Full-waveform Inversion of Seismic Data from the Juan de Fuca Ridge: Constraints on Interactions among Magmatic, Hydrothermal, and Tectonic Processes

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I. Introduction

Mass and energy transfer at mid-ocean ridges occurs through the interplay among magmatic, hydrothermal, and tectonic processes. Our understanding of these processes has been limited by the lack of high-resolution models of the subsurface seismic structure. Here we use full-waveform inversion[1] to obtain the highest resolution three-dimensional images, to date, of the upper crustal seismic structure of an oceanic spreading center, the Endeavour segment of the Juan de Fuca Ridge. Our results provide the first seismic constraints on the structure of the reaction zone that links the magmatic and hydrothermal systems and controls the patterns of heat transfer within a ridge segment.

II. ETOMO experiment

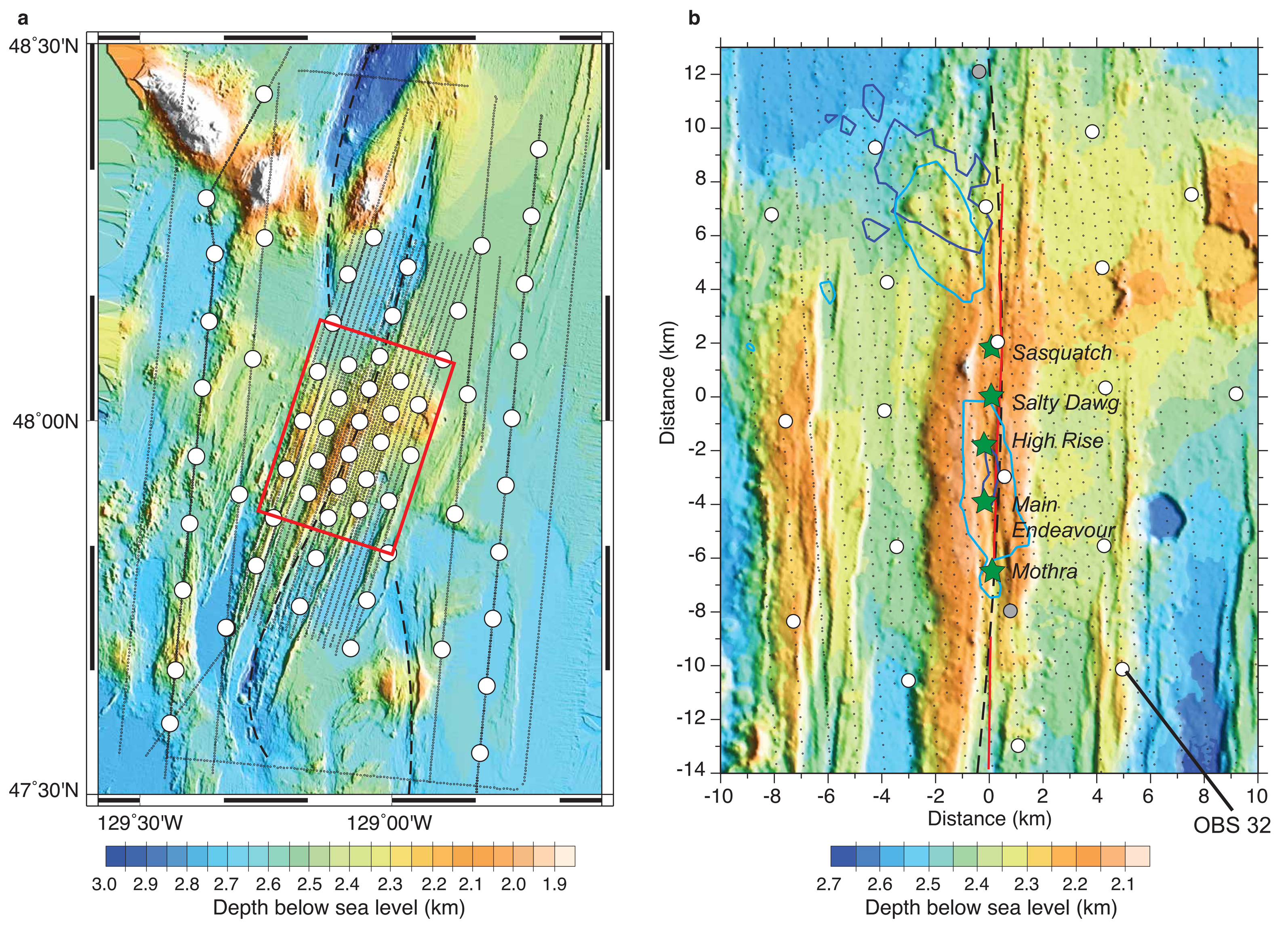

Figure 1 | (a) The Endeavour seismic tomography (ETOMO) configuration. (b) Crustal grid of the ETOMO experiment. Dark and light blue contour shows areas with earthquake densities >20 events per km² recorded during the February 2005 swarm[4] and >150 events per km² that occurred between August 2003 and October 2006 (ref. 5), respectively.

- The Endeavour segment hosts five large hydrothermal vents (green stars, Fig. 1b) that mine heat from an axial magma chamber (red lines, Fig. 1b)[2,3].
- The ETOMO experiment was designed to constrain the thermal and magmatic structure underlying the Endeavour hydrothermal system.
- Two OBSs used in the crustal grid did not record useable data (grey circles, Fig. 1b); the other 19 OBSs (white circles), which recorded 1673 airgun shots (black dots), are used in our analysis.

III. Full-waveform inversion

- Isotropic and anisotropic *P*-wave velocity models of the upper oceanic crust, derived via travel-time tomography[6] (right), are used as the starting models for FWI.
- FWI uses an acoustic approximation to the wave equation and includes the kinematic effects of *P*-wave anisotropy[1]; the velocity model is updated iteratively and anisotropy is kept constant.

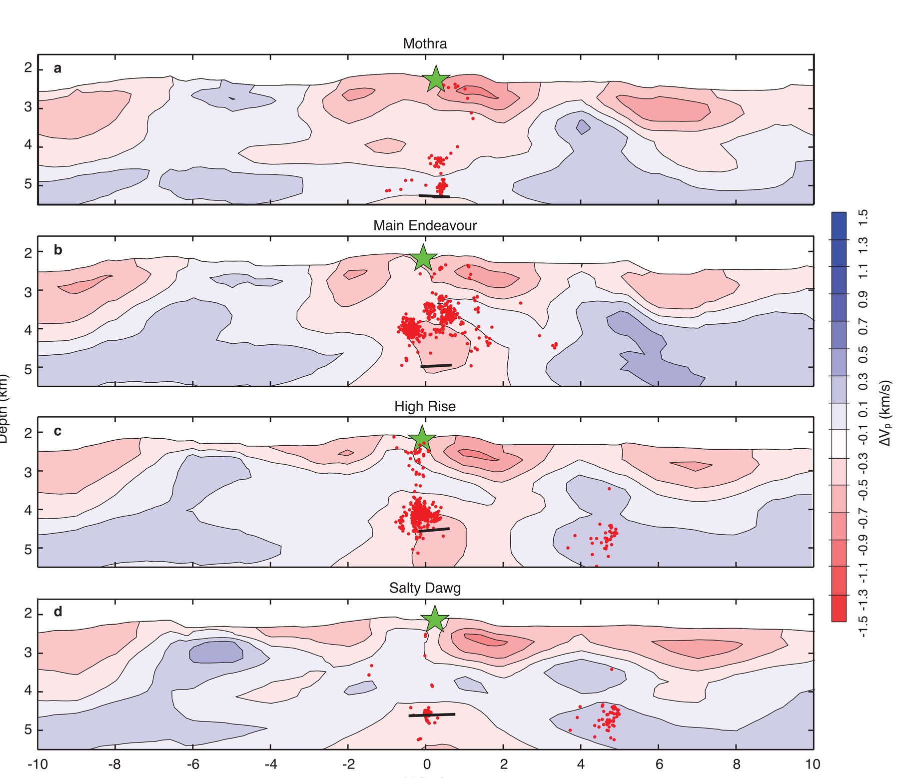

Figure 2 | Vertical sections showing travel-time tomography velocity anomalies for the central portion of the Endeavour Ridge. (a-d) Mothra (Y = -7), Main Endeavour (Y = -4.1), High Rise (Y = -1.7) and Salty Dawg (Y = 0). Overlain on the sections are earthquakes recorded between 2003 and 2004 (ref. 7), vent field locations (green stars), and the approximate location of the AMC[2]. Results are from travel time tomography[6].

Acknowledgements

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IV. Results

i. Velocity structure

- **FWI resolves structures that are 2-4 times finer than those present in the travel-time tomography results.**
- **The five large hydrothermal vent fields are underlain by a shallow (1-2 km depth) low-velocity anomaly (Fig. 4, 5) that correlates with the location of earthquakes that occurred during a 6-year spreading event[4,5,7].**
- **The northernmost low-velocity anomaly located <3 km beneath the ridge-axis (Figs. 3b; 5) coincides with a region of ongoing seismicity[5]. This region was also perturbed by intense seismic swarms in 2005[4,5].**
- **Low-velocity anomalies beneath the center of the ridge axis (~2.2 to 2.8 km depth) correlate with the location of a previously resolved, segmented axial magma chamber (AMC)[2,3].**
- **Lateral velocity variations directly above the AMC reflector occur in the inferred location of the reaction zone, a pattern that correlates with swarms of seismicity and the vent field heat fluxes (Fig. 3b).**

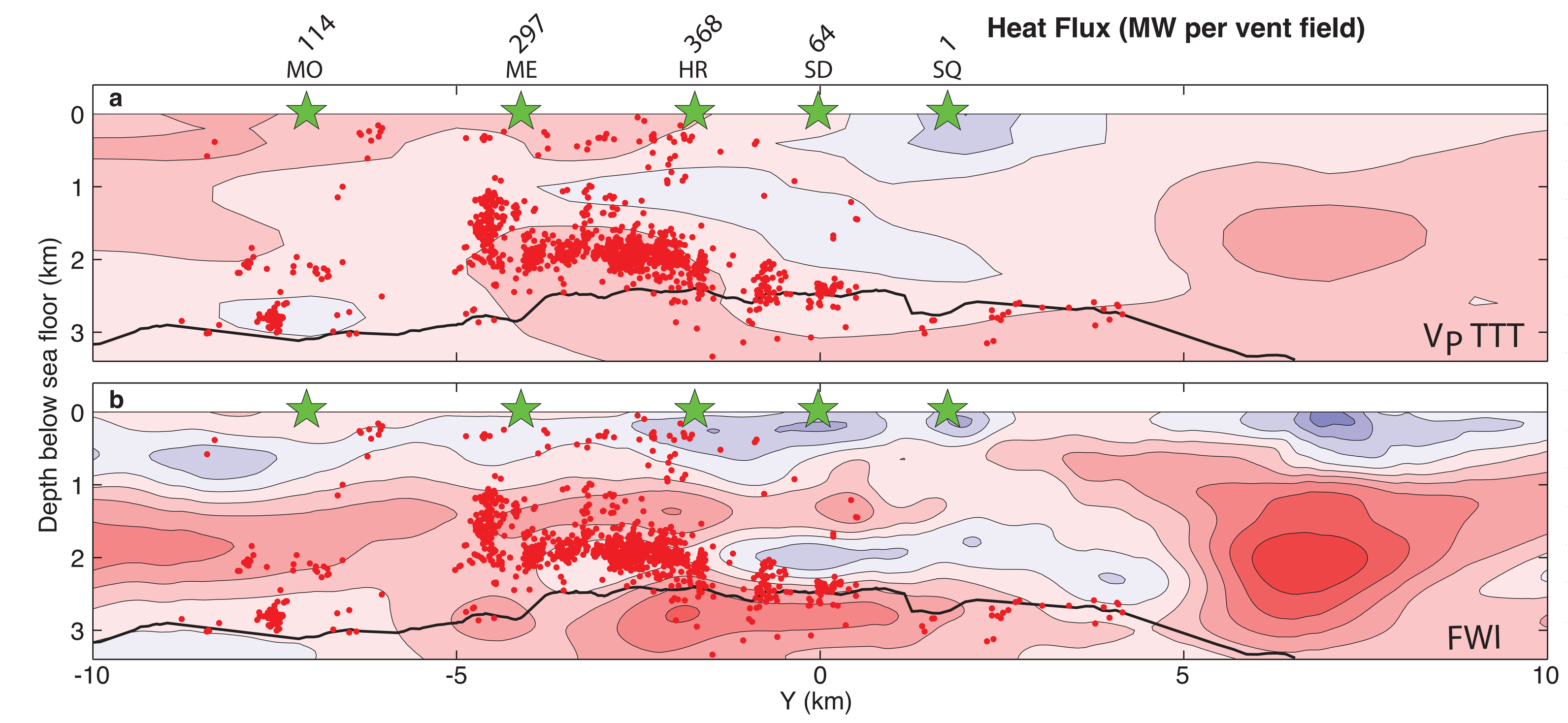

Figure 3 | Comparison between travel-time tomography (a) and full-waveform inversion (b) results. Sections show the locations of the vent fields (green stars), hypocenters for earthquakes recorded between 2003 and 2004 (ref. 7), and axial magma chamber reflector (solid black line). Heat fluxes for the five vent fields are provided above each vent[8].

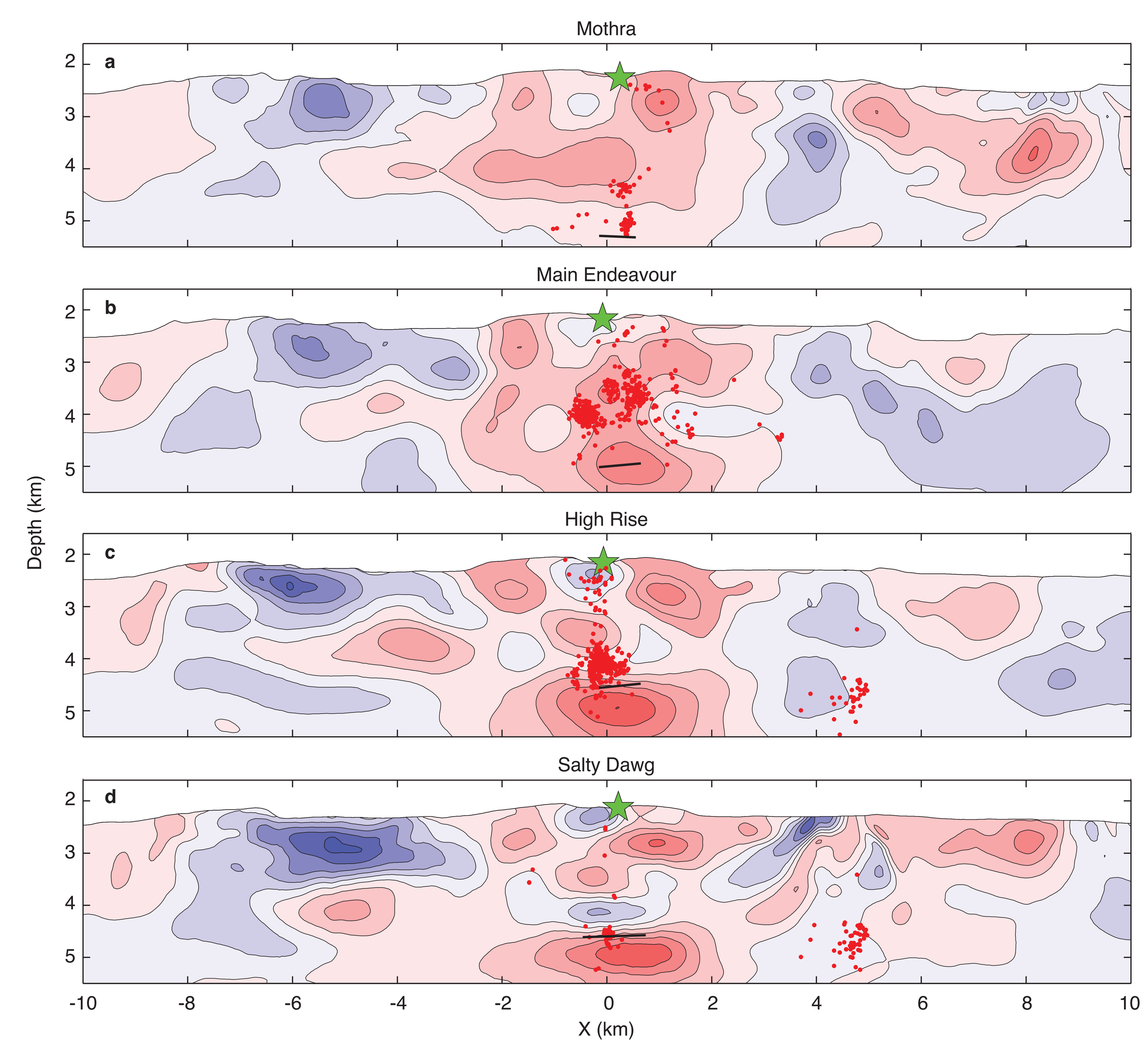

Figure 4 | Across-axis sections showing FWI velocity anomalies across the hydrothermal vent fields plotted with the same conventions as Figure 2.

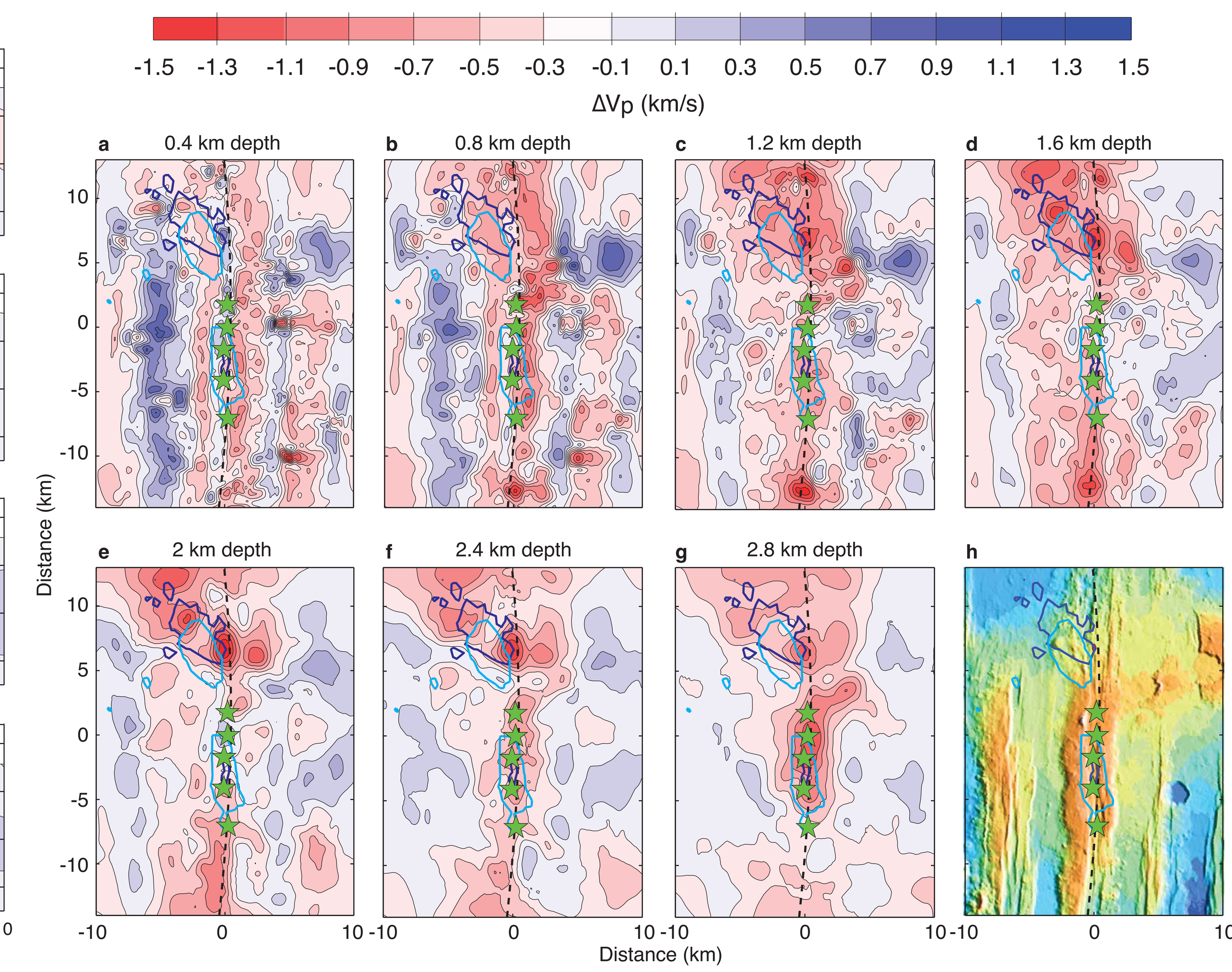

Figure 5 | Map view sections of three-dimensional segment-scale velocity anomalies. Plotted features are the same as those shown in Figure 1b.

ii. Model fit

- This 3D FWI technique matches the phase of the field data.
- To judge the fit of the model, we view the phase residuals (synthetic minus observed phase, Fig. 6a) between the field data and synthetics generated using the final FWI model. Phase residuals of zero indicate a perfect match.
- Trace comparison of the observed and synthetic data (Fig. 6b) are also used to determine the model fitness.
- The final FWI model is capable of predicting the first 700 ms of data after the onset of the first arriving crustal refraction (black line, Fig. 6b) between offsets of 2.9-15 km.
- Currently, the fit of secondary arrivals and data at larger offsets is poor.

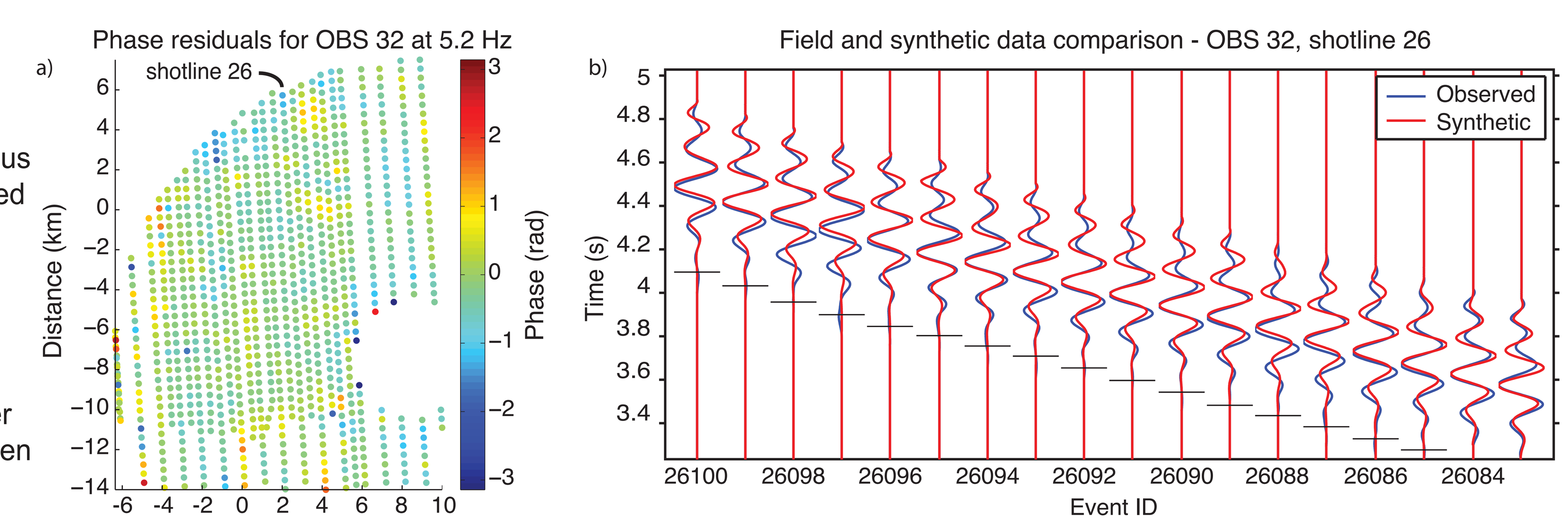

Figure 6 | Phase residuals and trace comparison for a sequence of events.

V. Conclusions and interpretations

- **This study represents the first application of acoustic anisotropic 3D FWI to an academic OBS dataset. We show that FWI is capable of recovering velocity anomalies with a resolution 2-4 times better than conventional travel time tomography when using a non-optimal, academic-sized dataset.**
- **We provide the first seismic constraints on the structure of the reaction zone that links the magmatic and hydrothermal systems and controls the patterns of heat transfer within a ridge segment.**
- **Along-axis variations in velocity above the AMC coincide with concentrations of seismicity and the heat fluxes of the overlying hydrothermal vent fields. We infer these variations represent fluctuations in the hydrologic permeability of the crust and may result from differing extents of cracking induced by earthquakes.**
- **Our results can motivate the development of more realistic models of hydrothermal flow that incorporate complex heat sources and heterogeneous permeability with the capability of linking seismicity with fluctuations in permeability.**