

Exploring the use of adjoint noise tomography to refine a shear-wave velocity model beneath the Iranian Plateau

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Abstract We apply adjoint waveform tomography using Rayleigh wave Empirical Green's Functions (EGFs) at 10–50 sec. periods to improve a prior 3D velocity model of the crust and uppermost mantle beneath the Iranian Plateau. EGFs were derived from cross-correlations of ~8 years of continuous vertical component seismic noise recorded by 119 broadband stations within the region. Adjoint tomography refines the initial model by iteratively minimizing the frequency-dependent traveltime misfits between the Synthetic Green's Functions (SGFs) and EGFs measured in different period bands. The total misfit has dropped by ~85 percent after 12 iterations. The use of a numerical spectral-element solver enables highly accurate wavefield simulations and, by exploiting full-waveform information, yields precise adjoint misfit kernels, resulting in more robust images compared to ray-theory tomography. Our study also demonstrates improved lateral resolution and depth sensitivity relative to the initial model obtained from conventional ambient-noise tomography. The final model adjusts the shapes of velocity anomalies at crustal and uppermost mantle depths especially in the Zagros convergence zone. Using a more limited dataset than some previous regional tomographic studies, the refined model captures along-strike variations in Arabian underthrusting beneath Central Iran, illustrating the potential of adjoint noise tomography to recover meaningful crustal-scale structural features.

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1 Introduction

The long-lasting collision between the Arabian plate and Eurasia, after the closure of the Neo-Tethys around ~35 Ma, resulted in underthrusting of the rifted Arabian lithosphere beneath the Eurasian plate and consequently significant lithospheric deformation in the Iranian plateau (e.g., Mouthereau et al., 2012). Induced stress resulting from the convergence is mostly accommodated in the form of thickening/shortening beneath the Zagros Fold and Thrust Belt (ZFTB) and Alborz and Kopet-Dagh mountain ranges (e.g., Agard et al., 2005, 2011; Mouthereau et al., 2012), as well as by lithospheric-scale displacements along the transcurrent faults within the less deformed microplates in Central Iran (Agard et al., 2005, 2011; Hatzfeld and Molnar, 2010; Paul et al., 2010). This is also confirmed by recorded seismic activity (Fig. 1) and the GPS measurements in the study area (e.g., Vernant et al., 2004; Zarifi et al., 2013). Lithospheric deformation in the region is investigated by various geological and geophysical studies, including GPS geodesy (Masson et al., 2005), geochemical and petrological analysis of magmatic rocks (Omran et al., 2008), passive seismic array imaging (Hatzfeld and Molnar, 2010), surface-wave to-

mography (Kaviani et al., 2007, 2020; Amiri et al., 2025), receiver function imaging (Paul et al., 2010; Motaghi et al., 2012), non-linear teleseismic tomography (Shad Manaman et al., 2011; Irandoust et al., 2022), Pn phase tomography (Al-Lazki et al., 2014), joint inversion tomography (e.g., Motaghi et al., 2017a,b; Zarunizadeh et al., 2024, 2026; Mehrdar et al., 2025) and adjoint noise tomography (Wu et al., 2021; Enayat and Ghods, 2023), revealing strong lithospheric contrasts and crustal thickening across the suture. These models suggest significant underthrusting of the Arabian plate, steep crust-mantle velocity gradients, and possible slab break-off. However, the depth extent, lateral continuity, and segmentation of underthrusting remain debated, partly due to limitations in resolution and data sensitivity. With advancements in data collection and computational resources, tomographic images across the Iranian plateau have significantly improved over the last decade (e.g., Irandoust et al., 2022; Enayat and Ghods, 2023; Zarunizadeh et al., 2024, 2026; Mehrdar et al., 2025; Amiri et al., 2025). These include a tongue-shaped low-Vs anomaly beneath Central Iran (Iranoust et al., 2022) and contrasting lithospheric structures across the Zagros (Zarunizadeh et al., 2024, 2026). Notably, they reveal mid-crustal low-velocity channels, crustal exhumation zones, and incipient mantle delamination.

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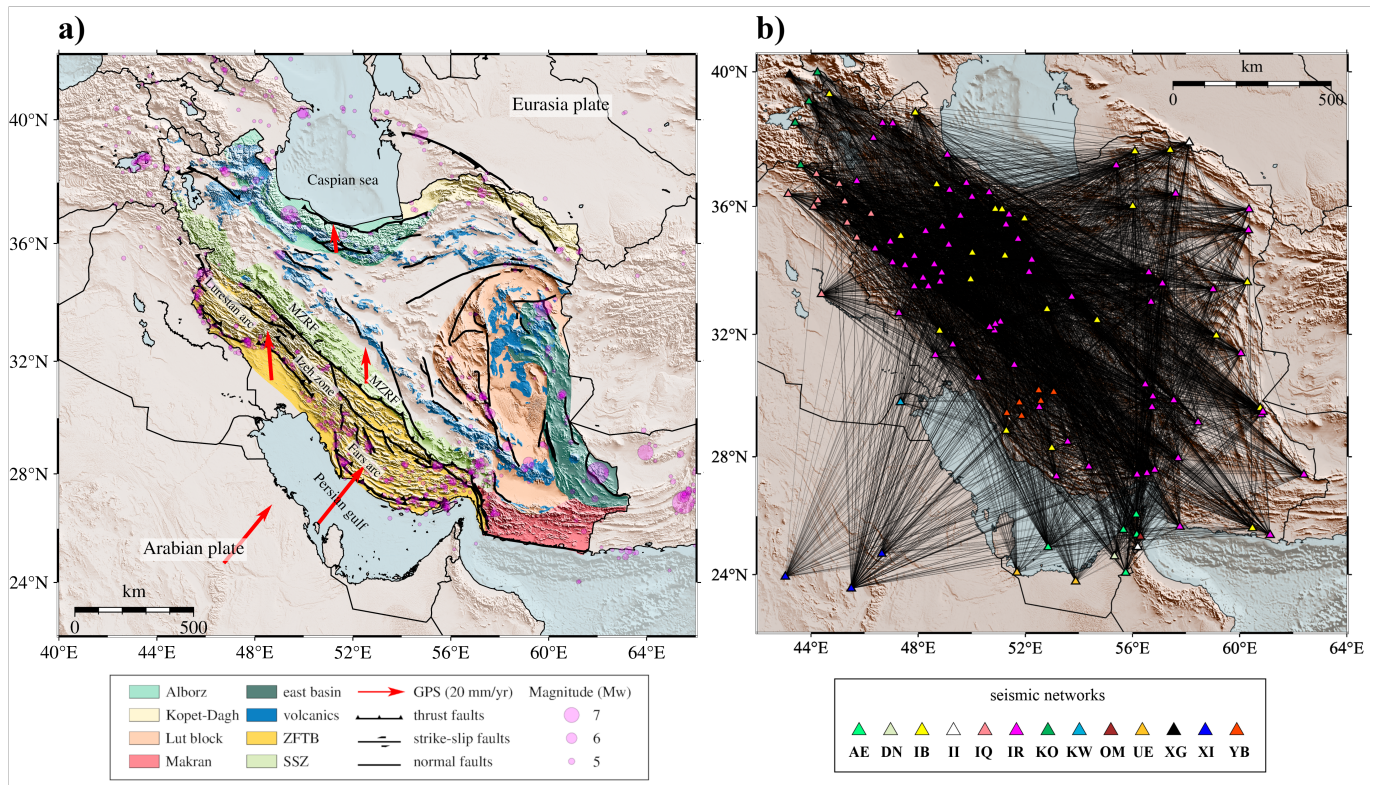


Figure 1 (a) Tectonic map featuring topography, bathymetry, and seismic activity within the study area. Seismic event data (earthquakes with a moment magnitude greater than 5, since 1990) sourced from the NEIC catalog (<https://earthquake.usgs.gov/earthquakes/search/>). The colors are associated with various geological structures as indicated in the legend. (b) Location map of 119 seismic stations (triangles) and raypaths across the study area, with the average raypath of ~ 774 km. Stations belonging to each specific network are represented using distinct colors. GPS measurements are taken from Zarifi et al. (2013). For more details about the networks shown in this Figure please refer to the data and code availability section.

These recent models also provide valuable benchmarks for testing and validating full-waveform imaging approaches such as adjoint noise tomography, as applied in this study.

The successful implementation of ambient noise tomography by Shapiro et al. (2005) was followed by many other studies (e.g., Lin et al., 2008; Chen et al., 2014; Gao and Shen, 2014). The method is based on the extraction of surface wave Green's function between different receivers by cross-correlation of long-time ambient seismic noise to image Earth structures. This method has proven to be particularly effective for investigating crustal structures. Its utility becomes evident in Iran, where seismic station distribution is sparse, limiting the effectiveness of traditional earthquake travel-time tomography. Over the past decade, this method has been employed to investigate the crustal and uppermost mantle structure beneath Iran (e.g., Mottaghi et al., 2013; Ansaripour et al., 2019; Movaghari and Javan Doloei, 2020; Pilia et al., 2021; Kaviani et al., 2020). However, the ray-theory assumption may inadequately capture finite-frequency sensitivity in the presence of strong velocity heterogeneities, potentially limiting the resolution of complex subsurface structures (e.g., Dahlen et al., 2000; Fichtner et al., 2009). This can result in limited resolution and accuracy, particularly in our study area which is regarded as a complex geological region (e.g., Mouthereau et al., 2012; Agard

et al., 2005). In recent decades, advancements in computational capabilities have opened up new possibilities for seismologists to employ more accurate numerical algorithms in 3D full waveform tomography (Tromp et al., 2005; Liu and Tromp, 2006; Fichtner et al., 2009; Tape et al., 2010; Liu and Gu, 2012). This has led to the exploration of more sophisticated approaches, such as adjoint noise tomography (ANT), which leverages precise 3D numerical simulations like the spectral element method (SEM, Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999). ANT involves misfit kernel computations based on the adjoint state method (Luo and Schuster, 1991; Tromp et al., 2005; Virieux and Operto, 2009; Liu and Gu, 2012), and it was first introduced by Chen et al. (2014), taking advantage of supercomputing facilities. This method shows promise in improving the resolution of crustal and uppermost mantle images (e.g., Wang et al., 2018, 2021; Lu et al., 2020). Using 3D misfit kernels allows for considering more realistic structural features of the Earth, surpassing the capabilities of ray-theory-based tomographic methods (e.g., Fichtner et al., 2009; Tape et al., 2009; Liu and Gu, 2012; Zhu et al., 2012).

In this study, we apply ANT to improve a pre-existing model (Kaviani et al., 2020) derived from traditional ambient noise tomography. We obtained a refined 3D shear-wave velocity model of the crust and uppermost mantle beneath the Iranian Plateau, resolving along-

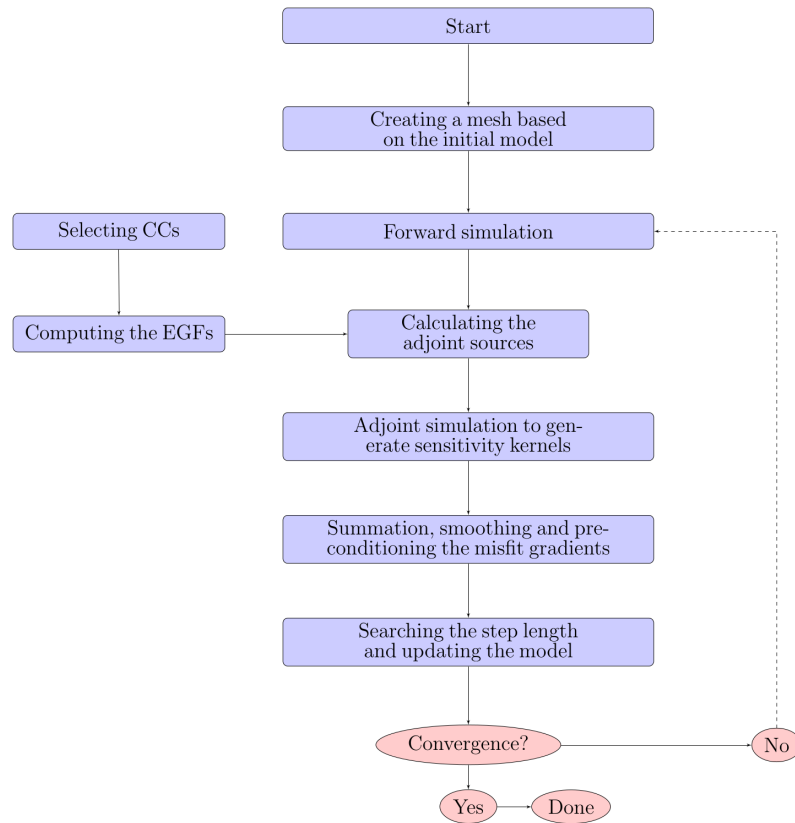


Figure 2 Workflow of the adjoint noise tomography in this study.

strike variations in Arabian underthrusting beneath Central Iran. These results demonstrate the potential of adjoint noise tomography to extract detailed crustal-scale features from ambient noise data.

2 Data and Method

The cross-correlations (CCs) employed in this investigation, serving as Empirical Green's Functions (EGFs), are obtained from a previous study conducted by Kaviani et al. (2020). A rigorous selection process resulted in having approximately 3000 CCs for our study area, each having a signal-to-noise ratio (SNR) greater than 5. These CCs were derived from eight years of continuous seismic noise data recorded between 2007 and 2015, utilizing records from 119 broadband stations situated within the study area (Fig. 1). Because the noise cross-correlations contain symmetric positive and negative time lags, we reverse one branch and stack both to obtain a one-sided seismogram that can be directly compared with synthetics generated using one station as the source and the other as the receiver. Since our analysis exclusively considers vertical components, the resulting set of cross-correlations is primarily characterized by Rayleigh wave signals. Assuming homogeneous noise sources, the obtained cross-correlations between two stations A and B are related to the EGFs as (Lobkis and Weaver, 2001):

$$-\frac{\partial C_{A,B}(t)}{\partial t} = G_{A,B}(t), \quad (1)$$

where C is the noise cross-correlation between points A

and B, and G is the corresponding Green's function.

The initial velocity model used in this study is provided by Kaviani et al. (2020), which was established through conventional ambient noise tomography. This model is a 3D isotropic shear-wave velocity (V_s) model of the crust and uppermost mantle beneath the Middle East. It is defined from near-surface depths to approximately 150 km. Horizontal resolution is adaptive, with cell sizes of 0.25° , 0.5° , and 1° , corresponding to an approximate spatial resolution of 100–200 km. The inversion directly constrains V_s only; V_p and density are derived using empirical relationships from Brocher (2005).

2.1 Setup and Implementation

We provide an overview of our implementation, focusing on the aspects associated with noise cross-correlation data. The underlying theory and concepts of adjoint noise tomography have been extensively covered in numerous prior studies (e.g., Chen et al., 2014; Gao and Shen, 2014; Wang et al., 2018, 2021; Lu et al., 2020). Our workflow, depicted in Fig. 2, begins with the selection of high-quality CCs from Kaviani et al. (2020). From these CCs, we construct EGFs using Equation 1. By defining a mesh based on the initial velocity model (as illustrated in Fig. 3), we are able to conduct forward simulations, computing SGFs at the receiver locations. The frequency-dependent traveltime misfit is used to construct the adjoint source, which is then time-reversed and injected at the receiver locations to compute misfit kernels. Further post-processing of these misfit kernels

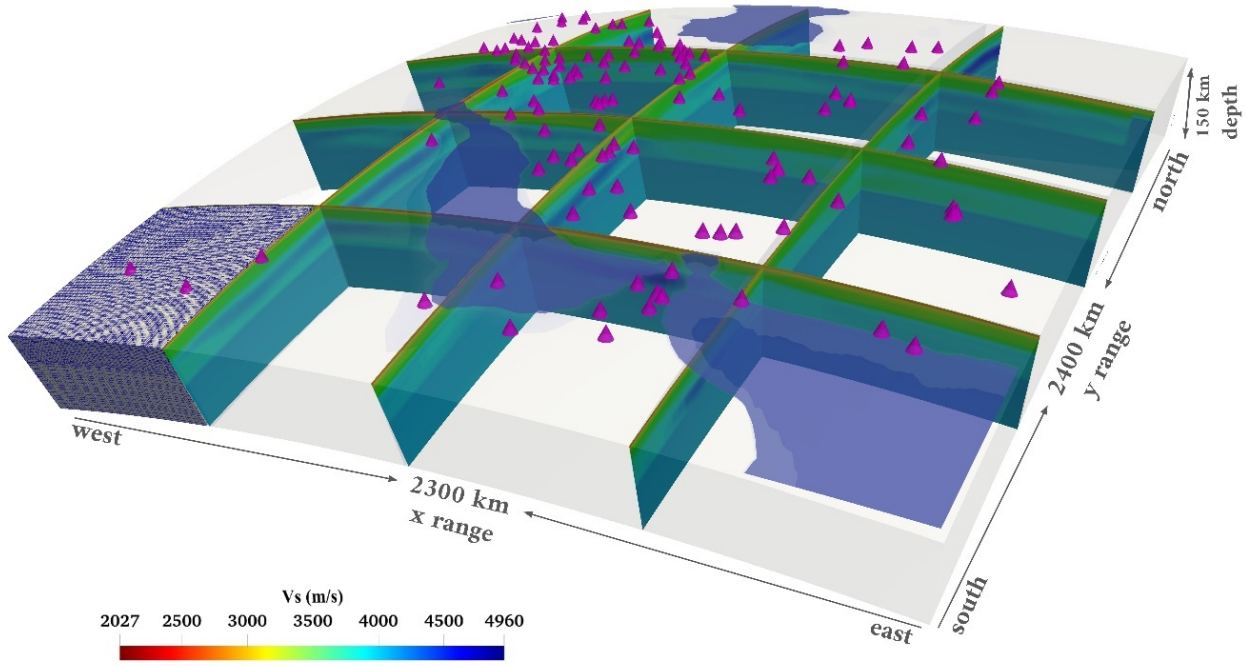


Figure 3 The mesh structure and shear wave velocity distribution of the initial model are shown. Shear wave velocity values of the initial model are displayed in six representative depth-sections, which also provide a schematic representation of the model's distribution across 16 GPU cores. A segment of the mesh for the southwest portion of the initial model is also illustrated. Seismic stations employed in this study are denoted by violet triangles, while the blue shading on top distinguishes between water and land.

involves summation, smoothing, and preconditioning. At each iteration, we perform a line search to determine the optimal step length for updating the model. This process, starting from the forward simulation, is iterated until the misfit values converge.

The SEM has proven to be an accurate and efficient method of wavefield simulation in 3D heterogeneous media (Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999, 2002a,b). It exploits the geometrical flexibility of finite-element methods and the exponential convergence rate of spectral methods. In this study, we utilize the open-source software package SPECFEM3D_Globe (version 8.1.0) (Komatitsch et al., 2023) for both the forward and adjoint simulations. We also used the mesher included in this software package to discretize our initial model, meshing a portion of the Earth that encloses our study area and taking the curvature of the Earth into account. This mesh has 256 elements in longitude and 256 elements in latitude and extends to a depth of 150 km with 32 elements (Fig. 3). The Gauss-Lobatto-Legendre (GLL) points are spaced at a minimum interval of approximately 2000 meters. These points serve as the nodes over which the partial differential equations are solved. The configuration of this mesh gives sufficient simulation accuracy at periods equal to or longer than 6.4 s. To optimize computational efficiency, we apply a bandpass filter ranging from 10 to 50 seconds to the signals, in contrast to the wider period band of 2 to 150 seconds applied to obtain the initial model. This choice reduces the computational burden

by allowing a coarser spatial discretization of the mesh and therefore fewer spectral elements. We performed the adjoint inversion using the full 10–50 s period band simultaneously across 12 iterations, rather than adopting a multiscale strategy. This decision was motivated by the fact that our starting model already yielded reasonable waveform fits within this band, minimizing the risk of cycle skipping. Given the limited bandwidth and computational constraints, we found the single-stage inversion to be both stable and efficient.

To generate the SGFs in forward simulations, we put a single vertical point force $\hat{F} = f\hat{z}$ at the location of a station, which serves as a source, while all other stations act as receivers. We use a Gaussian function as the source time function for the point force. With this setup, the vertical component of the Green's Functions between the pairs of stations are calculated as SGFs. While incorporating horizontal components could improve resolution near the subsurface (Wang et al., 2019), in this study we use only vertical components (Rayleigh waves) to keep computational costs lower. The SEM computations are performed in parallel implementation using the Goethe-HLR GPU cluster (equipped with AMD Instinct MI210) using 16 cores. Each forward simulation typically takes about 6 min to generate seismograms of 900 sec. duration, with a time step of 0.025 sec.

Both the EGFs and SGFs are tapered using a cosine taper to include only Rayleigh waves. This taper is applied within a time window defined as $[\frac{D}{V_{g(max)}} - 25, \frac{D}{V_{g(min)}} + 25]$, where D is the inter-station distance and $V_{g(max)}$

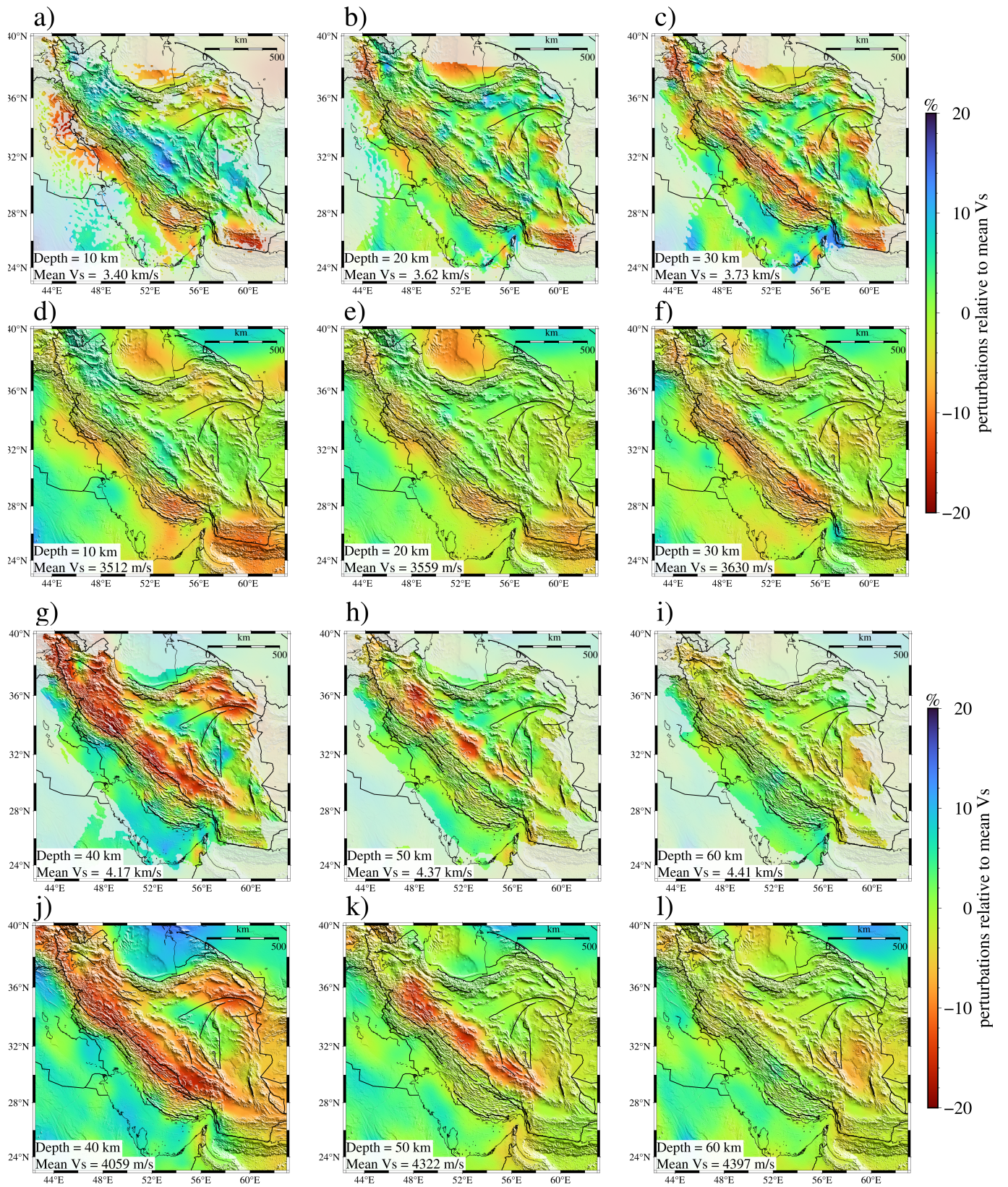


Figure 4 Comparison of shear-wave velocity (V_s) depth slices at 10, 20, and 30 km for the final model (a–c) and the initial model (d–f), and at 40, 50, and 60 km for the final model (g–i) and the initial model (j–l). The relative velocity perturbation, expressed as the deviation from the mean velocity of each slice (given in the lower-left corner of each map), is shown to highlight changes in the geometry and amplitude of the anomalies. The final model (M12) depth slices (a–c, j–l) are masked based on the misfit-kernel values; see also Figs. S4 and S5.

and $V_{g(\min)}$ are maximum and minimum group velocities in the period range of 10–50 seconds, derived from Kaviani et al. (2020). In this study, we use the frequency-

dependent multi-taper traveltime difference as the misfit function (Tape et al., 2009):

$$\chi(m) = \frac{1}{2} \int W(\omega) [\tau^{obs}(\omega) - \tau(\omega, m)]^2 d\omega, \quad (2)$$

where W denotes a bandpass filter, the width of which depends on the frequency range within which the measurements are considered reliable. This width is also scaled by error estimates specific to that window. $\tau^{obs}(\omega)$ and $\tau(\omega, m)$ denote the observed and synthetic frequency-dependent traveltime for a single source-receiver pair. It is worth noting that during the stacking of noise cross-correlation, amplitude information in the data is lost. To address this, we normalize both the SGFs and EGFs to eliminate any potential amplitude effects in our calculations. We employ a series of control factors, such as minimum cross-correlation coefficient between the SGF and EGF, at each iteration to include only high-quality signals in the inversion process, as detailed in Table S1. The final reported misfit value for each iteration is calculated as the average misfit value across all source-receiver pairs.

Following the computation of misfit kernels for all the sources, along with the Hessian kernel representing the second derivative of the misfit function, we stack these kernels (for a general review of misfit kernel calculations, see [Liu and Gu, 2012](#)). Subsequently, convolving these stacked kernels with a Gaussian function, we are able to remove artificial high-wavenumber gradient artefacts ([Trinh et al., 2017](#)). In SPEC-FEM3D_Globe, these Hessian kernels approximate the diagonal elements of the Hessian matrix, since the accurate value of the Hessian matrix is not available or difficult to achieve. The approximation is determined as the vector inner product of the forward and adjoint accelerations as outlined below:

$$\tilde{H}(x) = \int \partial_t^2 s(x, t) \cdot \partial_t^2 s^\dagger(x, T - t) dt, \quad (3)$$

where s and $s^\dagger$ are the forward and adjoint wavefields, respectively ([Zhu et al., 2015](#)). We use this approximate Hessian in the equation below to update the velocity model through a steepest descent gradient method:

$$m_{new} = m_{init} - \alpha \Delta m, \quad (4)$$

where α is the step length we choose toward the minimum of the gradient for updating the model and $\Delta m = -\nabla \chi H^{-1}$, representing the gradient of the misfit function χ (Eq. 2) with respect to the model parameters, which is scaled by the inverse of the Hessian matrix. However, it is important to note that other methods, such as the Limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) algorithm, have been shown to be superior to conjugate gradient or descent gradient methods. These methods, as discussed by [Modrak and Tromp \(2016\)](#), are more effective in finding the optimal gradient direction for minimizing model parameters. To determine the appropriate value of α , we employ a line-search strategy (Fig. S1). We set the α to values ranging from 1 to 3 percent with regard to the misfits. Since the forward calculations for each trial step length can be computationally expensive, we

select a specific set of sources with approximately uniform source-receiver ray-paths across the region (as illustrated in Fig. S2), to compute the misfits for each updated model with the respective step lengths. Finally, the step length corresponding to the minimum misfit value is selected to update the model at each iteration.

3 Results and Model validation

3.1 Horizontal cross-sections

In Fig. 4, we provide a comparative view between the initial (M00) and the final (M12) velocity models at depths 10, 20, 30, 40, 50, and 60 km. A difference map between the M00 and M12 models are illustrated in Fig. S3. In this figure, the final model is masked based on misfit kernel values (Figs. S4 and S5), illustrating only the valid areas of the resolved model. To prevent large values in the misfit kernels around the stations, we activated the “SAVE_SOURCE_MASK” flag in the software. This option outputs a source-region mask that sets the sensitivity kernels to zero near the stations, thereby preventing source-side singular amplitudes from dominating the model update. This is illustrated in Fig. S6, which shows the horizontal maps with the station locations marked. Generally, perturbations relative to the mean V_s become more pronounced in the lower crust (30–40 km) in the new model. The low-velocity anomalies observed in the Zagros convergence zone are coincident with the thickened crust in this region. High-velocity anomalies beneath the central Iranian microplates are primarily associated with the uppermost mantle, reflecting locally thinner crust and a shallower Moho. At depths of 20–30 km, the final model demonstrates significant differences from the initial model and reveals velocity anomalies with more detail. At these depths, new low/high velocity features emerge in the Izeh zone and central Iran, and Alborz is found to be inhomogeneous. The final model reveals a high-velocity anomaly on the western and eastern sides of the Alborz mountain range, while the central parts are dominated by low velocities. While the initial model did detect velocity contrasts in the central and northeastern parts of the study area, these contrasts are much better pronounced in the final model. For example, the high-velocity anomaly in central Iran at a depth of 40 km is 10 percent higher in M12 compared to M00. Furthermore, there is a notable shift in the average V_s values, which increases in all the depth slices. This change in the average V_s is probably related to the shift in the mean traveltime misfit due to incorporating longer periods (up to 150 s) for model M00; a shift that is corrected in model M12 (see Section 3.3). At the depth of 40 km, the shape of the low-velocity anomalies in the Zagros convergence zone and the northeastern area becomes narrower in the new model, and the high-velocity anomalies are more prominent. At depths greater than 50 km, the final model exhibits similar patterns to the initial model, with a slight increase in the average V_s values. In addition, some high-velocity features with more contrasts are observed in Central Iran, the Lut Block, and NE Iran.

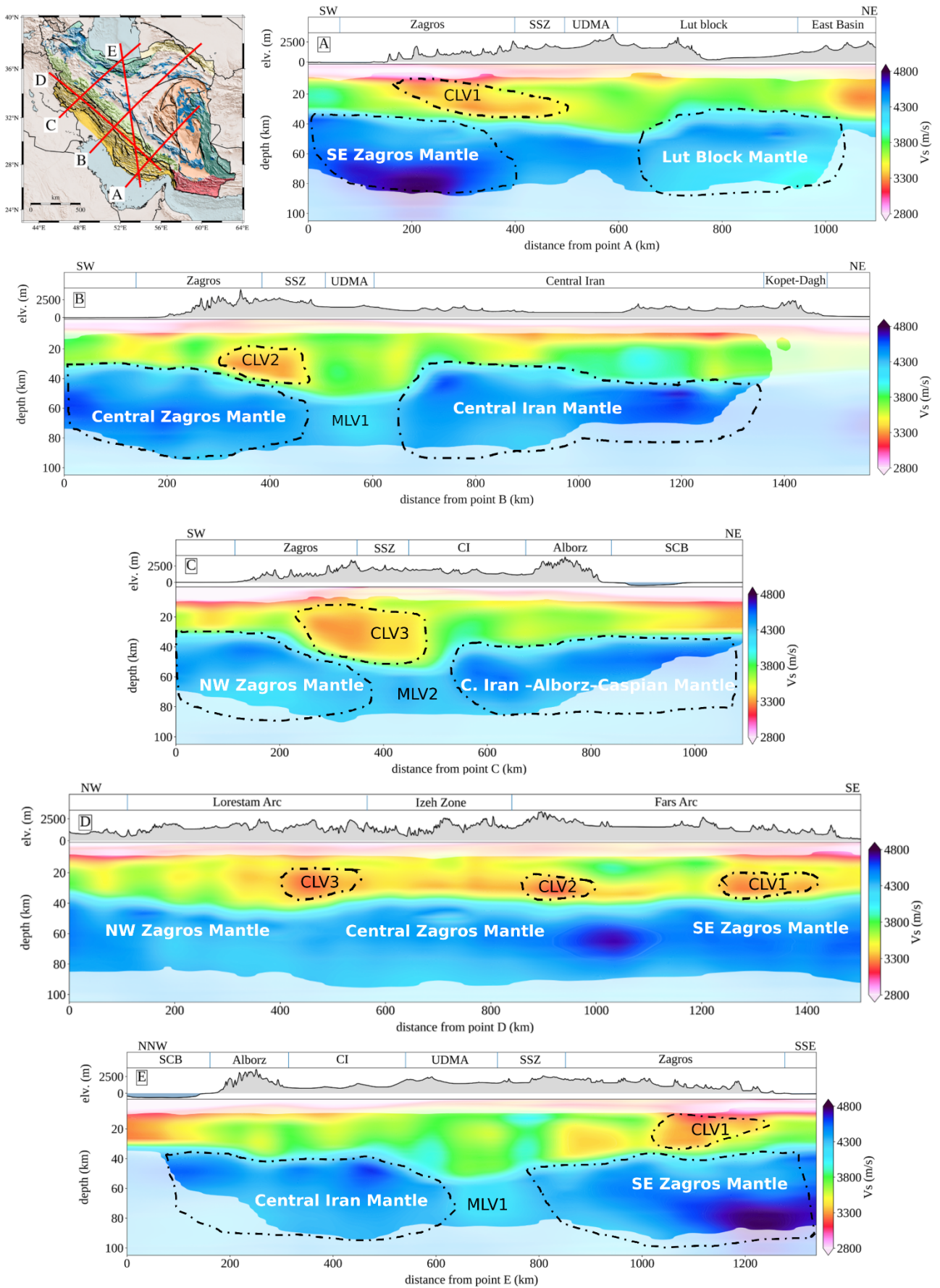


Figure 5 Vertical slices of the final shear wave velocity model (M12) along profiles A-E across the Iranian Plateau. The positions of these profiles are indicated on the map in the top-left corner. Vertical exaggeration: 4. Shear wave velocity values are masked according to the associated misfit kernel values (also refer to Figs. S4 and S5). CLV stands for crustal low velocity anomaly and MLV stands for mantle low velocity anomaly.

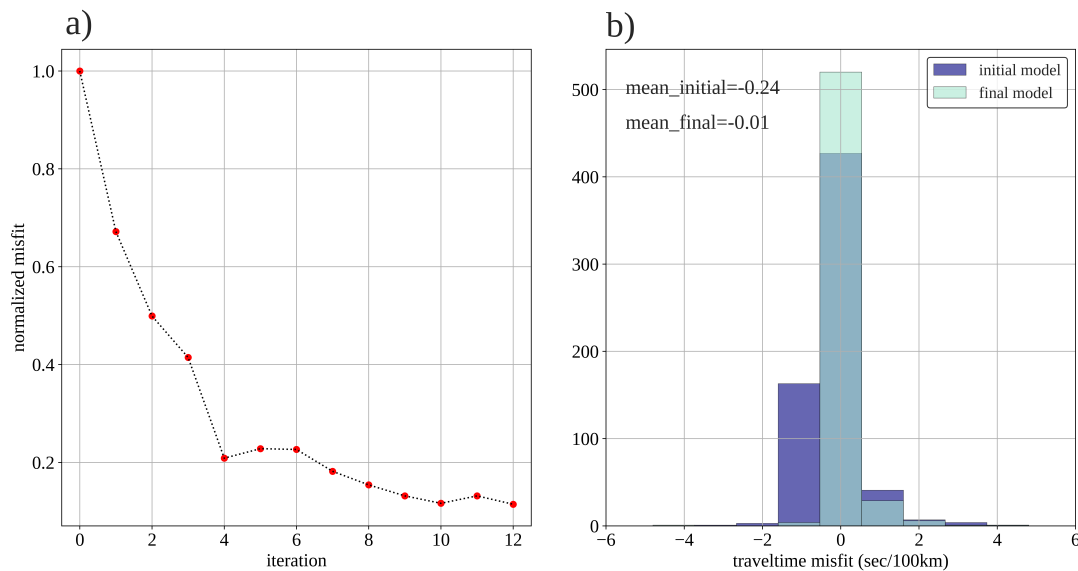


Figure 6 a) Total misfit reduction over iterations. b) Comparison of traveltime misfits between the final model (M12) and initial model (M00). SD stands for standard deviation.

3.2 Vertical cross-sections

In Fig. 5, we present four vertical sections from the final shear velocity model. The corresponding vertical sections from the initial model can be found in Fig. S7. Upon inspection of these figures, it becomes evident that the new model largely retains most of the pre-existing features from the initial model but with higher resolution and some refinements to the shape of the anomalies. We applied the same mask described in the previous section to exclude areas where model resolution is insufficient, ensuring model reliability. From south to north of Zagros (profiles A, B and C), a distinctive tongue-shaped low-velocity anomaly (CLV1, CLV2 and CLV3) is mapped beneath the Zagros convergence zone. With respect to the initial model, the tongue-shaped low-velocity anomaly has undergone modifications in the new model. For example, in profile B, this low-velocity anomaly (CLV2) does not extend continuously from SW to the east, beneath the SSZ and UDMA, in contrast to the initial model. In this profile, a Mantle low-velocity anomaly (MLV1) has emerged in the new model at subcrustal depths, beneath the SSZ and UDMA. In profile C, the geometry of the low velocity anomaly (CLV3) is modified. The elongated low-velocity anomaly from the South Caspian Basin (SCB) to the southern Alborz in the initial model is truncated far north beneath the Alborz region. We have extracted the iso-velocity depth map corresponding to $V_s = 4.2$ km/s, as illustrated in Fig. S8. The choice of $V_s = 4.2$ km/s as a proxy for Moho depth is consistent with previous tomographic studies in which this velocity threshold approximately marks the crust–mantle transition (e.g., [Lynner and Porritt, 2017](#); [Paul et al., 2010](#)). In comparison to the initial velocity model, the Moho depths across the region remain relatively consistent, with some adjustments around the Zagros collision zone and central Iran. Additional cross sections are shown in Fig. S9, for a better comparison with [Irandoost et al. \(2022\)](#).

3.3 Misfit reduction

The final model demonstrates a remarkable misfit reduction, approximately 85% relative to the initial model (Fig. 6a). In Fig. 6b, we provide a comparison of the corrected traveltime misfit histograms for both the initial and final models. Notably, the mean value of the misfits exhibits a positive shift (by about 0.21 s/100 km), indicating that the velocity values in the initial model tend to be lower than those in the true model. A possible explanation for this shift could reflect bias in the initial model towards higher periods, given that it was obtained within the period range of 2–150 seconds. Nevertheless, the final model demonstrates significant improvements in the histograms. The misfits in the final model are centered around zero and exhibit a smaller standard deviation (0.46 s/100 km) relative to the initial model (0.64 s/100 km). To investigate the differences in time shifts and waveform similarities across various period bands, we used the mean cross-correlation coefficient and mean delay times, as described in [Lu and Ben-Zion \(2022\)](#). These metrics were calculated for different period bands: 8–15 s, 12–20 s, 18–28 s, 25–35 s, 33–47 s, and 42–55 s. The results (Fig. S10) show variable performance across different phases and period ranges, with the best performance of the final model achieved in the 12–35 s period range. Additionally, we provide a map of the spatial distribution of the misfit values in Fig. S11. Examples of observed waveforms and synthetics computed from both the initial and final models are provided in Fig. 7. Although the final model improves the waveform fit overall, a residual phase offset remains for this station pair, and the improvement is period dependent. In particular, the gain is strongest in the full 10–50 s and 10–20 s bands, whereas the 20–50 s band shows little change, consistent with the broader period-dependent validation shown in Fig. S10. Further examples of observed and simulated waveforms for different station pairs are shown in Fig. S12.

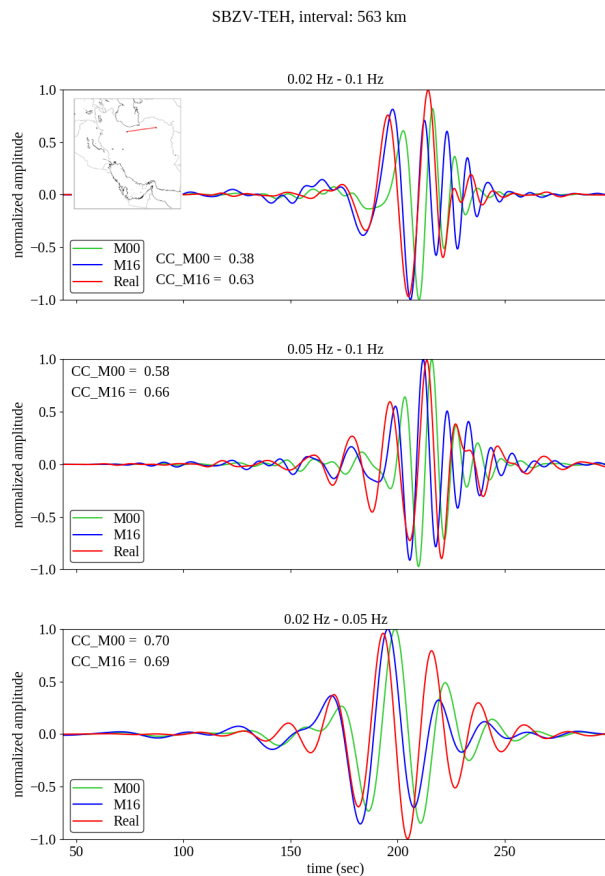


Figure 7 An example of waveform fitting for a source-receiver pair with 563 km distance is shown. In this graph the real waveform (EGF) with the waveforms resulting from the final model (M16, blue) and the initial model (M00, green) are compared. This comparison is done from top to bottom for period bands 10–50, 10–20, and 20–50 seconds, respectively. The value of the cross-correlation coefficient between the real and synthetic waveforms for both the initial and final models is denoted in the top left corner.

3.4 Resolution tests

Conducting traditional checkerboard tests to evaluate the quality of our 3D imaging is a resource-intensive process, demanding even more computational power compared to the actual structural inversion. This is due to the higher number of iterations required by the inversion process to converge. In two dimensions, such tests have been successfully executed, as demonstrated in a previous study (Kaviani et al., 2020), concluding that the success of anomaly retrieval is primarily influenced by ray coverage. Therefore, in such cases, ray density maps serve as excellent indicators of resolution (Luo et al., 2013). In this study, to assess the resolution of our final model, we established a synthetic resolution test comparable to conventional checkerboard tests. As illustrated in Fig. 8a, we distributed 11 positive and negative velocity anomalies across the study area. These anomalies have the form of vertical cylinders with a radius of ~ 50 km, a depth thickness of ~ 20 km, and 10 percent of velocity perturbation relative to the initial model. To maintain similar resolution characteris-

tics to the primary inversion process, we used the initial model (M00) as the background velocity model and introduced positive and negative anomalies of 10% to this background velocity model. We employed the same methodology described in Section 2 to generate synthetic waveforms, and subsequently, inverted them for the same source-receiver pair raypath coverage as in the observed data, following the workflow presented in Fig. 2. The results of the resolution test are presented in Fig. 8b and d, confirming that the velocity anomalies are relatively well-resolved along the Zagros collision zone. However, in the eastern and northeastern parts of the model, some smearing in the direction of Rayleigh wave propagation is observed. The observed smearing in the vertical direction could be related either to the period band under investigation in this study (10–50 sec.) or to insufficient data coverage in some parts of the model.

4 Discussion

By employing the highly accurate spectral element method to simulate the forward 3D wave propagation, coupled with the adjoint state method for addressing the inversion problem, we have successfully developed a refined 3D shear-wave velocity model for the crust and uppermost mantle across the Iranian Plateau. Our refined maps, revealing more details, represent an improvement relative to previous investigations (e.g., Kaviani et al., 2020; Motaghi et al., 2015; Shad Manaman et al., 2011; Shad Manaman and Shomali, 2010). The misfit kernel values (Fig. S4 and S5) indicate that based on the period range used in this study (10–50 sec), we are able to investigate the crustal and subcrustal structures, down to a depth of ~ 75 km, across the Iranian Plateau. The horizontal maps (Fig. 4) demonstrate that the final model represents the prominent geological structures in the region, encompassing the Zagros convergence zone, central Iran, and the Alborz-Kopet-Dagh system.

The shear-wave velocity model of Irandoust et al. (2022) currently provides one of the most comprehensive and well-constrained references for the lithospheric structure of the Zagros collision zone, owing to its extensive data coverage, broad period range, and joint inversion strategy. Taking this model as a benchmark, our results obtained using adjoint noise tomography show a high degree of consistency with respect to the first-order crustal features and along-strike variations imaged beneath the Zagros. Although based on a more restricted dataset and period band, the ANT-based inversion recovers comparable crustal-scale velocity patterns, particularly in the geometry and continuity of major anomalies. This agreement indicates that adjoint noise tomography can effectively refine crustal-scale structural features, even when applied under more limited data conditions.

As described in previous sections, the final model provides a better fit to the waveform data than the initial model, as expected. By comparing the initial and final models (Figures 4, 5 and S6, S7), it appears that this improved data fit is achieved through two key modifications in the final model relative to the initial model:

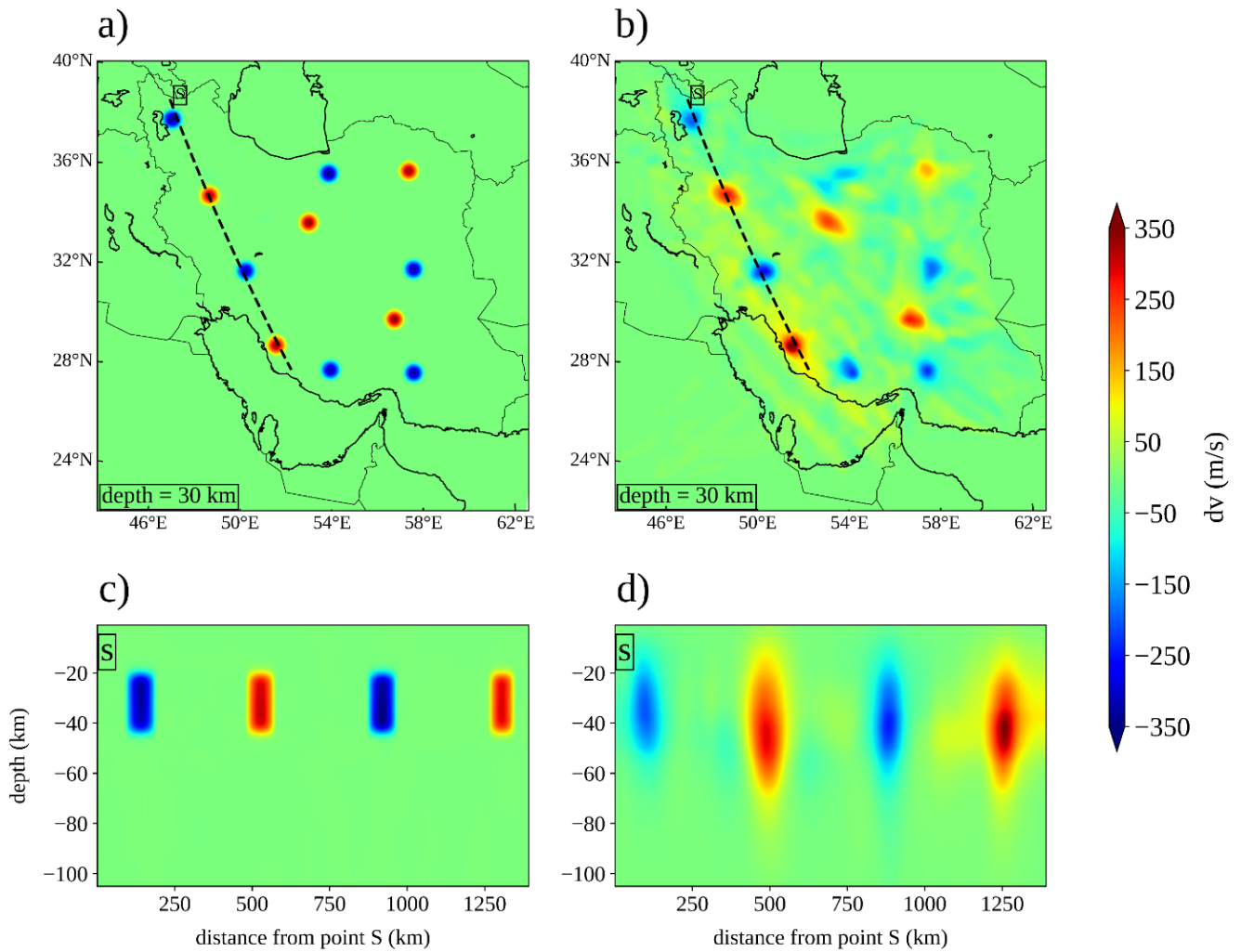


Figure 8 Evaluation of model resolution using a checkerboard-like test. Shown are 30 km depth slices and cross-sections of the initial model (a and c) and the recovered model (b and d) after subtracting the background model (M12). The black dashed line in (a) and (b) marks the location of the cross-section.

- 1) Lateral boundaries in the final model are better resolved and more prominently highlighted in both the crust and mantle. Synthetic tests support the ability of the data and method to resolve these lateral boundaries at various depths.
- 2) The absolute values of seismic velocities have been adjusted to higher values in the final model, particularly in the crust and upper mantle beneath Central Iran.

Due to the distribution of our data (Fig. 1) and the results of our resolution test (Fig. 8), the following discussion will mainly focus on the interaction between the Arabian and Eurasian plates within the Zagros collision zone at both the crustal and mantle scales.

4.1 Crustal scale

The most prominent features on a crustal scale in our seismic images are the low-velocity anomalies (CLV1-CLV3, Figure 4, profiles A, B, C and D) that initiate at shallow depths to the south of the Main Zagros Reverse Fault (MZRF) and extend to deeper levels in the

crust beneath the Sanandaj-Sirjan Zone (SSZ) and the Urumieh-Dokhtar Magmatic Arc (UDMA), where the Moho reaches its maximum depth (>55 km). These anomalies have also been observed in several previous studies (e.g., Paul et al., 2006, 2010; Shad Manaman and Shomali, 2010; Motaghi et al., 2015, 2017a,b; Kaviani et al., 2020; Irandoust et al., 2022; Zarunizadeh et al., 2024, 2026) and are considered evidence for the underthrusting of the northeastern margin of the Arabian plate beneath Central Iran. The intra-crustal low-Vs anomalies (CLV1-CLV3) beneath the Zagros and the Sanandaj-Sirjan Zone (SSZ) are interpreted as the result of crustal thickening and the geodynamic evolution of the Iranian lithosphere. Although a high-velocity signature might be expected from a cold, underthrusting slab, these anomalies instead reflect the subduction of the relatively low-density Arabian continental crust, which inherently exhibits lower seismic velocities (Paul et al., 2010; Kaviani et al., 2020; Irandoust et al., 2022; Zarunizadeh et al., 2026). Their pronounced low-velocity character is further enhanced by lithospheric delamination or convective removal of the Ara-

bian lithospheric root beneath the SSZ and Central Iran, permitting the upwelling of hot asthenospheric material (Motaghi et al., 2015; Mahmoodabadi et al., 2019, 2024). In addition, dehydration-related fluid release from the subducting slab, together with shear heating along the plate interface, contributes to further reductions in shear-wave velocity (Shad Manaman et al., 2011). The observed along-strike variations highlight the segmented nature of these coupled underthrusting and delamination processes across the Lurestan and Fars arcs.

Our seismic model suggests a lateral variation in the nature of these anomalies. The vertical cross-sections (Fig. 5) show relatively limited underthrusting in the Central Zagros (anomaly CLV2, profile B) compared to the higher volume of upper crust underthrust beneath the NW Zagros (anomaly CLV3, profile C). In the SE Zagros, a more extensive low-velocity anomaly (CLV1, profile A) suggests that the Arabian crust is being thrust further northeast beneath Central Iran. We also observe a relatively steep boundary between the Arabian and Central Iranian crust in the NW Zagros (profile C), contrasted with a more gently northeast-dipping underthrusting in the Central and SE Zagros (profiles B and A). This more extensive crustal thickening in NW Zagros was also reported by Shad Manaman et al. (2011) and Irandoust et al. (2022). Additionally, in profile D, which presents a cross-sectional view of the Zagros along its strike, the low-velocity anomaly (CLV3) extending into the lower crustal depths beneath the southern Lurestan Arc separates the northern part of the Zagros from the Central and SE Zagros.

The along-strike variation in the low-velocity anomaly beneath the SSZ provides compelling evidence for the proposed diachroneity of the structures and evolutionary processes along the Zagros collision zone, which was also observed by previous seismic tomography studies (Koulakov, 2011; Talebi et al., 2020; Mahmoodabadi et al., 2019, 2020; Rahmani et al., 2019; Veisi et al., 2021; Irandoust et al., 2022) and affirmed by geological observations (e.g., Agard et al., 2005, 2011; Mouthereau et al., 2012; Zhang et al., 2017). Specifically, regarding the underthrusting process, we argue that while the Arabian plate is actively underthrusting beneath the Iranian crust in the SE Zagros, the underthrusting process has slowed or ceased in the NW Zagros, where the underthrust Arabian crust has undergone significant thickening and may currently be experiencing exhumation due to its large negative buoyancy. These observations are remarkably consistent with the high-resolution lithospheric model of Irandoust et al. (2022), which identifies a more pronounced underthrusting of the Arabian crust in the northern Zagros (Lurestan arc) compared to the central and southern segments. Furthermore, the resolved features in our profiles align with the recent earthquake and ambient noise tomography results of Zarunizadeh et al. (2024), who highlighted the tectonic segmentation of the northern Zagros. The strong agreement between our adjoint-based model and these independent investigations, utilizing different datasets such as receiver functions and teleseismic data, provides a validation of

the interpreted lithospheric architecture.

Thermo-mechanical experiments (e.g., Tesauro et al., 2024) and plate tectonic reconstruction studies (e.g., Darin and Umhoefer, 2022) suggest that continental collision along the Tethyan suture initiated with a 'soft' collision, characterized by the subduction of stretched lithosphere from the Arabian passive margin, followed by a 'hard' collision, marked by the arrival of unstretched Arabian continental lithosphere in the subduction zone. The onset of this hard collision involved plate coupling, decelerating convergence, and the localization of collisional strain along the Zagros orogeny. Our seismic images reveal lateral variations in the volume of the underthrust Arabian crust during the 'soft' collision, which not only indicates a chronological sequence of collision events along the suture but also suggests along-strike variations in the characteristics of the colliding plates.

Geological observations also indicate significant diachroneity in the collision processes between Arabia and Eurasia, with the initial collision occurring in eastern Anatolia during the Middle Eocene and progressively later toward the southeast along the Zagros suture zone (Agard et al., 2011; Ballato et al., 2018; Mouthereau et al., 2012). GPS surveys conducted across the Zagros belt (e.g., Vernant et al., 2004; Walpersdorf et al., 2006; Khorrami et al., 2019) also reveal along-strike variation in the current rate of convergence.

The obliquity of the Neo-Tethys closure relative to the northward direction of plate convergence and along-strike heterogeneities of the colliding plates are proposed as the primary causes of this diachroneity (Agard et al., 2011; Mouthereau et al., 2012; Darin and Umhoefer, 2022; Tesauro et al., 2024). This diachroneity in collision processes results in lateral variations in the style and extent of crustal deformation, which in turn control the observed along-strike changes in crustal configuration and orogen altitude. In this context, the volume of felsic upper crust from the Arabian Plate that was thrust beneath the central Iranian crust along the SSZ, as well as its current configuration (as is imaged in our seismic model), depends on several factors, including the age and width of the original oceanic domain, convergence rate, specific properties of the subducting continental lithosphere, and the thickness of the overlying plate (Darin and Umhoefer, 2022; Tesauro et al., 2024).

Furthermore, it appears that the low-velocity anomalies in the central and NW Zagros regions are confined beneath the SSZ (anomaly CLV2 in profile B and anomaly CLV3 in profile C). This observation suggests that the underthrust edge of the Arabian crust beneath the SSZ can be decoupled from the rest of the crust in the central and NW Zagros, a hypothesis that could have significant mechanical implications for the crustal deformation of the Zagros. The northeastern extent of our model is captured in Profile B (also in profile I in Fig. S9), which shows a prominent high-velocity anomaly beneath the Kopeh-Dagh region. This feature is consistent with the presence of the rigid Turan Platform that underthrusts the northeastern Iranian plateau (e.g., Motaghi et al., 2015). Please note the limited data coverage (Fig. 1) and resolution (Fig. 8) in this part of the model.

Profiles C (SW-NE) and E (NNW-SSE) transect the Alborz. On both profiles the low-Vs shallow layers of the SCB, representative of its sedimentary cover, are present in the coastal regions. Unlike the initial model and some previous studies (e.g., Hollingsworth et al., 2008; Tatar et al., 2007), no clear evidence for underthrusting of SCB beneath the Alborz is observed. In a recent study by Motaghi et al. (2018), this absence of underthrusting is noted in the Alborz region. However, the underthrusting of the SCB beneath Alborz cannot be completely ruled out, as some studies (e.g., Rastgoo et al., 2018) attributed the low-velocity anomalies in western Alborz to post-collisional delamination of the lower part of the western Alborz lithosphere as a result of interaction between SCB and Alborz. In profile E, the crust beneath the Alborz is on average thinner than 40 km. The thin crust beneath the Alborz was also observed by some previous studies (Rodgers et al., 1997; Radjaee et al., 2010). However, in profile C, the crust thickens from Alborz toward central Iran in the SW direction, which is in agreement with results from Sodoudi et al. (2009). The local low velocity anomaly beneath Alborz (profile E), which can be associated with the addition of magma at the base of the crust, is coincident with the presence of volcanic material (Jackson et al., 2002; Verdel et al., 2011; Shabanian et al., 2012) at the surface. Nevertheless, the presence of velocity smearing in this region, as observed in the results of synthetic tests (Fig. 8), implies a need for caution in interpreting this particular feature.

In Northwest Iran, our adjoint tomography model reveals a prominent crustal low-velocity anomaly beneath the Sabalan volcano (Profile N in Fig. S9), which likely represents the thermal signature of the volcanic system or the presence of partial melt within the crust. While the ray coverage is relatively lower at the northwestern boundaries compared to the central and western parts of the plateau (as shown in Figure 1), the consistency of our results with previous studies remains acceptable. At sub-Moho depths, we observe a low-velocity zone beneath the Sabalan region that aligns with the findings of Bavali et al. (2016). This pattern supports the hypothesis of a mantle source for post-collisional volcanism in NW Iran, potentially driven by the melting of a subducted slab or lithospheric thinning, which facilitates the upwelling of hot asthenospheric material into the lithosphere. In the southeast, the recovered crustal structure (profile K in Fig. S9) is broadly consistent with the velocity contrasts and mid-crustal features seen in recent high-resolution studies (e.g., Enayat and Ghods, 2023; Mehrdar et al., 2025). However, our model lacks the resolution required to image the subducting slab geometry beneath the Makran arc.

4.2 Upper mantle

The verification of the misfit kernels (Fig. S4) shows that, due to the limited penetration depths of the ray paths, the velocity model obtained has reasonable sensitivity only within the top 80 km of the mantle. Therefore, on a mantle scale, we focus our discussion on the sub-crustal shallow depths.

The absolute values of shear wave velocities in the uppermost mantle vary within the range of 4–4.6 km/s (see Figs. 4 and 5). The highest and lowest velocities are imaged beneath the SE Zagros and Lut block, respectively. Surprisingly, sub-Moho mantle beneath the northern Zagros and Central Iran are characterized by comparable seismic velocities in our model. Relatively lower velocities are mainly confined to the boundary region between the two region of lithosphere beneath the SSZ and UDMA (Fig. 5, profiles B and C and E, anomalies MLV1 and MLV2). In the NW, the sub-Moho mantle beneath Central Iran and Alborz is characterized by even higher velocities relative to the NW Zagros (profile C). Previous Pn-velocity tomography studies (e.g., Al-Lazki et al., 2014) also indicate a strong velocity contrast in the shallow mantle between the southern Zagros and Lut block, while a lower velocity contrast is observed between the Central-NW Zagros and Central Iran. Numerous previous seismic tomography models (e.g., Maggi and Priestley, 2005; Kaviani et al., 2007; Mahmoodabadi et al., 2019; Rahmani et al., 2019; Veisi et al., 2021) revealed strong velocity contrasts in the mantle beneath the Zagros and Central Iran. However, most of the seismic images presented in previous studies focused mainly on depths below 80 km. A common feature of these studies is that the Zagros is characterized by a thick lithosphere (~220–250 km), whereas Central Iran has a relatively thin lithosphere (<120 km) and hot upper mantle (e.g., Tunini et al., 2014). Our model does not allow us to examine deep mantle structure, but it suggests that the mantle beneath the Zagros and Central Iran at shallow depths are in a comparable thermal state.

Assuming that a thermal anomaly is the main cause of the velocity contrast observed across the Zagros collision zone, different scenarios have been proposed within the framework of the geodynamic evolution of the Tethys subduction/collision system to explain the difference in thermal status. These hypotheses include the upwelling of hot mantle material after slab break-off and subsequent delamination of the subducted Arabian plate (Mahmoodabadi et al., 2019; Rahmani et al., 2019; Veisi et al., 2021) and thermal erosion of the Central Iranian lithosphere (e.g., Maggi and Priestley, 2005; Kaviani et al., 2007; Motaghi et al., 2017a,b). The presence of high-velocity anomalies in the deep upper mantle (e.g., Mahmoodabadi et al., 2019; Veisi et al., 2021) and mantle transition zone (e.g., Kaviani et al., 2018) beneath Central Iran is used as evidence for the presence of segments of delaminated mantle lithosphere of Central Iran, likely provoked by small-scale convective instabilities (François et al., 2014).

We are not able to discriminate the relative importance of these scenarios, which would require information on deep mantle structure. However, the comparable state of the mantle between the Zagros and Central Iran at shallow depths leads us to address some aspects of these scenarios. Assuming that temperature is the main factor determining shear-wave velocity anomalies in the mantle, the first conclusion from our seismic model is that there is not a strong contrast in thermal status at shallow mantle depths between the Zagros and Central Iran. Therefore, regardless of the dominant

mechanism causing the thin lithosphere and hot sublithospheric mantle beneath Central Iran, the remaining mantle lid beneath Central Iran seems currently to be stable. This contrasts with the weak or missing mantle lid beneath the neighboring Eastern Anatolian Plateau (Keskin, 2003; Wang et al., 2024).

Geological observations provide compelling evidence for rising hot asthenospheric material since the Eocene beneath Central Iran and Alborz, likely produced by delamination or slab break-off (Verdel et al., 2011; Shabanian et al., 2012). The question arising here is how the current thermal status of the upper part of the “thin” lithosphere beneath Central Iran is less affected by this hot, rising asthenosphere. On the other hand, the relatively lower velocities in the shallow mantle beneath the SSZ and UDMA region, located in the boundary zone between the two lithospheric plates, suggest that this region is likely in a hotter thermal state relative to the rest of Central Iran. Considering this evidence, one can conclude that the most recent rise of asthenospheric material following slab break-off has left its mark mainly beneath the SSZ and UDMA, where a gap had formed at the transition between the two lithospheric plates. Any large-scale mantle upwelling capable of destabilizing and erasing the base of the lithosphere beneath Central Iran seems to be active at depths below 100 km.

Another observation worth considering is the relatively low-velocity shallow mantle beneath the Lut block (Fig. 4 and profile A in Fig. 5). Previous seismic tomography studies (e.g., Al-Lazki et al., 2014; Namvaran et al., 2020) also revealed the presence of low-velocity upper mantle beneath this region. Signatures of a high-temperature anomaly at the upper-lower mantle transition have also been taken as evidence of a deep-rooted mantle upwelling beneath the Lut block (Kaviani et al., 2018). More extensive seismic imaging is required to answer the question of whether a large-scale, deep-seated mantle upwelling exists beneath the Lut block that could have a larger-scale effect further north on the Central Iranian mantle.

5 Conclusions

In this study, we utilized the adjoint noise tomography (ANT) technique to refine and create a more detailed 3D structural model for the Iranian Plateau, building upon an existing model (Kaviani et al., 2020) of shear-wave velocity in the crust and uppermost mantle derived from conventional ambient noise tomography. Our improved model offers enhanced resolution, revealing critical details about the tectonic structures, particularly within the Zagros collision zone, central Iran, and the Alborz-Kopet-Dagh system. We observed significant lateral variations in the underthrusting of the Arabian Plate beneath central Iran, with more extensive underthrusting in the southeast Zagros compared to the northwest, supporting the concept of diachronous collision processes along the Zagros suture zone. At the mantle scale, our findings suggest that the uppermost mantle beneath the Zagros and central Iran is in a similar thermal state, indicating stability in the mantle lid beneath central Iran despite historical mantle upwelling and delamination

events. The lower seismic velocities observed in the boundary region between the SSZ and UDMA suggest a hotter thermal state, reflecting the complex interactions between the colliding lithospheres. A local low-velocity feature beneath the southwest Alborz region may be linked to a magma addition at the base of the crust.

In summary, our new model refines and expands upon the features inherited from the initial model. In comparison with the shear-wave velocity model of Irandoust et al. (2022), which serves as a benchmark for the Iranian Plateau, our results are comparable to the first-order crustal features despite the use of a more limited dataset, demonstrating the potential of adjoint noise tomography to recover robust crustal-scale velocity structures.

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6 Data and code availability

Data: We used continuous waveforms from the permanent networks of Iranian Seismological Center (IRSC) and the Iranian National Seismic Network (ISNS), which are accessible through direct request from these centers. We also used the data from Global Seismograph Network (doi: 10.7914/SN/II) - IRIS/IDA (II), Kandilli Observatory and Earthquake Research Institute (KO), Kuwait National Seismic Network (KW), Earthquake Monitoring Program of Oman (OM), Seismological Network of United Arab Emirates (UE) and Iraqi Seismic Observatory (IQ), which are permanent networks and publicly accessible via IRIS Data Services. The initial 3D shear-wave velocity model is available online through the IRIS (Incorporated Research Institutions for Seismology) Earth Model Collaboration (IRIS DMC 2011, <http://ds.iris.edu/ds/products/emc-earthmodels/>) with the label “Midd_East_Crust_1”. The earthquake locations in Fig. 1 were taken from the National Earthquake Information Center (NEIC), which are available on the U.S. Geological Survey (USGS) website at <http://earthquake.usgs.gov>. The resulting model, from this study is available at <https://doi.org/10.17605/OSF.IO/D4CMT>.

Software: The data analysis was performed using the open-software SPECFEM3D_Globe code which is available on <https://specfem.org>.

Graphs: The figures presented in the paper were generated using the PyGMT (<https://www.pygmt.org>) and

Paraview (<https://www.paraview.org>).

7 Competing interests

The authors declare that there are no competing interests, financial or non-financial, that could be perceived to influence the objectivity, integrity, or interpretation of the work presented in this manuscript.

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