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Adjoint Waveform Tomography for Crustal and Upper Mantle Structure of the Middle East and Southwest Asia for Improved Waveform Simulations Using Openly Available Broadband Data

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1 **Adjoint Waveform Tomography for Crustal and Upper Mantle Structure of the Middle East**
2 **and Southwest Asia for Improved Waveform Simulations Using Openly Available Broadband**
3 **Data**

4
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16 Key Points:

- 17 • Adjoint tomography improves waveform fits for a large region of the Middle East and
18 Southwest Asia.
- 19 • Our new model resolves structure of a tectonically complex region using openly
20 available, but uneven data.
- 21 • The model could be improved with data from regional networks for better resolution to
22 fit shorter periods.

23 **Abstract**

24 We present a new model of radially anisotropic seismic wavespeeds for the crust and
25 upper mantle of a broad region of the Middle East and Southwest Asia derived from adjoint
26 waveform tomography. The new model enables fully three-dimensional simulations of
27 complete three-component waveforms and provides improved fits that were not possible with
28 previous models. We inverted over 32,000 waveforms from 192 earthquakes recorded by over
29 1000 openly available broadband seismic stations from permanent and temporary networks in
30 the region with highly uneven coverage. Inversion iterations proceeded from the period band
31 50-100 seconds in six stages and 54 total iterations reducing the minimum period to 30
32 seconds. Our final model, MESWA, improves waveform fits compared to the starting and other
33 models for both the data used in the inversion and an independent validation set of 66 events.
34 Restitution tests indicate that the model resolves features in the central part of the model to
35 depths of about 150 km. The new model reveals tectonic features imaged by other studies and
36 methods but in a new holistic model of anisotropic shear and compressional wavespeeds (v_s
37 and v_p , respectively) covering a larger domain with smaller scale-length and amplified features.
38 Examples include: low crustal v_s in the Tethyan Belt; and low mantle v_s following divergent (Gulf
39 of Aden, Red Sea) and transform (Dead Sea Fault) margins of the Arabian Plate. Low v_s is
40 imaged below Cenozoic volcanic centers of the Mecca-Madina-Nafud Line, Arabian Peninsula
41 and the Turkey-Iran border region. Elevated v_s tracks Makran subduction under southeast Iran
42 with near vertical dip. MESWA could be used as a starting model for further improvements, say
43 using waveforms from in-country seismic networks that are not currently openly available

44 and/or smaller-scale studies targeting shorter period. The model could be used to improve
45 earthquake hazard studies and nuclear explosion monitoring.

46

47 **Key Words:** Tomography, Waveform inversion, Computational seismology, Middle East,
48 Southwest Asia

49

50 **Introduction**

51 The Middle East and Southwest Asia (MESWA) is a geologically complex region including
52 the interaction of several tectonic plates. Figure 1a shows the study region, which includes all
53 of the Arabian Plate and parts of the Eurasian, African and Indian Plates. Plate boundaries
54 include: continental transforms of the North Anatolian and Dead Sea Faults; continental
55 convergence along the Turkish-Iranian Plateau, and Indian-Eurasian Collision (transpressional
56 plate boundary along Afghanistan-Pakistan border, Sulaiman Fold Belt, Central Afghanistan
57 Highlands, Hindu Kush, Pamirs); ocean spreading along the Red Sea, Gulf of Aden and Owen
58 Fracture Zone; and subduction of oceanic lithosphere along the Makran north of the Gulf of
59 Oman and Arabian Sea. Complex active tectonics of the region are revealed by abundant but
60 uneven seismicity including large damaging earthquakes and volcanic activity. Figure 1b shows
61 the events used for the model inversion and validation (discussed in detail below) and is
62 representative of the seismicity in the region.

63

64 Parts of the region have been intensively studied tracking the deployment of seismic
65 stations and networks, while other areas have received less attention. Many of the detailed

66 structural investigations of the region have benefited from access to closed (proprietary) data
67 from networks operating in specific countries (Al-Lazki et al., 2004; Al-Damegh et al., 2005;
68 Hansen et al., 2006; Tkalčić et al., 2006; Hansen et al., 2007; Park et al., 2007; Park et al., 2008;
69 Manaman et al., 2011; Priestley et al., 2012; Mohammadi et al., 2013; Al-Lazki et al., 2014;
70 Rahimi et al., 2014; Tang et al., 2019; Kaviani et al., 2020; Kim et al., 2023; Movaghari and
71 Doloei, 2023; Irandoust et al., 2022). Structure of the crust and upper mantle has been
72 revealed by seismic tomography using various methodologies and data sets. These include
73 travel time tomography (Hearn and Ni, 1994; Al-Lazki et al., 2003, 2004, 2014; Park et al., 2007;
74 Amini et al., 2012), receiver functions (Al-Damegh et al., 2005; Hansen et al., 2006; Mohammadi
75 et al., 2013), earthquake and ambient noise surface wave dispersion (e.g. Mokhtar et al., 2001;
76 Villasenor et al., 2001; Park et al., 2008; Rahimi et al., 2014; Kaviani et al., 2020; Kim et al.
77 2023), waveform modeling and inversion (Rodgers et al., 1999; Maggi and Priestley, 2005;
78 Chang et al., 2010a; Manaman et al., 2011; Priestley et al., 2012; Civiero et al., 2022;
79 Masouminia et al., 2023) and joint inversions of different data sets (Julia et al., 2003; Tkalčić et
80 al., 2006; Chang et al., 2010ab; Al-Hashimi et al., 2011; Tang et al., 2019; Movaghari and Doloei,
81 2020; Irandoust et al., 2022) with this list meant to be representative but not exhaustive.

82

83 Despite the many studies that have investigated seismic structure of this region, they
84 suffer from shortcomings. Firstly, very few studies have made their model available for use by
85 other researchers in public repositories. However more importantly, many of the existing
86 models cannot be used for important applications such as regional-scale ground motion
87 simulation or waveform modeling including source characterization (e.g. scenario earthquake

88 modeling, point source moment tensor, finite fault rupture inversions, source type inference).
89 No available model provides coverage of far regional distance source-receiver paths (> 2500
90 km) crossing major tectonic boundaries and geologic provinces (Figure 1a) along with the
91 necessary material properties from the surface to upper mantle depths for full waveform
92 simulation. For example, studies that have used data mainly from a single national network in
93 the region have only resolved structure within the footprint of that network usually isolated to
94 a single country (e.g., Al-Damegh et al., 2005; Park et al., 2007, 2008; Tang et al., 2019;
95 Movaghari and Doloei, 2020; Irandoust et al., 2022). Many studies have used limited seismic
96 observables and thus have sensitivity to only a subset of the full parameters needed for
97 waveform simulation. For example, many studies inferred only vertically polarized shear
98 wavespeeds (v_{sv}) using Rayleigh wave dispersion and/or receiver functions (e.g. Park et al.,
99 2008; Tang et al., 2019; Kaviani et al. 2020; Movaghari and Doloei, 2020; Irandoust et al., 2022)
100 or vertical component complete waveforms (Maggi and Priestley, 2005; Manaman et al., 2011;
101 Priestley et al., 2012; Civiero et al., 2022). These models do not include radial anisotropy which
102 is needed to fit the pervasive Love-Rayleigh discrepancy present in this region (e.g. Hansen et
103 al., 2007; Chang et al., 2010b). Other studies considered regional P-wave travel times and
104 resolved only compressional wavespeeds (e.g. Al-Lazki et al., 2004, 2014; Amini et al., 2012).
105 Regional-scale full waveform simulation requires a 3D description of seismic compressional and
106 shear wavespeeds, density and attenuation from the Earth's surface to upper mantle depths.
107 Adjoint waveform tomography is a methodology that addresses some of these shortcomings,
108 but comes with a higher computational cost. At the time of this writing, no model of the region

109 has been published and made available based on adjoint waveform tomography although one
110 investigation is in progress (Örsvuran et al., 2022).

111

112 This study reports a new model of radially anisotropic seismic wavespeeds for the MESWA
113 region shown in Figure 1a spanning the Earth's surface to upper mantle depths. The model is
114 derived from adjoint waveform tomography using broadband seismic waveform data from only
115 openly available sources through Federation of Digital Seismic Networks (FDSN) webservices.
116 Several permanent seismic networks operate stations in the region, however those with global
117 coverage and openly available data are sparse (e.g. IRIS-IDA, IRIS-USGS, Geofone, Geoscope).
118 Regional networks in Turkey, Greece and Central Asia provide open data for clustered stations.
119 Temporary networks have been deployed in specific areas, typically for 1-2 year durations, and
120 these improve the coverage. This study establishes a baseline of what features can be imaged
121 with openly available sparse data for this large and tectonically complex continental-scale
122 domain and will be useful to compare against other studies that included data from seismic
123 networks that are not openly available.

124 Adjoint waveform tomography is a waveform inversion methodology which uses the full
125 three-dimensional (3D) sensitivity of observed seismograms to Earth structure (usually only
126 seismic wavespeeds). The methodology is now widely used and is described in seminal studies
127 (e.g., Tarantola, 1988, Tromp et al., 2005; Liu and Tromp, 2005; Fichtner et al, 2006; Tape et al.,
128 2007) and reviews (e.g. Fichtner, 2010; Liu and Gu, 2012; Tromp, 2020). Adjoint waveform
129 tomography is superior to other tomographic imaging methods for producing models for
130 complete waveform simulation because: the method inverts observed seismogram data

131 requiring all necessary material parameters be defined; and uses the full 3D sensitivity of the
132 waveform to infer structure including finite frequency scattering and diffraction effects. This
133 has two important consequences. Firstly, it models the complete three-component (albeit
134 filtered) seismograms, not derived measurements such as arrival times, dispersion or
135 amplitudes, which have limited sensitivity to Earth structure compared to the whole waveform.
136 Secondly, it produces a consistent 3D model with all the necessary material properties required
137 for 3D simulations (wavespeeds, attenuation and density). Simulation of the complete
138 waveform response of many events in 3D Earth models for many iterations requires high-
139 performance computing. Because the goal of this study is to develop a model that can be used
140 for waveform simulations, adjoint waveform tomography is the method of choice. In this study,
141 we closely followed the methodology of Rodgers et al. (2022) for the western United States.
142 The resulting model provided improvement in quantitative measures of waveform misfit
143 compared to the starting and other available models and many known large-scale tectonic
144 features were imaged.

145

146 This article is organized as follows. In the next section we describe the data selection
147 and considerations for choosing a starting model. We follow this with a description of the
148 adjoint waveform tomography methodology applied to the region and data set. We then
149 describe the resulting model, demonstrate its efficacy for fitting observed waveforms and
150 interpret the imaged features in terms of known tectonic processes. Model resolution is
151 evaluated with a new procedure: restitution analysis. We conclude with a summary of the
152 model and discussion of strategies and recommendations for future improvements.

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Data Selection and Starting Model

We started by selecting earthquakes from the Global Centroid Moment Tensor (GCMT) catalog (Ekström et al., 2012) in the domain with moment magnitude, M_w , between 5.5 and 7.0 for the time period 1995-2020. This resulted in 327 events. We then collected openly available broadband waveforms for these events that were recorded by permanent and temporary seismic station networks in the domain from Federation of Digital Seismic Network (FDSN) webservices using ObsPy (Krischer et al., 2015a). Based on the initial waveform fits (described below) and the number and spatial coverage of paths, we selected 192 events for the inversion and 66 events for model validation (Figure 1b). These events were recorded by over 1000 stations in the domain. Figure 1c and 1d show the broadband stations from 347 permanent and 672 temporary seismic networks used in the inversion, respectively. Openly available permanent networks (Figure 1c) cover the region very sparsely. Permanent networks cover the Aegean Sea and Turkish Plateau (Greece and Turkey), Eastern Mediterranean Sea (Cyprus, Israel), the Caucasus (Armenia, Georgia) and the Hindu Kush, Pamir and Tien Shan (Kyrgyzstan, Tajikistan). Some whole countries are covered by no or only a few openly available permanent stations (e.g., Iran, Saudi Arabia, Pakistan, Oman, Yemen, UAE, Turkmenistan, Uzbekistan, Egypt, Sudan). Temporary networks (Figure 1d) provide about twice as many stations as the permanent networks although they are typically deployed for a short duration (e.g., 1-2 years). These stations provide complementary coverage in some regions poorly covered by permanent stations (e.g., Ethiopia, Eretria, Yemen, Oman, Saudi Arabia, Iran and the Hindu Kush and Pamir

174 Mountains in Central Asia). A complete listing of events and seismic stations used in both the
175 inversion and validation data sets is provided in Rodgers (2023).

176

177 Adjoint waveform tomography requires numerical waveform simulations in a three-
178 dimensional (3D) seismic Earth model describing wavespeeds, density and attenuation.
179 Measurements of differences between the observed waveforms and those simulated from the
180 current model (the misfit) are used to compute sensitivity kernels for model updates. Adjoint
181 waveform tomography uses a multiscale iterative inversion procedure (e.g. Bunks et al., 1995;
182 Fichtner et al., 2009, 2013; Tape et al. 2010) to improve fit and avoid getting trapped in local
183 minima. An essential step in adjoint waveform tomography is identifying waveform segments
184 (“windows”) where observed and simulated waveforms are in reasonably good agreement with
185 slowly varying phase delay (less than a half-cycle for phase measurements). Sensitivity kernels
186 are computed from waveform misfit metrics based on these windows. A good starting model
187 should generate simulated waveforms that fit observed waveforms at many receivers (paths)
188 within the half-cycle criterion. Such a model should provide long durations of well-correlated
189 observed and synthetic waveforms. Ideally, a starting model should provide good waveform
190 fits, cover the central area and depth extent of the target domain and provide the necessary
191 parameters (wavespeeds, density and attenuation). Radial anisotropy is important to model
192 the Love-Rayleigh discrepancy commonly observed in long-period (> 20 seconds) regional
193 surface waves and upper mantle phases (e.g. Gaherty and Jordan, 1995; Hansen et al., 2008;
194 Chang et al., 2010b).

195

196 Doody et al. (2023a) showed that a conservative multiscale inversion approach can
197 result in models that are robust to the choice of starting model. We followed that approach
198 here and considered three possible starting models. Figure 2 shows the vertically polarized
199 shear wavespeeds, v_{SV} , for the three models considered and the target domain at 20 and 100
200 km depths, along with our final model. These models show common features related to
201 tectonics that will be discussed in the Results section.

202

203 The SPiRaL model (Simmons et al., 2021) is a global model based on travel times and
204 surface wave dispersion. It includes radial anisotropy as vertically and horizontally polarized
205 shear wavespeeds (v_{SV} and v_{SH} , respectively) and compressional wavespeeds (v_{PV} and v_{PH} ,
206 respectively) along with the η parameter describing wavespeeds for intermediate angles.
207 Density and attenuation quality factors were scaled from wavespeeds. This model conforms to
208 the global crustal thickness model CRUST1.0 (Laske et al., 2013). Although this model is not
209 based on waveform simulations, it has been shown to produce good long-period waveform fits
210 in various regions (Simmons et al., 2021; Rodgers et al., 2022).

211

212 The Collaborative Seismic Earth Model version 2.0 (CSEM, Noe et al. 2022) is a global
213 model based on multiscale adjoint waveform tomography following the approach of Afanasiev
214 et al. (2016) and Fichtner et al. (2018). This model spans our domain and depth range and
215 includes all the necessary material properties including radial anisotropy, density and
216 attenuation (radial, one-dimensional, 1D). It is based on at least two regional models that
217 overlap our target domain and updated the global material properties by waveform inversion.

218 Specifically, CSEM2.0 includes the waveform inversion models of Masouminia et al. (2023)
219 which imaged the Zagros Mountains collision zone and adjacent Iranian Plateau and Arabian
220 Plate and van Herwaarden et al. (2023) which imaged the African and Arabian Plates and
221 surrounding areas.

222

223 Midd_East_Crust_1 (MEC-1; Kaviani et al., 2020) is a regional shear wavespeed (v_s)
224 model covering the Middle East, Arabian Peninsula and the Eastern Mediterranean. This model
225 is available at the IRIS-EMC. It is based on vertical component Rayleigh surface wave dispersion
226 measurements from earthquakes and ambient noise cross-correlations. This model covers all
227 but the African Plate, the Arabian Sea, the northern $\sim 5^\circ$ and eastern $\sim 10^\circ$ of our target domain
228 (Figure 1) and extends from the surface to 105 km depth. MEC-1 benefits from data from at
229 least two major national seismic networks that are not openly available (International Institute
230 of Earthquake Engineering and Seismology in Iran and the Saudi Geological Survey in Saudi
231 Arabia). Because MEC-1 is based on vertical component Rayleigh wave data, it only constrains
232 vertically polarized shear wavespeeds, v_{SV} , and unfortunately has no constraints on transversely
233 polarized shear wavespeeds, v_{SH} , compressional wavespeeds, v_P , or density, ρ . Without
234 constraints on anisotropy in MEC-1, we interpreted MEC-1 as an isotropic model.
235 Compressional wavespeeds and density were scaled from v_s following Brocher (2005). The
236 model was tapered (with a 2° taper width) into isotropic PREM (Dziewonski and Anderson,
237 1981) to span the computational domain.

238

239 Figure 2 shows maps of the vertically polarized shear wavespeeds, v_{sv} , at 20 and 100 km
240 for the three models described above. These maps show the broad features that are known
241 about the seismic structure of the region: ocean-continent differences, low crustal wavespeeds
242 along the Tethyan margin (Turkish-Iranian Plateau, Central Afghan Highlands); low wavespeeds
243 along the spreading margins in the Red Sea, Dead Sea Fault and Turkey-Iran border regions; and
244 high wavespeeds in the Eurasian mantle. We also included v_{sv} from our inferred MESWA model
245 (Figure 2dh) and will be described below.

246
247 In order to objectively select a starting model, we computed synthetic waveforms for
248 the three models described above for all events and paths in the computational domain.
249 Waveform simulations relied on the spectral-element method (Komatitsch and Tromp, 1999)
250 and the Salvus waveform modeling and inversion package (Afanasiev et al., 2019). Simulations
251 were based on spherical shell geometry including topography and bathymetry, ellipticity and
252 ocean loading. We considered five period bands with minimum periods of 50, 40, 30, 25 and 20
253 seconds and a maximum period of 100 seconds. All observed and simulated waveforms from
254 all 327 events were compared to define time windows for adjoint sources and gradients using a
255 procedure similar to the FLEXWIN algorithm of Maggi et al. (2009). We used the data selection
256 method of Krischer (2015b) following recent studies (e.g. Gao et al., 2021; Wehner et al., 2022;
257 Rodgers et al., 2022; Doody et al., 2023ab). The algorithm finds time windows where
258 agreement in amplitude and phase are good enough so that misfit can be measured, adjoint
259 sources can be defined and sensitivity kernels can be computed. Waveforms with high noise
260 levels, interfering events, incorrect instrument response or amplitude errors were rejected by

261 the algorithm. Note that using a maximum period of 100 seconds may introduce noise for
262 smaller events recorded at long distance.

263

264 We then used metrics of the resulting windows to evaluate model performance.
265 Specifically, we measured the time-bandwidth product of the picked windows as introduced in
266 Rodgers et al. (2022). The time-bandwidth product is simply the product of the duration and
267 frequency bandwidth of the selected windows. It is proportional to the information content in
268 the selected windows, hence the larger this number is for a fixed data set (pairs of observed
269 and simulated waveforms and period band) the better the model is at explaining the observed
270 seismograms. Figure 3 shows the time-bandwidth product as a function of the minimum period
271 for the three models considered and all recordings of the 327 events. For a given model, the
272 time-bandwidth product generally increases as the minimum period decreases due to the
273 increase in bandwidth and the consistency of waveform agreement. We see how the time-
274 bandwidth product for the SPiRaL and MEC-1 models closely track each other except for the
275 shortest minimum period of 20 seconds and that the CSEM model has slightly lower time-
276 bandwidth product values compared to other models. We chose to use the SPiRaL model for
277 our starting model (0th inversion stage) based on the time-bandwidth product performance and
278 that it includes radial anisotropy and covers the entire target domain and depth range. Note
279 that we also included the time-bandwidth product for the resulting MESWA model after
280 inversion iterations in Figure 2, which shows how our adjoint waveform tomography approach
281 results in a model that improves waveform fits over the starting models and will be discussed
282 below. Note furthermore that the MESWA model provides good performance (large and

283 increasing time-bandwidth product) for periods shorter than those used in the inversion (30
284 seconds).

285
286 Using these data selections based on window picking, two subsets were created from all
287 events: one for the inversions and another for validation of the resulting model. Initial analysis
288 of the waveform fits (confirmed below) showed that the SPiRaL model generally performed
289 better than the MEC-1 and CSEM models across the period bands considered. We then chose
290 192 events for the inversion using windows picked with the SPiRaL model in the period band
291 50-100 seconds that met two criteria: each event had at least 10 receivers with windows and
292 about half of the receivers that recorded the event had windows. These choices were made to
293 select the most well recorded events that best cover the domain. Earthquakes with a small
294 fraction of paths reporting windows may indicate a complex rupture or errors in the source
295 parameters. Similar event lists were found with the other models, though fewer and/or shorter
296 windows were picked. A validation data set was created with 66 events also requiring that
297 windows were picked on least 10 receivers and a slightly lower fraction of receivers reporting
298 windows (35%). The validation events were selected to provide comparable waveform fits (in
299 terms of window statistics) but with redundant path coverage compared to the inversion
300 events. In this way these events were good to leave out of the inversion and be used to
301 evaluate model performance. The inversion and validation events are shown in map view in
302 Figure 1b. Figure 4 shows the events, stations and path coverage of the inversion and
303 validation data sets based on the windows selected from the SPiRaL model synthetics in the

304 period band 50-100 seconds. Although the validation data set has fewer paths (only about 25%
305 of the inversion data set), the coverage of the domain is very similar.

306

307 **Adjoint Waveform Tomography Methodology**

308 We followed a multiscale approach (Bunks et al., 1995; Fichtner et al. 2013) similar to
309 other adjoint waveform tomography studies (e.g., Tape et al., 2009; Zhu et al. 2015; Gao et al.,
310 2021; Wehner et al., 2021; Rodgers et al., 2022; Doody et al., 2023ab). We chose to start with
311 the longest periods (50-100 seconds) in order to make adjustments to the large-scale structure
312 including the deep structure sampled by the longest period surface waves. We then reduced
313 the minimum period and relaxed the smoothing to increase sensitivity to finer-scale structure in
314 six inversion stages. Within each inversion stage the time windows were re-picked and kept
315 constant throughout the stage along with inversion parameters. Inversions relied on the L-
316 BFGS algorithm (Nocedal and Wright, 2006; Kennett and Fichtner, 2021), which has been shown
317 to improve convergence in waveform inversion (Modrak and Tromp, 2016; Thrastarson et al.,
318 2021; Liu et al., 2022). More specifically, we ran a trust-region L-BFGS inversion algorithm
319 including a smoothing operator based on the diffusion equation on the initial approximation of
320 the Hessian (Bunks et al., 1995; Conn et al., 2000; Boehm et al., 2018). Because seismic
321 wavespeeds vary much more strongly with depth than laterally, isotropic smoothing can have
322 the undesirable effect of smearing sensitivity across a broad depth range. We designed the
323 smoothing operator to be anisotropic with shorter smoothing length in the radial direction, λ_r ,
324 than in the arc directions, λ_θ and λ_ϕ . The smoothing length is defined as a fraction of the local
325 v_{SV} wavelength in spherical coordinates. Our waveform data have constraints on this

326 parameter through vertically polarized shear body-waves and Rayleigh surface waves on
 327 vertical and radial components.

328
 329 Within each stage we allowed the inversion to iterate until it converged by failing to
 330 further reduce the misfit, by the trust region shrinking to small values or the algorithm rejecting
 331 models (all indicating the descent direction is poorly determined and minimum has been
 332 reached). The final model, which we refer to as MESWA was obtained as the seventh (7th) and
 333 final iteration from the sixth inversion stage (stage 5). The inversion stages and various
 334 parameters described in this section are provided in Table 1.

335
 336 **Table 1.** Parameters describing the six inversion stages used to develop MESWA. Receiver
 337 tapers follow Ruan et al. (2019) and additionally include minimum and maximum taper
 338 distances for receiver weighting. Source/receiver cutouts are given in km. Smoothing lengths
 339 ($\lambda_r, \lambda_\theta, \lambda_\phi$) are given in units of the local v_{sv} wavelength in spherical coordinate directions. The
 340 Region-of-Interest (ROI) depth is the shallowest depth for which model updates are included.
 341 “Iterations in stage” tabulates the total number of unique iterations for each stage.

342
 343

Stage	Period Band (sec)	Receiver Tapers (km)	Cutouts (source/receiver, km)	Smoothing lengths $\lambda_r, \lambda_\theta, \lambda_\phi$	ROI depth (km)	Iterations in stage
0	50-100	180/400	250/50	0.2, 1.0, 1.0	25	7
1	50-100	180/400	250/50	0.2, 0.5, 0.5	20	10
2	40-100	150/300	220/40	0.2, 0.5, 0.5	20	9
3	40-100	150/300	220/40	0.2, 0.5, 0.5	10	11
4	30-100	100/225	160/30	0.2, 0.5, 0.5	10	11
5	30-100	100/225	160/0	0.2, 0.5, 0.5	0	7

344
 345

346 The data set was updated by re-picking the time windows for the 192 inversion events
 347 at the start of each inversion stage. Improvement in the model is indicated by the general

348 increase of the time duration (window length) of windows picked for each inversion stage and
349 the time-bandwidth product of selected time windows relative to the starting model, similar to
350 Figure 3.

351

352 Inversions solved for updates to the vertical and horizontally polarized shear and
353 compressional wavespeeds and density (v_{SV} , v_{SH} , v_{PV} , v_{PH} and ρ). The parameter describing
354 wavespeeds for angles between horizontal and vertical, η , is keep constant from SPiRaL. We
355 solved for the material properties on the Gauss-Lobatto-Legendre (GLL) points defining the
356 spectral element method mesh with at least one element per minimum period (wavelength)
357 and 5 GLL points per element. These choices are common for spectral element method
358 simulations. The long periods waveforms considered here were dominated by surface waves,
359 but windows including first arriving P-waves also constrained the compressional wavespeeds.
360 Rayleigh waves provided some sensitivity to compressional wavespeeds, but these wavespeeds
361 and their anisotropy were likely poorly resolved, particularly without isolating P-waveforms
362 over broad distances and increasing the influence of these measurements in the inversion, say
363 by up-weighting them. While density can have an effect on waveforms (Płonka et al., 2016;
364 Blom et al., 2017), our waveform misfits were based on phase (arrival time) and were most
365 sensitive to wavespeeds. Our analysis here is focused on imaging shear wavespeeds, but we
366 included compressional wavespeeds, density and attenuation quality factors in the model for
367 interested readers (Rodgers, 2023)

368

369 In this study, we used time-frequency phase misfit for the waveform misfit objective
370 function (Fichtner et al., 2009, 2013; Fichtner, 2010; Krischer et al., 2015b) which has been used
371 in several recent waveform tomography studies (Krischer et al., 2016; Gao et al., 2021; Wehner
372 et al., 2022; Rodgers et al., 2022; Doody et al. 2023ab; van Herwaarden et al., 2023). This
373 method decomposes the observed and simulated waveforms into the time-frequency (wavelet)
374 domain following Fichtner et al., (2008) where phase delays of different frequency components
375 is measured. The method is based on time-frequency composition of Kristeková et al., (2006;
376 2009). Time-frequency phase misfits have the advantage of tracking time- and frequency-
377 varying phase errors between the observed and synthetic waveforms that can occur in
378 dispersed (e.g., surface waves) or interfering signals (e.g., triplicated arrivals, scattered waves).
379 Sensitivity kernels based on these frequency-dependent misfits include information across the
380 entire range of periods and wavelengths in the bandwidth considered. This misfit function is
381 thus multiscale like other misfit metrics such as generalized seismological data functionals (Gee
382 and Jordan, 1992), multitaper (Tape et al., 2010) or instantaneous phase (Bozdağ et al., 2011).
383 As such it includes sensitivity to the full period bandwidth in a selected waveform window, so
384 for a long duration surface wave window it can constrain deep and shallow structure with long
385 and shorted periods.

386

387 Once the misfits and adjoint sources were computed, gradients for the volumetric
388 inversion for model wavespeed updates were computed. These included various manipulations
389 to mitigate potential problems due to: the outsized influence of near-source and near-receiver
390 structure; the uneven distribution of receivers recording each event; and smoothing of rapid

391 spatial variations in the kernels. To mitigate the outsized influence of misfits at short epicentral
392 distances from the event, we applied a tapered weight to the near-source receivers. The taper
393 function has two values: a minimum distance within which receiver contributions to the event
394 kernel are zero; and a maximum distance beyond which receivers can contribute fully to the
395 kernel (receiver taper values in Table 1). To address the uneven station distribution, we
396 followed the strategy proposed by Ruan et al. (2019) and applied weights to the misfit
397 measurements based on the density of recording stations. In this scheme, isolated stations
398 away from the source contribute fully to the event kernel and densely clustered stations
399 contribute less. Station weighting should be especially important in this region where stations
400 are often clustered (e.g. Turkey, Greece, Israel, Kyrgyzstan, Tajikistan, Ethiopia) and in other
401 regions station coverage is very sparse. To address the high sensitivity of waveforms to near-
402 source and near-receiver structure, we used a cut-out to simply set the kernel values to zero
403 within a spherical volume around the source and receiver. The cut-out radii for each inversion
404 stage are compiled in Table 1. Smoothing of the gradients for inversion (after summation of
405 event kernels) was performed as described above with a diffusion equation applying an
406 anisotropic smoothing operator with characteristic length scales proportional to the local v_{SV}
407 wavelength. Finally, we applied the “Region of Interest” (ROI) approach described in Rodgers et
408 al. (2022) to only solve for wavespeed updates below a certain depth for each inversion stage.
409 The ROI started at 25 km depth and was reduced and then eliminated as the inversion stages
410 progressed. Both the receiver cut-outs and ROI were eliminated in the final inversion stage (5)
411 so that the inversion could make updates to the wavespeeds in the upper crust throughout the
412 domain. The relative misfit reductions within each of the six inversion stages are plotted in

413 Figure 5. Within each inversion stage except the final (sixth) stage, we obtained 12-27% misfit
414 reduction. Initial iterations in an inversion stage obtained larger reductions and these
415 reductions decreased as the iterations approached convergence.

416

417 To measure performance in terms of waveform fits we computed the misfit reduction
418 between the final (MESWA) and other models relative to the SPiRaL starting model in the final
419 period band 30-100 seconds. For this analysis we computed both the time-frequency phase
420 misfit used in the inversion and the normalized L2 misfit for the windows selected with our final
421 model. Figure 6a shows the event-averaged relative misfit reduction relative to the SPiRaL
422 starting model for all inversion events (sorted from high to low reduction corresponding to
423 most to least improved fit). Note that positive values correspond to improvement in waveform
424 fit relative to SPiRaL and negative values correspond to deterioration in waveform fit relative to
425 SPiRaL. These show that some events have time-frequency phase misfit reduction as high as
426 75% while a few have a smaller (<20%) misfit reduction. The average time-frequency phase
427 misfit is 59.7% and the normalized L2 misfits closely tracks the time-frequency phase misfits
428 with an average misfit of 55.3%. This is encouraging and quantifies the model performance in
429 terms of the waveform misfit reduction within the selected windows for all data from the 192
430 events considered in the inversion. Also shown in Figure 6a are the event-averaged misfit
431 reductions relative to the SPiRaL starting model of the two other models considered (MEC-1
432 and CSEM2.0). These models increased the misfit compared to SPiRaL and MESWA and these
433 results provide clear evidence that the choice of SPiRaL for the starting model was justified.

434

435 A more objective measure of model performance can be found by analyzing the
436 performance of MESWA with the independent validation data that was not used in the
437 inversion. These paths (Figure 4b) are representative of the paths for the inversion data set
438 shown in Figure 4a. The event-averaged relative misfit reductions for our MESWA model
439 relative to the starting model for these events are shown in Figure 6b. The range of these misfit
440 reductions are comparable with those of the inversion data set and the mean values are only
441 slightly smaller (1-2%). This provides powerful evidence that our final model provides
442 waveform fits for the validation data set that are as good as those obtained in the inversion.
443 Good performance on independent validation data gives us confidence that the resulting model
444 is not a result of overfitting the inversion data. Also note that the validation data further
445 support the choice of SPiRaL as our starting model over the MEC-1 and CSEM models
446 considered.

447

448 Another metric of model performance is seen in the time-bandwidth products of
449 selected waveform segments plotted in Figure 3. Our MESWA model consistently shows larger
450 time-bandwidth products than the SPiRaL (starting), MEC-1 or CSEM models, with the values for
451 MESWA about 40% higher than those for SPiRaL. This indicates that the MESWA model
452 produces simulated waveforms that on average agree better than any of the starting models
453 considered as measured by the selected window metrics from all 327 events. Note that the
454 inversions described above were performed with a minimum period of 30 seconds in the sixth
455 and final inversion stage. However, the time-bandwidth products values show that the MESWA
456 model has larger values than the SPiRaL starting model across the bandwidth shown including

457 periods shorter than 30 seconds. This suggests that the adjoint waveform tomography
458 approach adopted here may provide models that can produce good waveform fits for shorter
459 periods than those used in the inversions.

460

461 **Results**

462

463 We now describe the results of the waveform inversions described in the previous
464 section. We start by showing some example waveforms to illustrate the improved fits obtained
465 with the inversions. This is followed by presentation of the imaged shear wavespeed and
466 anisotropy structure. Finally, we investigated the model resolution through model restitution
467 tests.

468

469 *Waveform Fits*

470 Firstly, we show waveforms from a single event and synthetics for the four models
471 discussed: our MESWA model (our final inversion model); the SPiRaL (Simmons et al., 2021)
472 starting model, MEC-1 (Kaviani et al., 2020) and CSEM (Noe et al., 2023). Figure 7a shows a
473 map of an M_w 5.90 inversion event that occurred 2003-08-21 in Southern Iran along with
474 selected stations that recorded the event with good signal-to-noise ratios on three
475 components. The observed and synthetic waveforms for the four models are shown as record
476 sections in Figure 7b-e. Waveforms shown in this section are scaled with distance but each pair
477 of observed and synthetic are shown with true relative amplitudes. The MESWA model (Figure
478 7b) shows the best fits across distances and components compared to the other models: SPiRaL

479 (Figure 7c); MEC-1 (Figure 7d) and CSEM (Figure 7e). Generally, waveform misfits (errors in
480 phase alignment) tend to be small at short distances and increase with distance as phase errors
481 cause misalignment to accumulate along the path and the entire ‘banana-doughnut’ sensitivity
482 kernel of the waveform. The MEC-1 and CSEM models show clear phase errors approaching
483 half a cycle or more for surface waves at the longest distances. Not surprisingly we see poor
484 fits for the MEC-1 Love waves on the transverse component. Recall MEC-1 is based on Rayleigh
485 wave data, is most sensitive to vertically polarized shear wavespeeds, v_{SV} , and does not
486 constrain v_{SH} . MEC-1 also performs poorly for some body waves. The SPiRaL starting model fits
487 the observed waveforms shown in Figure 7c better than the MEC-1 or CSEM models, consistent
488 with the misfit reduction analyses presented in the previous section. However, the MESWA
489 model fits the body waves and dispersed surface waves at long ranges better than SPiRaL, also
490 consistent with the misfit reduction analyses (Figure 6). Note the good fit of first motions and
491 relative amplitudes suggests the GCMT source parameters (i.e., moment tensor, depth, M_w) are
492 reasonably good.

493

494 We show additional examples of waveform fits for the MESWA and SPiRaL models for a
495 few inversion and validation events scattered around the domain with paths sampling the
496 diverse tectonic structures of the region. Figure 8 shows an M_w 6.14 inversion event in Crete,
497 Greece (2011-04-01). The waveforms for the MESWA model (Figure 8b) show good fit to the
498 Rayleigh waves at stations GO.AKH (Georgia), II.RAYN (Saudi Arabia) and II.ABKT
499 (Turkmenistan). In particular the path to II.ABKT is better fit by MESWA (Figure 8b) than SPiRaL

500 (Figure 8c) for a path crossing several tectonic provinces including the thick sediments of the
501 Caspian Sea known to complicate surface wave propagation (e.g. Priestley et al, 2001).

502

503 Figure 9 shows an M_w 5.61 validation event in western Turkey in the Turkey-Iran border
504 region (2011-10-25). The fundamental mode surface waves are well-fit by the MESWA model,
505 particularly at longer distances (Figure 9b). Phases errors for Rayleigh waves for the SPiRaL
506 model (Figure 9c) at stations GE.EIL (Israel), HL.SMG (Greece), RO.BUR31 (Romania), II.UOSS
507 (United Arab Emirates), IU.KBL (Afghanistan) and 5H.CAYE (Eritrea) are corrected for MESWA
508 (Figure 9b). A path crossing the Caspian Sea and Kopet Dagh to Central Asia (IU.KBL,
509 Afghanistan) shows better agreement of the fundamental mode for the MESWA model (Figure
510 9b). Similar results are seen for an M_w 5.70 validation event in the Afghanistan-Tajikistan
511 border region (2012-05-12) shown in Figure 10. The long paths crossing the Caspian Sea:
512 KO.KARS, KO.BAYT, TU.KEMA, KO.RSDY, KO.BKK, IU.ANTO, KO.SHUT (Turkey); and RO.BUR31
513 (Romania) are well fit by the MESWA model as are paths crossing the Afghan Central Highlands
514 and Lut Block (IU.OUSS, United Arab Emirates) and further across Arabia to Eritrea (5H.TIOE).

515

516 Finally, we show two events from the southwestern and southern parts of the domain:
517 an M_w 5.54 Red Sea (2013-07-08) inversion event in Figure 11 and an M_w 5.51 validation event
518 in the Owen Fracture Zone (2012-02-04) in Figure 12. These events provide paths crossing the
519 Arabian Plate at closest distances with some paths extending across the Turkish and Iranian
520 Plateaus and Suleiman Fold Belt. The closest paths sampling Arabia and more distant paths
521 sampling adjacent tectonic regions are better fit by the MESWA model than SPiRaL. The paths

522 from the Red Sea to central Asia (IU.KBL, Kabul Afghanistan; 5C.MAR2, Tajikistan; and KR.BTK,
523 Kyrgyzstan) show Rayleigh waves poorly fit by SPiRaL (Figure 11c) that are fit better by MESWA
524 (Figure 11b). The waveforms from the Owen Fracture Zone validation event are better fit by
525 the MESWA model (Figure 12b) than the SPiRaL model (Figure 12c). The path from this event
526 to crossing the Arabian Platform and Turkish Plateau to IU.ANTO shows significant phase delays
527 for the SPiRaL model (Figure 12c). However, the accumulated phase errors for this long path
528 are adjusted by the iterative waveform inversion performed here and the resulting MESWA
529 model fits the waveforms better (Figure 12b). The waveforms shown above are representative
530 of the fits achieved in the inversion. The fit improvements can be seen qualitatively in these
531 figures and quantitatively from the analysis in the previous section for the aggregate fit
532 improvement for window picking statistics for all events (Figure 3) and the misfit analyses of
533 inversion and validation data sets (Figures 6). While fits are good, there are still dispersed, later
534 arriving and shorter period surface waves that could be fit better and misfits to body-waves
535 that could be improved. This motivates further study with additional data and inversion
536 iterations.

537

538 *Maps and Cross-Sections*

539 We now show the imaged 3D structure as the isotropic shear wavespeed, $v_s =$

540 $\sqrt{\frac{v_{SH}^2 + 2v_{SV}^2}{3}}$, and anisotropy parameter, $\xi_s = \left(\frac{v_{SH}}{v_{SV}}\right)^2$, (Panning and Romanowicz, 2006). Figures

541 13-16 show the v_s and ξ_s structure in map view for the MESWA model and the natural

542 logarithm ratio (MESWA/SPiRaL) at depths of 5, 20, 60 and 150 km below to sea level. The

543 MESWA model is broadly similar to the SPiRaL starting model, but adjustments made to the 3D

544 wavespeed structure during the multiscale waveform inversion process have improved the
545 waveform fits as described in the previous sections. Generally, the updates to the SPiRaL
546 model obtained with the adjoint waveform tomography methodology described above tend to
547 increase the amplitude of lateral variations in v_s and ξ_s structure and reduce the scale-length of
548 variations.

549

550 At 5 km in the upper crust (Figure 13) the main adjustments to SPiRaL (Figure 13b) are a
551 reduction by more than 5% of v_s in the sedimentary structures of the eastern Mediterranean
552 Sea, Caspian Sea, Arabian Platform, the (Arabian/Persian) Gulf and the continental margins.
553 Shear wavespeeds for MESWA are increased relative to SPiRaL at this depth for the Turkish
554 Plateau, Central Iran Block and Central Afghan Highlands. MESWA also reveals a general
555 reduction of ξ_s across the domain (Figure 13d). At this depth, $\xi_s < 1$ ($v_{sv} > v_{sh}$) for most of the
556 continental regions.

557

558 Figure 14 shows the v_s and ξ_s structure at 20 km below sea level. At this depth shear
559 wavespeeds for the MESWA model tracks the major geologic provinces (Figure 14a). The
560 oceanic regions (Arabian Sea, Gulf of Aden, Red Sea) have much higher v_s values corresponding
561 to lower crust or mantle material, while the continental regions show lower v_s values with
562 significant variability (standard deviation of about 7%). The MESWA model at this crustal depth
563 shows a band of low v_s values tracing a long arc across the Tethyan Belt (Turkish Plateau, Zagros
564 and Alborz Mountains and the Sulaiman Fold Belt). Adjustments to SPiRaL's v_s structure also
565 show reductions of 5% or more in regions of sedimentary basins (eastern Mediterranean Sea,

566 Caspian Sea and Arabian Platform, Gulf) similar to 5 km depths and suggesting the long-period
567 (30 seconds) waveforms considered here are weakly sensitive to shallow crustal structure. At
568 this depth the waveform inversion process requires the scale-length of wavespeed adjustments
569 to v_s and ξ_s (Figure 14c and 14d) to have shorter wavelength variability than for SPiRaL.
570 Similar to the upper crust, MESWA shows a reduction of the shear wave anisotropy parameter,
571 but with $\xi_s < 1$ ($v_{SV} > v_{SH}$) for most of the continental regions.

572

573 At 60 km depth the MESWA model reveals low v_s values surrounding much of the
574 Arabian Plate along the active spreading centers of the Red Sea, Gulf of Aden and Owen
575 Fracture Zone, the Ethiopia/Afar Hotspot as well as the continental transform of the Dead Sea
576 Fault (Figure 15a). These areas of low v_s were intensified from the SPiRaL model as seen in the
577 natural logarithm ratio map (Figure 15c). Low v_s values in the mantle lithosphere under the
578 Arabian Shield and Afar as have been reported in several studies (e.g. Rodgers et al., 1999; Park
579 et al., 2007; 2008; Hansen and Nyblade, 2013; Irandoust et al., 2022; Civiero et al., 2022; Kim et
580 al., 2023;). These low v_s values at mantle depths follow the Mecca-Madina-Nafud (MMN)
581 volcanic line. Higher v_s values were intensified at this depth in the Zagros Mountains, Central
582 Iran Block and north of the Makran subduction zone (Figure 15c). Shear wave anisotropy at this
583 depth broadly indicates that $\xi_s > 1$ ($v_{SH} > v_{SV}$). Lateral variations in radial anisotropy were
584 modified in MESWA relative to SPiRaL, including lowering ξ_s beneath Iran north of the Main
585 Zagros Thrust.

586

587 Finally, we show the model at 150 km depth (Figure 16). MESWA reveals lower v_s along
588 the Gulf of Aden, Red Sea and Dead Sea Transform into eastern Turkey. The connected low
589 shear wavespeeds in the upper mantle have been interpreted as lateral flow from the Afar
590 Hotspot northward along the Red Sea and MMN Line (Park et al., 2008; Civiero et al., 2022) and
591 is supported by upper mantle anisotropy from shearwave splitting and lithospheric thickness
592 (Hansen et al., 2006, 2007; Park et al. 2008). The high v_s underlying the eastern Arabian
593 Platform and Zagros Mountains at 150 km depth is consistent with strong continental
594 lithosphere participating in active continental collision (e.g. Maggi and Priestley, 2005;
595 Movaghari and Doloei, 2019). Higher than average v_s follows Makran subduction at mantle
596 depths but suggests a steeper dip than the slab model of Hayes (2018) (Figures 16a). Across the
597 domain anisotropy indicates that $\xi_s > 1$ ($v_{SH} > v_{SV}$) at this depth consistent with Chang et al.
598 (2010b).

599

600 We now visualize the MESWA model with cross-sections of the isotropic shear
601 wavespeed, v_s , and anisotropy parameter ξ_s . Figure 17 shows the locations of four cross-
602 sections sampling the diverse tectonic provinces of the MESWA model domain. Figure 17 also
603 includes contours of the CRUST1.0 (Laske et al., 2013) crustal thickness model used in the
604 SPiRaL starting model (Simmons et al., 2021) and honored by our spectral element meshes.
605 Crustal thickness is also shown with the cross-sections that follow. For each profile we show
606 the topography with major features labeled, the absolute isotropic shear wavespeed in the
607 upper part of the model (surface to 100 km depth), the relative shear wavespeed, $d\ln(v_s)$, from
608 the domain-wide MESWA depth-averaged model (as percent) followed by the absolute

609 anisotropy parameter, ξ_s . The last two fields are shown from the surface to 400 km depth. The
610 absolute shear wavespeed images in the crust show the model with its full range of values,
611 while the $\ln(v_s)$ images help identify more subtle variations across the upper 400 km
612 associated with tectonic provinces or features.

613

614 The first cross-section A-A' covers the Nubian Shield to the Hindu Kush (Figure 18). This
615 profile transects the low mantle v_s under the Red Sea spreading, the transition to higher v_s
616 under the Arabian Platform, even higher mantle v_s under the Zagros Thrust, lower v_s under the
617 Lut Block and Afghan Central Highlands to very high v_s values under the Hindu Kush. These v_s
618 variations imply a thin mantle lid under the Arabian Shield, Lut Block (Iranian Plateau) and
619 Afghanistan, while the mantle lid is thicker under the Arabian Platform and Zagros Mountains.
620 Note that the anisotropy variations correlate with tectonic provinces. Specifically, ξ_s is greater
621 than 1.0 ($v_{SH} > v_{SV}$) in the Arabian Shield crust. In the mantle ξ_s is greater than 1.0 ($v_{SH} > v_{SV}$) in
622 the Arabian Platform and less than 1.0 ($v_{SV} > v_{SH}$) under the Red Sea and at the boundary
623 between the Arabian Shield and Platform. ξ_s is strongly greater than 1.0 ($v_{SH} > v_{SV}$) in the thick
624 mantle lithosphere of the Arabian Platform and under the Zagros Mountains.

625

626 Profile B-B' covers a roughly south-to-north transect from the Afar Hotspot to the
627 Eurasian Plate (Figure 17). This profile (Figure 19) shows the very low v_s associated with the
628 Afar Hotspot, southern Red Sea and southern Arabian Shield. Here too anisotropy shows $v_{SV} >$
629 v_{SH} under the Red Sea and at the boundary between the Arabian Shield and Platform, while v_{SH}
630 $> v_{SV}$ under the Arabian Shield. The central part of this profile spans the northern Arabian

631 Platform and Meopotamian Foredeep which indicates high v_s , $\xi_s > 1$ and implies a thick mantle
632 lithosphere. The Bitlis zone marks the boundary between the northernmost Arabian Platform
633 and the Turkish-Iranian Plateau. This boundary is clearly indicated by a transition from higher
634 to lower crustal and mantle v_s in the Turkish-Iranian Plateau. North of the Bitlis there is
635 Cenozoic volcanism which MESWA images as very low v_s values in the crust and uppermost
636 mantle. The northern extent of the Caucasus marks a transition from low mantle v_s to more
637 average values in the Eurasian Plate at the northern end of the profile (B').

638

639 Profile C-C' extends northwest-to-southeast from the Black Sea in the Eurasian Plate to
640 the Arabian Sea (Figure 17). This transect (Figure 20) shows high v_s in the lower crust of the
641 eastern part of the Black Sea, then lower v_s in the crust and underlying shallow mantle beneath
642 Cenozoic volcanic centers near the border of Turkey and Iran. The transect parallels the Zagros
643 Mountain Belt in Iran which is characterized by low v_s and $\xi_s < 1$ ($v_{sv} > v_{sh}$) in the crust. The
644 mantle beneath the southern Zagros has high v_s and mostly $\xi_s > 1.0$ ($v_{sh} > v_{sv}$) consistent with
645 underthrusting of thick Arabian Platform lithosphere near the Gulf. The Oman Line of southern
646 Iran and marks the transition between Zagros continental collision and the Makran subduction
647 zone (Kadinsky-Cade and Barazangi, 1982). The Makran subducting slab intersects the Oman
648 Line in the crust of the coastal plain (Hayes, 2018). In the mantle beneath the Makran region of
649 southern Iran MESWA images evidence of a high v_s in the mantle but, we cannot distinguish if
650 this is underthrust Arabian mantle lithosphere or Arabia Sea oceanic slab. The mantle v_s
651 reduces by about 6% from the Oman Line to the Arabian Sea.

652

653 Profile D-D' extends roughly south-to-north from the Arabian Sea across eastern Iran to
654 the stable Eurasian continental interior (Figure 17). Within the Arabian Sea the crust is about
655 11 km thick with relatively high wavespeeds (Figure 21). At the Oman Fracture Zone MESWA
656 images low crustal and mantle v_s and $\xi_s < 1$ ($v_{sv} > v_{sh}$) in the mantle. Proceeding onshore in the
657 Makran region of southern Iran the crust thickens and v_s is reduced. Mantle wavespeeds are
658 high slightly north of the highest topography (the Makran Range). This high v_s feature, likely
659 the subducting Arabian Sea Plate slab entering the mantle, has near vertical dip from the Moho
660 to ~300 km depth and is steeper than the inferred slab model of Hayes (2018). The Lut Block in
661 eastern Iran is underlain by low v_s , to depths of 100-300 km in the upper mantle. The Kopet
662 Dagh marks a transition in the crust and shallow mantle, where v_s increases and the mantle lid
663 thickens. Strong anisotropy with $\xi_s > 1.0$ is imaged beneath the northeastern Iran and the
664 Turan Platform.

665

666 *Restitution Tests*

667 Formal covariance analysis is difficult in full waveform inversion due to the large number
668 of model parameters (in our case seismic wavespeeds at every spectral element mesh point)
669 and the computational expense of forward and adjoint simulations, the storing of checkpoints
670 and the requirement to run many iterations (e.g. Liu and Gu, 2012). For other more
671 conventional and less computationally intensive tomographic methods such as travel time,
672 surface wave dispersion or partitioned waveform tomography the resolution is often evaluated
673 with synthetic tests such as checkerboard tests where synthetic data are easily generated by
674 forward calculation with an alternating pattern of low and high anomalies and inverted for

675 structure. Recovery of the checkboard pattern indicates successful resolution of that structure.
676 This is much more difficult for adjoint waveform tomography because of the computational
677 expense of forward and adjoint simulations for many iterations. A proxy for resolution used in
678 many adjoint waveform tomography studies involves the so-called Hessian-vector product
679 (HVP's) or point spread functions (PSF's) where the Hessian (second derivative of misfit with
680 respect to model parameters) is computed for perturbations of the final model to infer
681 curvature of the objective function and trade-offs in spatial resolution (e.g. smearing) and
682 between parameters (Fichtner and Trampert, 2011; Liu and Gu, 2012). HVP's and PSF's have
683 been used in many previous adjoint waveform tomography studies (e.g. Zhu et al., 2015;
684 Bozdağ et al., 2016; Gao et al., 2021; Wehner et al., 2022; Rodgers et al., 2022).

685
686 In this study we followed a new approach to assess resolution introduced by van
687 Harwaarden et al. (2023) and used recently by Doody et al. (2023b) called model restitution
688 tests. This method imposes known perturbations, δm , to the final model, m_f (our MESWA
689 model). We then ran adjoint inversion iterations to attempt to recover the final model from
690 the perturbed model ($m_f + \delta m$). The agreement/discrepancies between the recovered and final
691 models provide qualitative assessment of good/poor spatial resolution. With ideal data
692 coverage, the recovered model should be identical to the final model. However, where
693 sensitivity kernel coverage is poor and cannot triangulate wavespeed anomalies, the recovered
694 model is dissimilar to the final model and resolution is inferred to be poor. Unlike the point-
695 spread functions or Hessian-vector products mentioned above, restitution analysis relies on
696 non-linear iterative inversions of the perturbed model ($m_f + \delta m$) and the same data used in the

697 model inversions. It is therefore computationally intensive but has several advantages (van
698 Herwaarden et al., 2023). Firstly, the final model is integral to the test. It evaluates the
699 resolution of the final model using the same data with its path coverage and noise, rather than
700 unrelated synthetic data. Also, restitution analysis involves the non-linear nature of the full
701 waveform inversion problem. On the downside, restitution analysis can require many
702 iterations to converge making it computationally expensive.

703

704 In our case we performed restitution test for two spatial scale-lengths: 300 and 600 km.
705 The final wavespeed model was perturbed with a regular pattern of alternating positive and
706 negative wavespeed anomalies. In this case we used spherical Gaussian distributions peaked
707 $\pm 4\%$, with standard deviations (radii) of 150 and 300 km, offset laterally by this twice distance
708 and centered at this depth. We then ran iterative inversions with this perturbed final model
709 using the same data as in the model inversions. The model converged to the same misfit value
710 as the final inversion iteration of MESWA after 18 iterations. These iterations made
711 adjustments to the perturbed model. Model resolution can be inferred by the extent to which
712 the restitution iterations removed the imposed perturbations, δm . We measure this by taking
713 the ratio of the perturbed model (final model plus perturbations) and the recovered model
714 (after iterative inversion).

715

716 Figure 22 shows the results after model restitution iterations to determine what regions
717 of the domain can be recovered. Here we show the 300 km scale-length at 20 and 60 km
718 depths (Figure 22ab, respectively) and the 600 km scale-length at 60 and 150 km depths (Figure

719 22cd, respectively). Each panel shows both the final model (MESWA), the final model with
720 perturbations added, the recovered model, followed by the perturbations and the restitution.
721 The last two columns show the natural logarithm of the perturbed to the final model to
722 highlight the perturbations and the natural logarithm of the perturbed to the recovered model
723 to show where the alternating pattern of features can be resolved. The full set of restitution
724 plots for these both scale-lengths and five depths are included in the Electronic Supplement.
725 Results indicate that the model resolves v_s features of these scale-lengths at depths of 5, 20, 60
726 and 100 km for the large central region of our domain including the Turkish-Iranian Plateau, the
727 northern and central Arabian Plate and Afghanistan. Parts of the eastern Mediterranean,
728 Caspian Sea, Oman (southeastern Arabian Plate) and Pakistan are marginally resolved. Some
729 regions are not resolved at all such as the Egypt and Sudan in the African Plate, the Arabian Sea
730 away from the continents and the northernmost area in the Eurasian Plate. Restitution at 150
731 and 200 km depth is poor for the 300 km scale-length and marginal at 600 km, likely due to the
732 dominant contributions of surface waves to the model. Note how the well-resolved areas
733 correspond to those well-covered by the selected inversion event-receiver paths shown in
734 Figure 4. Also, note that the areas covered by long paths without many crossing paths (e.g.
735 Arabia) are correlated with smearing of anomalies and amplitudes are not fully recovered, but
736 this might improve with additional data and further iterations. If new data become available
737 and path coverage improves this analysis could be repeated to measure improvement in
738 resolution.

739

740 **Discussion and Conclusions**

741 In this study we sought to infer a three-dimensional model of radially anisotropic
742 seismic wavespeeds for the greater Middle East and Southwest Asia region suitable for
743 waveform simulations and using only openly available data. Adjoint waveform tomography was
744 the chosen method to achieve this goal. The inversions reduced the minimum period from 50
745 to 30 seconds and resulted in a model (MESWA) that improves waveform fits relative to the
746 SPiRaL (Simmons et al., 2021) starting model and two other models (MEC-1 of Kaviani et al.,
747 2020; and CSEM of Noe et al. 2022). Improvement in waveform fit by our MESWA model was
748 demonstrated by the larger time-bandwidth product of selected windows (Figure 3) and largest
749 misfit reductions (Figure 6). The misfit reductions obtained from inversion and independent
750 validation data sets are comparable (Figure 6). Example waveform fits demonstrate that
751 MESWA fits the observed waveforms better for a single event compared to three models
752 (Figure 7) and other events comparing just MESWA to SPiRaL (Figures 8-12). The updates to the
753 SPiRaL model tended to increase the strength of anomalies (often by 5-10%) while decreasing
754 their scale-length (Figures 13-16). Restitution analysis suggests that the central part of the
755 model is well-resolved to a depth of about 150 km (Figures 22, S2, S3). It also indicates regions
756 with poor path coverage (Figure 4) are poorly resolved, specifically the Nubian Shield (Egypt,
757 Sudan), parts of southern Arabia, the southern margin (Arabian Sea away from the continents)
758 and the northern margin (Eurasian Plate and Turan Platform). While the spatial resolution can
759 clearly be improved, MESWA provides a new radial anisotropic 3D seismic model for this
760 tectonically complex region including all the necessary parameters for regional waveform
761 simulation. The model is available for use by other researchers at the Incorporated Research

762 Institutions for Seismology Earth Model Collaboratory (IRIS-EMC,
763 <http://ds.iris.edu/ds/products/emc/>, last accessed Jan. 5, 2024).

764

765 Our MESWA model reproduces many of the shear wavespeed features that have been
766 reported by previous tomographic studies of the region. The following features can be seen in
767 Figures 2, 13-16. We find low crustal wavespeeds in the Turkish-Iranian Plateau consistent with
768 continental convergence as reported numerous studies (e.g. Maggi and Priestley, 2005;
769 Fichtner et al., 2013; Movaghari and Doloei, 2019; Kaviani et al., 2020; Irandoust et al., 2022).
770 The mantle of Turkish-Iranian Plateau generally has low wavespeeds except where the Arabian
771 Platform is underthrusting the Zagros Mountains (Hearn and Ni, 1994; Mokhtar et al., 2001;
772 Villasenor et al., 2001; Al-Lazki et al., 2004, 2005; Maggi and Priestley, 2005; Manaman et al.,
773 2011; Priestley et al., 2012; Movaghari and Doloei, 2019; Kaviani et al., 2020; Irandoust et al.,
774 2022; Civiero et al., 2022; Kim et al., 2023). MESWA images low v_s in the shallowest mantle
775 under the Cenozoic volcanics near the border of Turkey and Iran (Figures 15, 19 and 20).

776

777 MESWA infers the structure of the Arabian Peninsula to be broadly consistent with
778 previous studies imaging western Arabian Shield with fast crustal and slow mantle wavespeeds
779 and the eastern Arabian Platform with slow crustal and fast mantle wavespeeds (Rodgers et al.,
780 1999; Al-Damegh et al., 2005; Hansen et al., 2006; Tang et al., 2019; Kaviani et al., 2020; Lim et
781 al., 2020; Civiero et al., 2022; Kim et al., 2023). Our model images a continuous low shear
782 wavespeed feature in the upper mantle from the Afar Hot Spot extending northward along the
783 Red Sea and Arabian Shield (60 and 150 km depths in Figures 15, 16, respectively) consistent

784 with several studies (Park et al., 2008; Chang et al., 2010ab; Civiero et al., 2022; and Kim et al.,
785 2023). We infer lower v_s in the southern Red Sea compared to the northern Red Sea. The
786 mantle lithosphere within the Arabian Shield thickens away from the Red Sea (Figures 18, 19)
787 consistent with lithosphere-asthenosphere boundary estimates of Hansen et al. (2008), Park et
788 al. (2008) and Tang et al. (2019). The low shear wavespeeds in the shallow mantle beneath the
789 western margin of the Arabian Plate are consistent with interpretations of northward flow,
790 partial melt and the source of Cenozoic volcanism in the Arabian Shield (e.g. the Mecca-
791 Medina-Nafud Line) as reported by Park et al. (2008), Tang et al. (2019), Lim et al. (2020) and
792 Civiero et al. (2022). For comparison, in Figure 23 we show maps of the vertically polarized
793 shear wavespeeds at 60 and 150 km depths for the SPiRal (Simmons et al., 2020) and MESWA
794 (this study) models, along with two models available in the Incorporated Research Institutions
795 for Seismology Earth Model Collaboratory (<http://ds.iris.edu/ds/products/emc-earthmodels/>,
796 last accessed 12 Jan. 2024): EAV09 (Chang et al., 2010a) and AF2019 (Civiero et al., 2020).
797 These maps show agreement of the broad features mentioned above with differences arising
798 from the different data sets, methodologies and smoothing applied.

799

800 MESWA infers elevated v_s in the mantle in the southeast of Iran (Figures 15a, 16a, 23be)
801 not seen in other models in Figure 23 suggestive of the Makran subducting slab but with a
802 steeper dip than the slab model of Hayes (2018). This feature has been imaged by the shear
803 wavespeed waveform tomography of Manaman et al. (2011). Irandoust et al. (2022) reported
804 similarly steeply dipping higher v_s under the Jazmurian Depression in the shallow mantle (< 100
805 km depth). Recent high-resolution crustal-scale imaging by Priestley et al. (2022) found high v_s

806 closer to the coastline and different Moho depths than used herein. Thick sediments and wide
807 accretionary wedge possibly further complicate imaging structure in this region (Haberland et
808 al., 2020). Studies based on long-period waveforms or surface waves do not show a distinct
809 high v_s feature in this region (Maggi and Priestley, 2005; Priestley et al., 2012). The results
810 reported here alluring, but more persuasive imaging of the Makran subducting slab deserves
811 further investigation.

812

813 Radial anisotropy inferred in our model can be compared to two studies of smaller
814 regions based on national seismic network data from Saudi Arabia and Iran. Kim et al. (2023)
815 inferred a radially anisotropic shear wavespeed model for the Arabian Plate based on surface
816 wave dispersion. In the middle crust (20 km depth, Figure 14) our model agrees with Kim et al.
817 (2023) and we both infer $\xi_S > 1$ ($v_{SH} > v_{SV}$) for the Arabian Shield and $\xi_S < 1$ ($v_{SV} > v_{SH}$) for the
818 Arabian Platform and Zagros (Figures 14 and 18). In the shallow mantle both models infer weak
819 anisotropy $\xi_S \sim 1$ ($v_{SV} > v_{SH}$) for the Arabian shield and stronger positive anisotropy $\xi_S > 1$ ($v_{SH} >$
820 v_{SV}) for the Arabian Platform (Figure 15). It is encouraging that these models show this level of
821 agreement, especially because they were derived from different methods and data sets. Note
822 that Kim et al. (2023) used a large data set from the Saudi Geologic Survey that was openly not
823 available.

824

825 Movaghari et al. (2021) inferred a radially anisotropic shear wavespeed model for Iran
826 based on ambient noise tomography. Our model infers $\xi_S < 1$ ($v_{SV} > v_{SH}$) for most of the crust
827 throughout Iran (Figures 13, 14, 18, 21), while Movaghari et al. (2021) generally infer $\xi_S < 1$ in

828 the upper crust and $\xi_S > 1$ in the middle and lower crust. For the mantle MESWA images $\xi_S > 1$
829 in Iran (Figures 15 & 18), while Movaghari et al. (2021) infer $\xi_S > 1$ beneath central Iran but $\xi_S <$
830 1 beneath the Zagros and Kopet Dagh. While these model show some agreement between
831 anisotropy structures, disagreement likely arises from the different data and methods as well as
832 the period bands and paths lengths analyzed. Movaghari et al. (2023) considered shorter
833 periods (8-60 seconds) and paths contained within Iran, while MESWA considered longer
834 periods (30-100 seconds) and longer paths from openly available stations in the region (Figure
835 4).

836

837 The reliance on openly available broadband waveform data places this study at a
838 disadvantage compared to other models based on data with denser coverage, but that is not
839 openly available. Consequently, the path coverage for our model is highly uneven with large
840 regions with little or no broadband recordings of the moderately large earthquakes considered.
841 Specifically, the large territories of Iran, Saudi Arabia and other Gulf countries have few openly
842 available data, although broadband seismic networks exist in these countries. This data set is
843 well-suited for the station weighting scheme used in previous inversions (e.g. Ruan et al., 2019;
844 Wehner et al. 2020; Rodgers et al., 2022; van Herwaarden et al., 2023; Doody et al. 2023ab). In
845 this scheme, misfits from areas of dense station sampling are downweighted and areas of
846 sparse sampling are upweighted. These weights directly impact the contributions to the
847 gradients so that we do not fit data in densely sampled region at the expense of sparsely
848 sampled regions. Gradient treatments such as smoothing, cut-outs and the “region-of-interest”
849 may also mitigate undesired effects of uneven path coverage. One effect we cannot address

850 with these inversions and the uneven path coverage is azimuthal anisotropy. By inverting for a
851 radial anisotropic we are essentially averaging over all azimuths, but our path coverage is far
852 from ideal to infer subtle azimuthal wavespeed variations. This will have to await methodology
853 improvements and more dense and diverse path coverage. Further iterations with more data
854 will be needed to reduce the minimum period well below 30 seconds and resolve upper crustal
855 structure. Finally, the computational expense of adjoint waveform tomography requires
856 parallel computing resources, but comes with the benefit of improved waveform fits.

857

858 The MESWA model presented in this study demonstrates improvements in waveform
859 fits for minimum periods of 30 seconds. The time-bandwidth product measured from picked
860 windows shows that MESWA produces longer time-segments of good waveform correlations
861 for periods below 30 seconds compared to the other models considered (Figure 3). It remains
862 for further work to continue inversion iterations with the current openly available data to
863 investigate if further details can be reliably imaged. One possibility is to consider smaller
864 events, say with M_w 5.0-5.5, that may improve path coverage. Alternatively, adding waveform
865 data from the many seismic networks from the region that do not make their data available
866 could greatly improve the resolution of smaller scale-length features, reduce the minimum
867 period, improve waveform fits and increase the time-bandwidth product of selected waveform
868 segments. Many tomography and structural studies of the region mentioned above have
869 shown the value of closed network data for imaging details of seismic wavespeed variations.
870 We expect similar benefits would be found adding closed network data to the adjoint
871 waveform tomography analysis of open data described here.

872

873 Finally, the MESWA model described in this study achieves the goal of improved
874 regional long-period waveform simulations. An important practical application of the model
875 could be for source characterization using moment tensor inversion. Greens functions for 3D
876 models have been shown to provide better waveform fits and reduce uncertainties in source
877 type estimate inversion (Liu et al., 2004; Covellone and Savage, 2012; Zhu and Zhou, 2016;
878 Sawade et al., 2022; Chiang et al., 2023; Doody et al., 2024). For example, the MESWA model
879 could be used to routinely estimate moment tensors in the region, to model sub-crustal events
880 in the Zagros Mountains and Makran subduction zone (e.g., Engdahl et al., 2006) or the 1998
881 nuclear explosions in India and Pakistan (Barker et al., 1998). The value of the MESWA model
882 will have to be tested compared to other regional 3D or path-specific 1D models.

883

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896

897 **Data and Resources**

898 All openly available earthquake and network/seismic data used in this study are listed in
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900 with Salvus (Afanaisev et al., 2019). The SPiRaL (Simmons et al., 2021) and Midd_East_Crust_1
901 (Kaviani et al., 2020) models are available at the Incorporated Research Institutions for
902 Seismology Earth Model Collaboratory (IRIS-EMC, [https://ds.iris.edu/ds/products/emc-
903 spiral_14/](https://ds.iris.edu/ds/products/emc-spiral_14/) and http://ds.iris.edu/ds/products/emc-midd_east_crust_1/, respectively). The
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906 currently a provisional website: <https://ds.iris.edu/ds/products/emc-meswa/>. The
907 Supplemental Material contains maps of (v_{SV} , v_{SH} , v_{PV} , v_{PH} and ρ) and a more complete set of
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909

910 **Declaration of Competing Interests**

911 The authors acknowledge there are no conflicts of interest recorded.

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1296 **Figures Captions**

1297
1298 **Figure 1. (a)** Map of the Middle East and Southwest Asia (MESWA) study area showing major
1299 geologic provinces (labels), tectonic plate boundaries (red lines) and volcanic centers (yellow
1300 diamonds). Abbreviations for tectonic features are: ACP, Afghanistan Central Highlands; Alb,
1301 Alborz Mountains; ArPI, Arabian Platform; AS, Arabian Shield; B Sea, Black Sea; C, Caucasus; CIB,
1302 Central Iranian Block; C Sea, Caspian Sea; DSF, Dead Sea Fault; G, Persian/Arabian Gulf; GoO,
1303 Gulf of Oman; HK, Hindu Kush; KD, Kopet Dag; LB, Lut Block; Med. Sea, Mediterranean Sea; MF,
1304 Mesopotamian Foredeep; NAF, North Anatolian Fault; OFZ, Owen Fracture Zone; SFB, Sulaiman
1305 Fold Belt; TP, Turkish Plateau; TuP, Turan Platform; Z, Zagros Mountains. Makran subduction
1306 slab depths (10, 25, 50 & 100 km) from Hayes (2018) are shown as dashed black lines. The inset
1307 global map shows the spectral element mesh domain (blue) with the target domain (black). **(b)**
1308 Map of earthquake moment tensors for inversion events (red) and validation events (blue).
1309 Maps of the open access seismic stations used in this study for: **(c)** permanent; and **(d)**
1310 temporary networks.

1311
1312 **Figure 2.** Maps of vertically polarized shear wavespeeds at depths of 20 and 100 km for the
1313 three starting models considered: SPiRaL (Simmons et al., 2021); MEC-1 (Kaviani et al. 2020);
1314 CSEM (Noe et al., 2023). Also shown is the resulting MESWA model for this study.

1315
1316 **Figure 3.** Time-bandwidth product versus minimum period for windows selected by comparing
1317 observed and simulated waveforms for over 320 events. The models are discussed in the text:
1318 SPiRaL (Simmons et al., 2021); MEC-1 (Kaviani et al. 2020); CSEM (Noe et al., 2023) and MESWA
1319 (this study).

1320
1321 **Figure 4.** Map of events (circles), stations (triangles) and paths (dotted lines) for the **(a)**
1322 inversion and **(b)** validation data sets for the SPiRaL starting model in the period band 50-100
1323 seconds.

1324
1325 **Figure 5.** Misfit evolution as a function of iteration number for the relative misfit reduction
1326 within each inversion stage (symbols), with period bands indicated.

1327
1328 **Figure 6.** Event-averaged time-frequency phase (TF) and normalized L2 (NL2) misfit reductions
1329 for our final MESWA model (green triangles) relative to the SPiRaL starting model for the **(a)**
1330 inversion data set and **(b)** validation data set. Also shown are the misfit reductions for the
1331 MEC-1 (cyan squares) and CSEM (red plus signs) models. Events are sorted by misfit reduction
1332 highest-to-lowest for the MESWA model and the mean TF and NL2 reductions for MESWA are
1333 recorded in the upper left of each panel.

1334
1335 **Figure 7.** Examples of waveform fits for an M_w 5.90 earthquake in Southern Iran (date: 2003-
1336 08-21). **(a)** Map of the event (moment tensor), stations (blue triangles) and paths for which
1337 waveforms are shown. Three-component (vertical, radial and transverse) observed (black) and
1338 synthetic (colored) waveforms filtered 30-100 seconds for four models: **(b)** MESWA (green); **(c)**
1339 SPiRaL (blue); **(d)** MEC-1 (teal) and **(e)** CSEM (red).

1340

1341 **Figure 8.** Examples of waveform fits for an M_w 6.14 inversion event in Crete, Greece (date:
1342 2011-04-01). **(a)** Map of the event (moment tensor) and stations (blue triangles) for which
1343 waveforms are shown. Three-component (vertical, radial and transverse) observed (black) and
1344 synthetic (colored) waveforms filtered 30-100 seconds for two models: **(b)** MESWA (green) and
1345 **(c)** SPiRaL (blue).

1346

1347 **Figure 9.** Examples of waveform fits for an M_w 5.61 Turkey validation event on the Turkey-Iran
1348 border region (date: 2011-10-25). **(a)** Map of the event (moment tensor) and stations (blue
1349 triangles) for which waveforms are shown. Three-component (vertical, radial and transverse)
1350 observed (black) and synthetic (colored) waveforms filtered 30-100 seconds for two models: **(b)**
1351 MESWA (green) and **(c)** SPiRaL (blue).

1352

1353 **Figure 10.** Examples of waveform fits for an M_w 5.70 validation event in the Afghanistan-
1354 Tajikistan border region (date: 2012-05-12). **(a)** Map of the event (moment tensor) and stations
1355 (blue triangles) for which waveforms are shown. Three-component (vertical, radial and
1356 transverse) observed (black) and synthetic (colored) waveforms filtered 30-100 seconds for two
1357 models: **(b)** MESWA (green) and **(c)** SPiRaL (blue).

1358

1359 **Figure 11.** Examples of waveform fits for an M_w 5.54 Red Sea inversion event (date: 2013-07-
1360 08). **(a)** Map of the event (moment tensor) and stations (blue triangles) for which waveforms
1361 are shown. Three-component (vertical, radial and transverse) observed (black) and synthetic
1362 (colored) waveforms filtered 30-100 seconds for two models: **(b)** MESWA (green) and **(c)** SPiRaL
1363 (blue).

1364

1365 **Figure 12.** Examples of waveform fits for an M_w 5.51 Owen Fracture Zone validation event
1366 (date: 2012-02-04). **(a)** Map of the event (moment tensor) and stations (blue triangles) for
1367 which waveforms are shown. Three-component (vertical, radial and transverse) observed
1368 (black) and synthetic (colored) waveforms filtered 30-100 seconds for two models: **(b)** MESWA
1369 (green) and **(c)** SPiRaL (blue).

1370

1371 **Figure 13.** Maps of the MESWA model at a depth of 5 km below sea level showing: **(a)** isotropic
1372 shear wavespeed, v_s ; and **(b)** anisotropy parameter, ξ_s . The natural logarithm ratio
1373 (MESWA/SPiRaL) of **(c)** v_s and **(d)** ξ_s indicate changes made to the starting model.

1374

1375 **Figure 14.** Maps of the MESWA model at a depth of 20 km, similar to Figure 12.

1376

1377 **Figure 15.** Maps of the MESWA model at a depth of 60 km, similar to Figure 12.

1378

1379 **Figure 16.** Maps of the MESWA model at a depth of 150 km, similar to Figure 12.

1380

1381 **Figure 17.** Map showing the locations of four labeled cross-sections. Symbols are the same as
1382 in Figure 1a. Also shown are contours of the crustal thickness from the CRUST1.0 (Laske et al.,
1383 2013) honored by the spectral element mesh.

1384

1385 **Figure 18.** Cross-section A-A' (location indicated in Figure 17) showing: **(a)**
1386 topography/bathymetry along the line; **(b)** absolute shear wavespeed in the upper 100 km
1387 including the crust and uppermost mantle; **(c)** relative shear wavespeed, $d\ln(v_s)$, in percent; and
1388 **(d)** anisotropy parameter, ξ_s , from the surface to 400 km. Also shown are the crustal thickness
1389 from CRUST1.0 (heavy black dashed lines). Locations along the profile are indicated in **(a)**: Red
1390 Sea, Arabian Shield (ArSh), Arabian Platform (ArPl), Arabian/Persian Gulf, Zagros Mountains (Z),
1391 Lut Block, Afghan Central Highlands (ACH) and Hindu Kush (HK).

1392

1393 **Figure 19.** Cross-section B-B' (location indicated in Figure 17) same as Figure 18. Locations along
1394 the profile are indicated in **(a)**: Afar Hotspot, Arabian Shield (ArSh), Arabian Platform (ArPl),
1395 Mesopotamian Foredeep (MF), Cenozoic volcanic centers (volc.) in the Turkish-Iranian Plateau,
1396 Caucasus Mountains (Cauc.) and Eurasian Plate.

1397

1398 **Figure 20.** Cross-section C-C' (location indicated in Figure 17) same as Figure 18. Locations along
1399 the profile are indicated in **(a)**: Black Sea, Cenozoic volcanic centers (volc.) in the Turkish-Iranian
1400 Plateau, Zagros Mountain Belt, Oman Line (OL), Makran subduction zone (M), Arabian Sea
1401 (ArSea). Makran subducting slab location from Hayes (2018) is indicated by the green dashed
1402 line.

1403

1404 **Figure 21.** Cross-section D-D' (location indicated in Figure 17) same as Figure 18. Locations
1405 along the profile are indicated in **(a)**: Arabian Sea (ARSea), Oman Fracture Zone (OFZ), Makran
1406 subduction zone (M), Lut Block (LB), Kopet Dagh (KD) and Turan Platform (TuPl). Makran
1407 subducting slab location from Hayes (2018) is indicated by the green dashed line.

1408

1409 **Figure 22.** Model restitution test maps of v_s after 18 iterations for two spatial scale-lengths: **(a)**
1410 300 km at 20 km depth; **(b)** 300 km at 60 km depth; **(c)** 600 km at 60 km depth; and **(d)** 600 km
1411 at 150 km depth. Each row shows from left to right: the final MESWA model; the perturbed
1412 model; the recovered model following restitution iterations; and the perturbations and
1413 restitution as natural logarithm ratios, (perturbed/MESWA) and (perturbed/recovered),
1414 respectively. Wavespeed models use the colorbar on far left and ratio maps use the colorbar
1415 on the far right.

1416

1417 **Figure 23.** Maps of vertically polarized shear wavespeeds at depths of 60 and 150 km for SPiRaL
1418 (Simmons et al., 2021), our MESWA model and two other published models: EAV09 (Chang et
1419 al., 2010a) and AF2019 (Civiero et al., 2022).