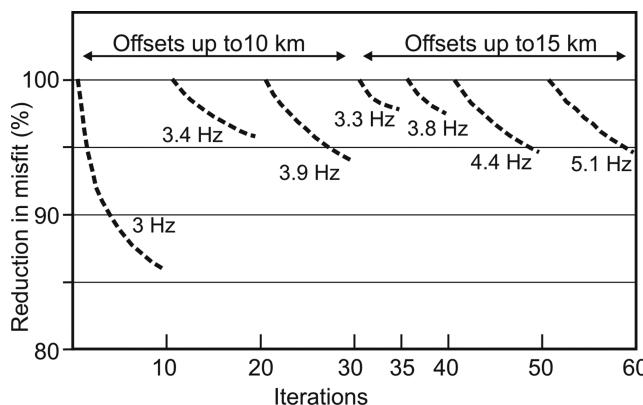
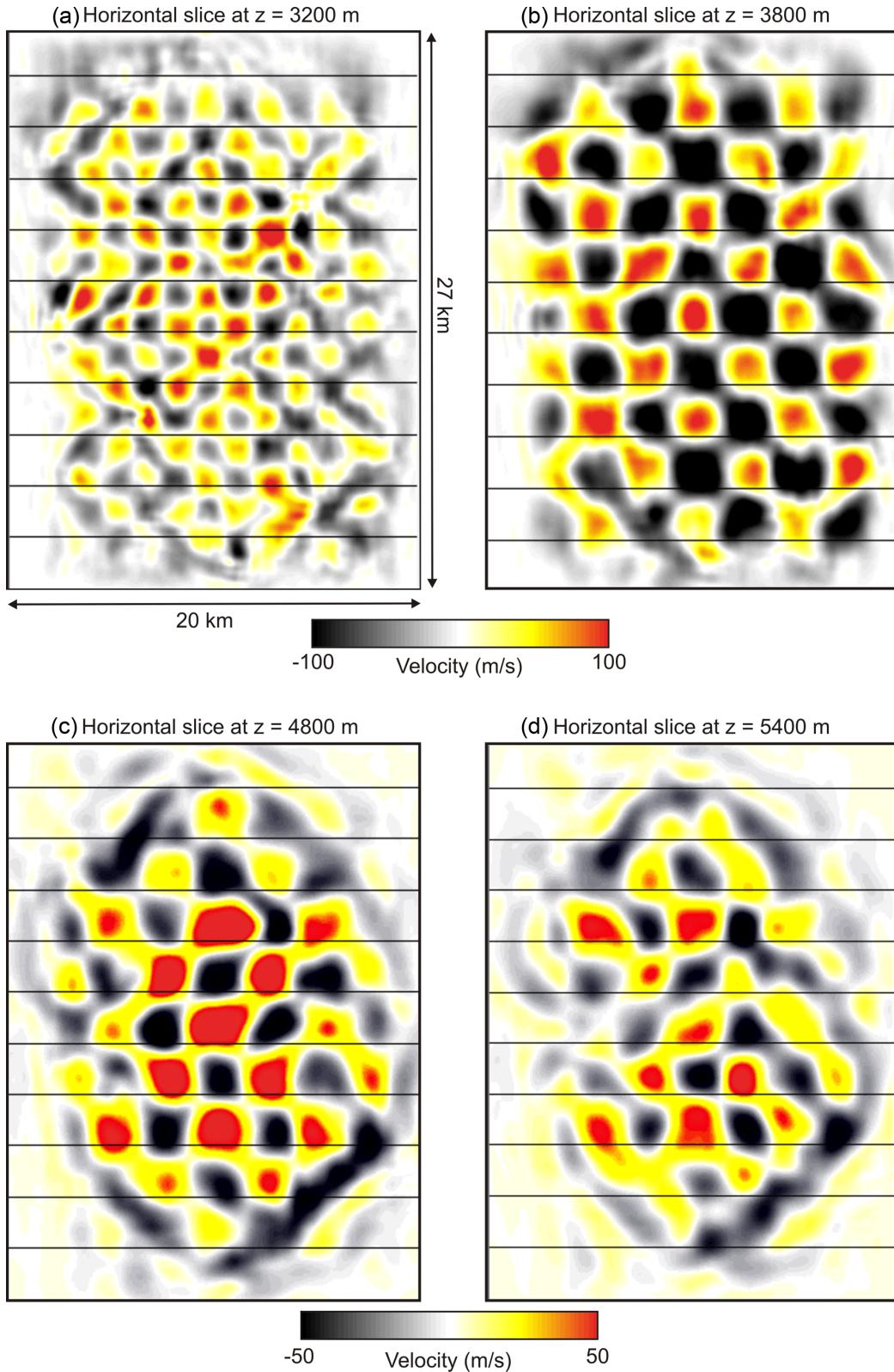
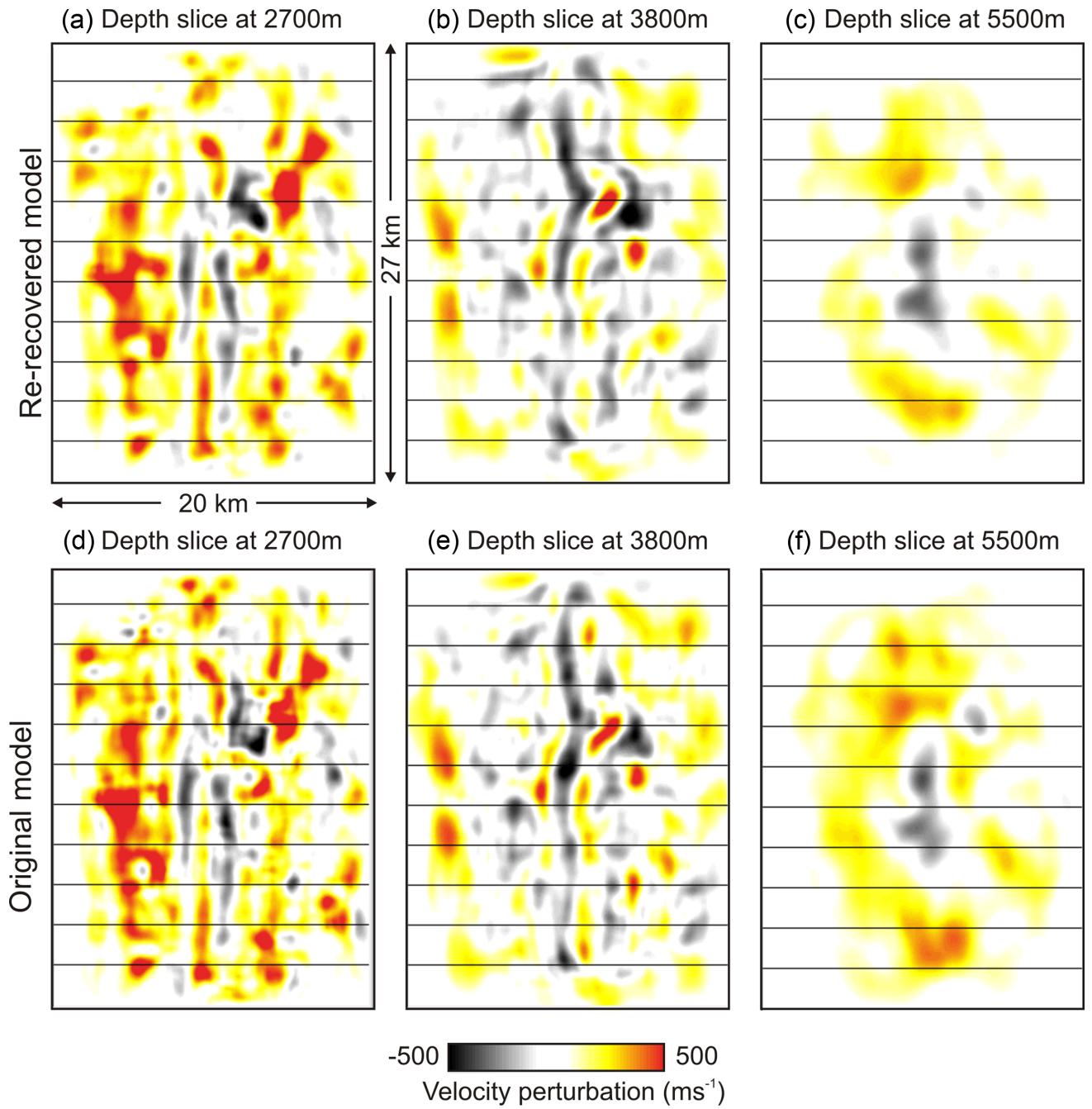


Figure 14. Plot showing the reduction in misfit at each iteration for the final inversion strategy used to recover the velocity model shown in Fig. 10.



**Figure 15.** Checkerboards at (a) 3200, (b) 3800, (c) 4800 and (d) 5400 m bsl, recovered using the same inversion strategy as in the final FWI model shown in Fig. 10. The checkerboard in panel (a) was 1.5 wide and 1.0 km deep and placed between 2.8 and 3.8 km bsl. In the other three plots, a checkerboard 2.5-km wide and 2-km deep was placed between (b) 3 and 5 km bsl and (c,d) 4.5 and 6.5 km bsl. The velocity perturbation was  $\pm 100 \text{ ms}^{-1}$ .

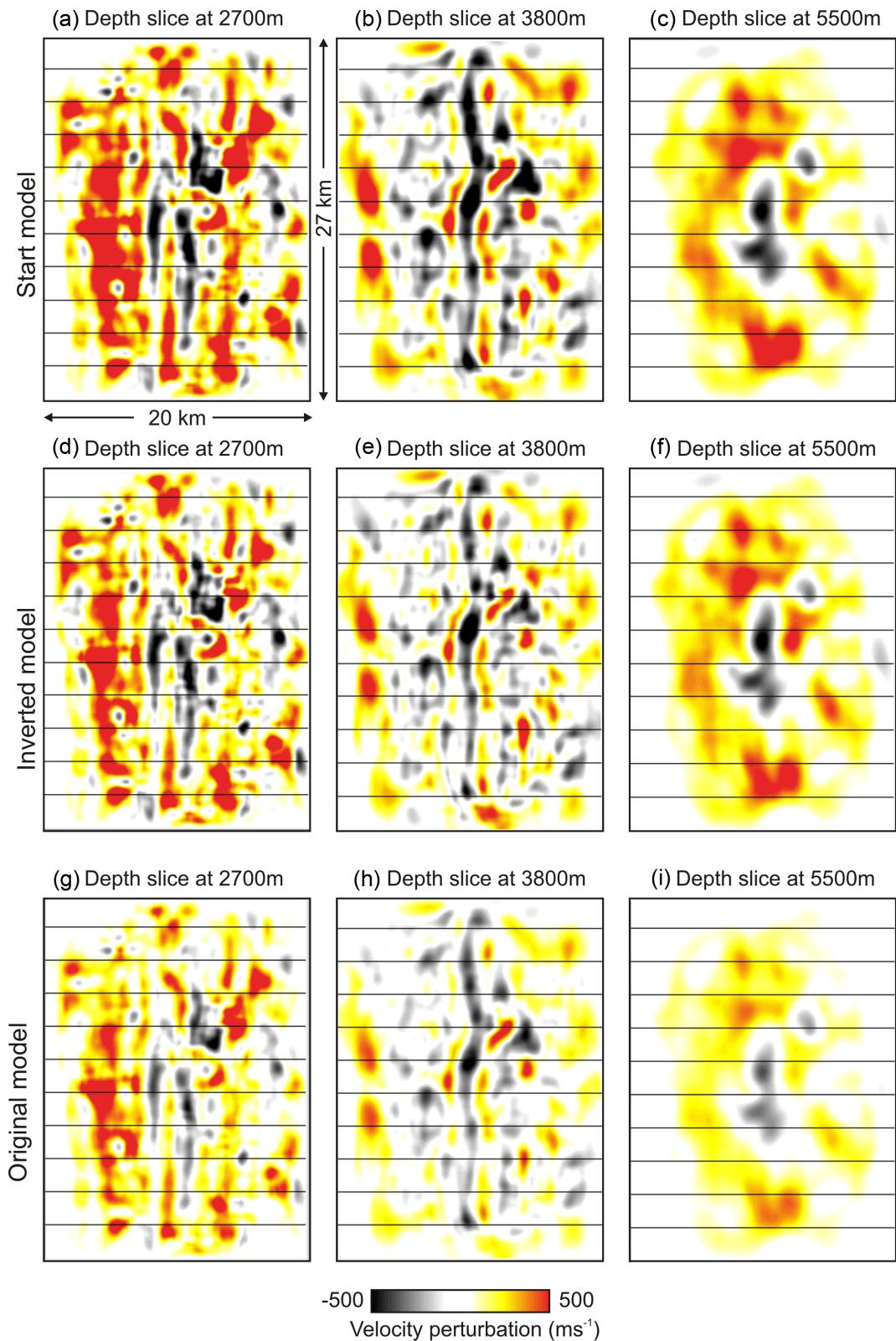


**Figure 16.** Depth slices showing velocity perturbation through: (a–c) a re-recovered and (d–f) original FWI velocity model at  $z = 2700, 3800$  and  $5500$  m bsl. In the re-recovered velocity model, the final velocity model shown in Fig. 10 was used to generate synthetic data, which were then treated as the observed data and inverted using the original inversion strategy and starting model. Each of the depth slices has the same structural features in the re-recovered and original FWI models, and all the areas of high and low velocity are matched.

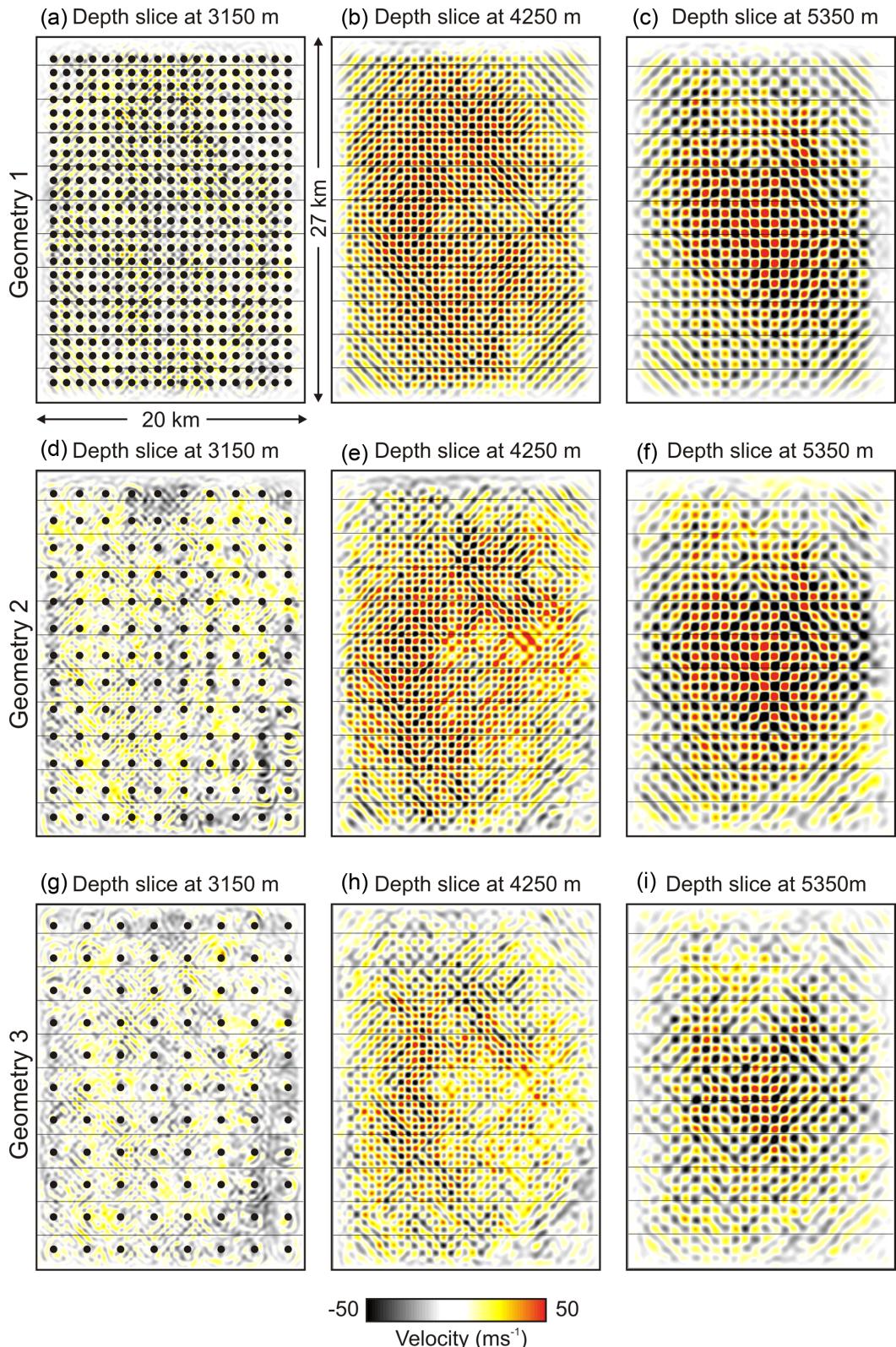
more iterations and the inversion of higher frequencies, but the recovered finer-scale features were more variable and the available quality assurance procedures were unable to distinguish whether one of these models was definitely better than another. Resolution for the Endeavour data set is almost certainly affected by the data sparsity, and may also be limited by noise and the fact that the original starting model was unable to accurately predict the secondary arrivals.

In order to investigate how the full potential resolution of FWI could be obtained, a suite of checkerboard tests were performed to explore the effect of denser experimental geometries. Since the

expected resolution at 5 Hz is  $\sim 300$  m in the upper crust and  $\sim 750$  m in the lower crust, three checkerboards were placed in the model: a 300-m check was placed between 3000 and 3300 m, a 500-m check was placed between 4000 and 4500 m, and a 750-m check was placed between 5000 and 5750 m. Fig. 18 shows the recovered checkerboards for three experimental geometries: (a–c) OBS spacing of 1 km and shot spacing of 250 m, (d–f) OBS spacing of 2 km and shot spacing of 250 m, and (g–i) OBS spacing of 2.5 km and shot spacing of 400 m. Not surprisingly, the checkerboards are best recovered using the closest OBS and shot spacing, but the checkerboard is still partially recovered using the



**Figure 17.** Horizontal slices at depths of 2700, 3800 and 5500 m bsl showing velocity perturbation relative to the original starting velocity model for (a–c) the FWI velocity model multiplied by 1.5; (d–f) FWI model obtained from inverting the field data using the perturbed velocity model shown in panel (a–c) as a starting model; and (g–i) the original FWI velocity model.



**Figure 18.** Recovered checkerboards for three experimental geometries: (a–c) OBS spacing of 1 km and shot spacing of 250 m, (d–f) OBS spacing of 2 km and shot spacing of 250 m, and (g–i) OBS spacing of 2.5 km and shot spacing of 400 m. OBS locations are shown as black dots; shots are located on a regular grid that extends a few hundred metres outside the OBS grid. There are three checkerboards in the model: (i) a 300-m check placed between 3000 and 3300 m bsl; (ii) a 500-m check placed between 4000 and 4500 m bsl; and (iii) a 750-m check placed between 5000 and 5750 bsl. The velocity perturbation was  $\pm 100 \text{ ms}^{-1}$ .

larger OBS and shot spacing. These tests suggest that we could obtain the full potential resolution of this technique using OBS spacings of between 2–2.5 km while inverting for frequencies up to 5 Hz.

## CONCLUSIONS

The inverted velocity anomalies in the final FWI model are roughly 2–4 times finer than can be recovered using traveltimes tomography. This improvement in resolution demonstrates that 3-D FWI can be used to recover fine-scale structure within the crust even when data are acquired using a relatively sparse shot and receiver spacing. In contrast to inversions performed on industrial data, additional regularization was required, with smoothing in both the horizontal and vertical directions. In addition, a laborious quality assurance procedure is needed to verify the validity of the adopted workflow, including checking the adequacy of the source wavelet and starting model, checking for problems with cycle skipping, investigating the effect of inputting different data bandwidths, window lengths and regularization, monitoring the progress of the inversion and performing additional model assessment. The full potential resolution of FWI could be obtained in future marine seismic surveys if data are collected using a 3-D acquisition geometry with a denser OBS spacing than is typical for academic surveys.

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