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A local earthquake tomography on the EAFZ shows dipping fault structure

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Abstract: The East Anatolian Fault Zone (EAFZ) is a left-lateral transform fault zone located between the Anatolian and Arabian plates. In this study, in order to image the upper crustal structure beneath the eastern segments of EAFZ, 3D seismic velocity variations are computed using local earthquake tomography. The initial catalog for the tomography process consists of 2200 well-located earthquakes recorded at 49 seismic stations around the study region between 2007 and 2020. 1D initial velocity model is constructed based on previous studies in the region. The maximum number of iterations and the velocity perturbations which sustain the linearity of the inversion are determined based on the detailed tests. Reliable zones of the final model are decided based on the Derivative Weighted Sum and Hit Count distribution. The resulting velocity model displays a clear velocity contrast across the surface trace of the EAFZ down to a depth of 12 km. While the Anatolian side of the fault displays higher velocities associated with the ophiolitic units in the region, the south of the fault zone is represented by lower velocities due to sedimentary deposits. The vertical cross-sections of tomographic models show a north dipping fault between Palu and Çelikhan. The complete earthquake catalog is relocated using the 3D velocity model. Together with the obtained velocity model, the relocated hypocenters indicate that the dip of the EAFZ is not uniform, the Palu segment dips to the north with an angle of $\sim$80°, while the Pütürge and Erkenek segments dip to the north with a lower angle of $\sim$60–70°.

Key words: East Anatolian Fault, fault structure, fault geometry, local earthquake tomography

1. Introduction
The East Anatolian Fault (EAFZ) is a ~400-km-long left-lateral strike-slip fault along Anatolia–Arabia Plate boundary (Arpat & Şaroğlu, 1972; Hempton et al. 1981) (Figure 1). Together with the Bitlis-Zagros Fold and Thrust Belt and the Caucasus Fold and Thrust Belt, the EAFZ accommodates the relative motion between Eurasia and Arabia (McKenzie 1972; Şengör et al. 1985; Le Pichon & Kreemer 2010).

The EAFZ displays complex seismicity patterns with gaps, localized clusters, and sections with diffuse seismic activity (Figure 1). Most of the seismicity along the EAFZ occurs to the NE of Çelikhan along Palu, Pütürge, and partly Erkenek segment where the plate motion is parallel to the main fault. The western sections of the EAFZ have a relatively lower seismicity rate due to oblique plate motion, reducing geodetic and geological slip rates and geodetic strain accumulation (Weiss et al., 2021, Duman & Emre 2013, Güvercin et al., 2022). On the eastern segments where the seismicity rate is relatively high compared to the western parts, the depth distribution of the seismicity implies that the dip angle of EAFZ is changing along the fault, at least between Palu and Çelikhan. The reported focal mechanisms along the EAFZ display left-lateral strike slip motion on a north dipping fault plane with some normal and thrust components (Tan et al., 2011; Güvercin et al., 2022).

However, both seismicity and dip angles from focal mechanisms contain uncertainties due to the use of a 1D velocity model for both in the locations and computation of Green's functions for the moment tensor inversion. This uncertainty can be reduced with a reliable 3D velocity model. However, the accuracy of the 3D crustal model along the EAFZ is hampered by the heterogeneous seismicity distribution, especially in the southwest of the main fault.

The lower crust and upper mantle structure of beneath the EAFZ is relatively better constrained. Several types of tomographic models using body waves (Piromallo and Morelli, 2003), Pn and Sn studies (Mutlu and Karabulut, 2011; Lü et al., 2017), surface-waves (Legendre et al., 2012, 2020; Cambaz and Karabulut, 2010), and receiver function studies (Özacar et al., 2008; Gök et al., 2011, Vanacore et al., 2013; Karabulut et al., 2019) revealed the complexity of the crust and constrained crustal thickness variations in eastern Anatolia. To the NE of Çelikhan, a zone between the EAFZ and the Bitlis Thrust Belt towards the north displays slow velocity anomalies (Medved et al., 2021)
To the southern side of the EAFZ, the lower crust displays faster velocities related to the crystalline massifs and the Arabian lithosphere (Delph et al., 2015). The crustal thickness is smoothly changing between 40–50 km along the EAFZ, getting thicker from SE to NE (Karabulut et al., 2019). Moreover, a strong contrast in...
anisotropy between the south and north of the main fault also implies that the crustal properties on both sides along the main fault are different (e.g., Legendre et al., 2020). The undetermined velocity contrasts in the crustal velocity model can lead to inaccuracies in earthquake locations, fault plane solutions. The velocity contrast across the fault might also influence the rupture properties of large earthquakes on the EAFZ (Oppenheimer et al. 1988; Ben-Zion & Andrews, 1998; Özakin et al., 2012). However, most of the lithospheric structure models either rely on regional or teleseismic data which result in a limited resolution in the upper crust, leaving its short wavelength properties poorly resolved. The number of reliable local earthquake tomography studies focusing on the EAFZ is limited due to the lack of a comprehensive and accurate seismicity catalog. Recently, Medved et al., (2021) imaged the upper crust using a seismic catalog from AFAD with residuals up to 1s. However, the catalog was not revised before inversion therefore contains large uncertainties.

In this study, an improved seismicity catalog from Güvercin et al., (2022) is utilized in order to resolve the details of the seismogenic part of crust (<15km) beneath the EAFZ. The compiled catalog includes the phase picks of more than 26,000 earthquakes from the bulletins of Kandilli Observatory and Earthquake Research Institute (KOERI, 2001; http://www.koeri.boun.edu.tr), Disaster and Emergency Management Authority (AFAD, 1990; https://tdvms.af ad.gov.tr) and The Scientific and Technological Research Council of Turkey (TUBITAK-MRC, 2020; https://mam.tubitak.gov.tr/en). We interpret the tomographic model for the large velocity contrast across the fault and the variations of dip angle along the fault.

1.1. Geological setting of the EAFZ
The EAFZ evolved as a consequence of the final stage of the Eurasia–Arabia collision during Middle Late Miocene (16–20 Ma) (Şengör & Yılmaz 1981; Dewey et al. 1986; Hempton 1987; Yilmaz 1993; Robertson 2000) (Figure 1). The EAFZ was exposed to several tectonic inversions between Middle Miocene (~12 Ma) and Early Pliocene (3 Ma) resulting in changes of tectonic regime, basin type and deformation pattern (Koçyiğit et al. 2001). During the Neogene deformation, the compressional Miocene structures with favorable orientations were reactivated and the EAFZ was transformed into its current geometry with segments (Hempton et al. 1983; Westaway & Arger 1996; Duman & Emre 2013).

The EAFZ is also characterized by several extensional and compressional geometric complexities such as the Göynük paired bend, the Gökdere restraining bend, the Lake Hazar releasing bend, the Gölbaşı releasing step over, the Türkoğlu releasing step over, the Nurhak Fault Complexity, the Gökşun releasing bend and the Delihalil releasing bend from east to west (Duman & Emre 2013; Figure 1). The releasing bends are accompanied by pull-apart basins such as Bingöl, Karakoçan, Kovancilar, Palu-Uluova, Lake Hazar, Malatya, and Gölbaşı from east to west (e.g., Lyberis et al. 1992; Westaway 1994; Duman & Emre 2013).

The most recent work on the segmentation along the EAFZ based on field observations was presented by Duman & Emre (2013) where they divide the main strand of the EAFZ into seven segments. In addition, they also considered the subparallel faults that split from the EAFZ around the Sürgü Fault as the northern strand of the EAFZ (Figure 1a). The main fault, from east to west, comprises of the Karlova, İlaca, Palu, Pütürge, Erkenek, and Pazarcık segments. The northern strand consists of Sürgü, Toprakale, and Yumurtalık segments. In their fault map, the Sürgü Fault splays from the main fault, near Çelikhan and extends towards the west for ~30 km.

The geology of the EAFZ is bounded by large bodies of metamorphic massifs at both sides. These are Pütürge massif to the SW and Bitlis massif to the NE. The metamorphic massifs are surrounded by ophiolitic rocks, melanges, and volcanic rocks. The composition of Pütürge massif is defined by pre-Triassic gneisses and micaschists, and granitoids (Michard et al. 1984; Aktaş & Robertson 1990) having an Afro–Arabian origin. The upper Cretaceous–early Tertiary melange units, drifted to the south by sedimentary sequences of the Arabian plate, underlain the Pütürge massif and surrounding volcanic and ophiolitic rocks (Herece at al., 2008) (Figure 1b).

To the east, the Bitlis massif which consists of a metamorphic basement, is based on metamorphosed Palaeozoic to Triassic carbonate rocks (Gönçüoğlu & Turhan 1984; Helvaci & Griffin 1984), and Palaeozoic to late Mesozoic granitoids (Figure 1). The massif is also suggested to be composed of a stack of nappes formed during Southern Tethys closure (Oberhansli et al. 2008). The whole massif is an intricate complex exhibiting doubly plunging, multiply folded anticlinorium with overturned limbs both to the north and the south (Dilek & Moores 1990).

The surface geology along the EAFZ is not uniform, exhibiting significant variations in rock types (Figure 1). These variations can be represented by rapid velocity changes on shallow tomographic images between 0–4 km. Whether the complex geology along the EAFZ influences the vertical fault geometry can be clarified from the deeper tomographic images.

2. Data and methods
2.1. Data
The improved earthquake catalog used in this study is from Güvercin et al., (2022). The catalog includes more
than 26,000 events recorded at more than 100 broadband stations operated between 01.01.2007–31.12.2019. The mean horizontal location uncertainty of the catalog is less than 2.0 km in NS and EW directions and the mean of the depth uncertainty is -3.5 km in directions. The azimuthal gap is between 90 and 150 for most of the earthquakes and the mean RMS of the catalog is ~0.2 s.

The events used for the tomographic inversion are selected in the region located between Palu and Çelikhan, based on the criteria such as the number of stations recorded (>15), azimuthal gap < 100°, horizontal location uncertainties < 3 km. The spatial distribution of the selected earthquakes and station distribution is displayed in Figure 2. The selected events catalog consists of 2200 earthquakes with a total of 23,676 P arrivals and 8530 S arrivals. As the number of observed S wave travel times is much less than P wave travel time observations, the results of S wave images will not be presented.

### 2.2. Method

We use SIMULPS (Simultaneous tomographic inversion for Vp and Vs) code (Thurber, 1983-1993; Eberhart-Phillips, 1993) to invert arrival times for P wave velocity (Vp) and hypocenter parameters. Due to the strong nonlinearity of tomographic imaging, SIMULPS uses an iterative damped least squares inversion technique to linearize the problem. The residuals between observed and computed travel times are minimized by computing Vp and Vp/Vs at nodes of a 3D grid and the bending technique is used for the ray tracing (Um and Thurber, 1987). The earthquakes are simultaneously relocated after each iteration using the new 3D velocity model.

The tomographic inversion is highly dependent on the initial velocity model as well as the model parameters such as damping value and grid spacing. The initial 1D velocity model is adjusted based on available tomographic models in the region (Delph et al. 2015; Cambaz and Karabulut 2010). The average P wave velocity and Vp/Vs ratios (1.74 km s⁻¹) for the seismogenic crust are obtained using the Wadatti method. After building an initial 1D velocity model, an improved 1D velocity model for the region is computed from 700 selected earthquakes using VELEST (Kissling et al. 1994) inversion code. The selection criteria for 700 events are based on the number of phase readings (>25) and azimuthal gap (<80°) for each event. The deviations from 1D velocity model are accounted in the station corrections. The inversion results of the initial 1D model and previously suggested 1D models (Pausse-Beltran et al., 2020; Medved et al., 2021) are compared and yield similar variance reductions but slightly better with the initial 1D model of this study due to denser ray coverage (Güvercin et al., 2022). The comparison of the previously suggested 1D initial velocity models and the initial model used in this study is presented in Figure S1.

The selection of grid size relies on the station and earthquake distribution and the expected sizes of vertical and horizontal velocity heterogeneities. A node spacing smaller than the average distance between the source and receiver biases the inversion as the nodes in the vicinity of the source are dominated in the inversion. To avoid artificial velocity perturbations, the horizontal node spacing in both directions is chosen as 10 km based on synthetic tests and the average receiver and source spacing in the study area (Figure 2). The vertical size of the grids is chosen as 2 km. The model space is rotated in 26° clockwise direction and aligned with the fault strike (Figure 2).

The optimal damping can be determined considering a value satisfying small data misfit versus large model variance. The best damping parameter (40) is obtained by making a series of single-iteration inversions for damping values between 1 and 1000 (Figure 3a). To avoid strong and unrealistic anomalies, the maximum number of iterations and velocity perturbation in each iteration must sustain the linearity of the inversion. The maximum number of iterations at which the model variance versus data variance curve reaches a minimum is 4 for a value maximum Vp perturbation = 0.1 km/s (Figure 3b). The inversion parameters are fixed during the iterations. The residual distributions of initial and final earthquake catalogs for P waves are displayed in Figure 4. Significant improvements can be observed in the travel time residuals.

### 2.3. Quality of the inversion

Reliable zones of tomographic inversion results are defined based on the quality estimators of resolution such as Derivative Weighted Sum (DWS) and Hit Count (HC). The value of HC represents the number of rays sampling a node. HC gives a first-order definition of ray coverage but does not account for ray segment lengths. The DWS is sensitive to the ray segment lengths which samples the volume of a node. In order to identify the reliable zones of the final velocity model, we used a DWS value greater than 100 and an HC value greater than 1500 (e.g., Haslinger et al. 1999; Husen and Kissling 2001).

Figure S2 and Figure S3 display the DWS and HC of the final 3D Vp model for layers between 0.0 km and 12.0 km depth. The distribution of DWS at depths <4 km is uneven around the EAFZ indicating a low resolution possibly resulting from the lack of shallow earthquakes. Between 4–10 km depths, the DWS shows similar coverage and similar HC contours. At 12 km depth, DWS shows a narrower zone of resolution in the NS direction while the HC contour still covers most of the study area. Hence, we rely on the images down to 12 km.

We applied the Checkerboard Test showing the image distortion in the medium (Spakman, 1993; Benz et al., 1996; Zelt & Barton, 1998; Zelt et al., 2001; Tong et al., 2003). The checkerboard pattern comprises 40 km sinusoidal...
checkerboard patterns having a cell size of $20 \times 15 \text{ km}$ in the horizontal (EW and NS) and 4 km in the vertical directions (Figure 5a). The sinusoidal velocity undulations of the checkerboard with maximum amplitudes of %10 of the initial velocity model were computed and added to the 1D initial model. Synthetic travel times were computed by a 3-D ray tracer (Um & Thurber 1987) using the same source-receiver distribution as for the real data.

The resulting velocity model from the inversion of the checkerboard model allows the identification of the well-

Figure 2. The model space used in travel-time inversion for tomography. Grid nodes used during inversion are shown by black squares. Green triangles show the seismic stations. The earthquakes selected for the inversion are indicated by blue circles. Faults are displayed by bold black lines (Emre et al. 2013). The red line shows the surface trace of the imaged section of the EAFZ.

Figure 3. Selection of the optimum damping value. a) The data and model variances for different damping values. Damping values are shown near the circles. b) Data variance with the selected damping (40) with iteration.
recovered areas (Figure 5b). The polarities and shapes of the perturbed velocity model are well-determined within the selected DWS and HC contours. The checkerboard patterns within a band of ±0.4° (±40 km) along the surface trace of the EAFZ are better resolved down to a depth of 12. The zone of resolved checkerboard patterns diminishes with depth and concentrates at the center of the grid space.

3. Results
The results of SIMULPS inversion for the $V_p$ model are presented in Figure 6. The most prominent observation is the velocity contrast between two sides of the EAFZ reaching to ±8% at all depths down to 12 km. The northern side of the fault has higher velocities, where the uppermost crust is dominated partly by Pütürge metamorphic massif to the SW and the units of ophiolites located to the north of the main fault (Figure 5). To the south of EAFZ, the crustal velocities dramatically decrease making a clear contrast to its north. Reduced velocities are in good agreement with local volcanic Flysches which cover a large area to the south of the EAFZ. The signatures of the Bitlis and Pütürge massifs are observed on the south of the main fault, especially at shallower depths (Figure 6).

In addition to the first order velocity contrast between the two sides of the EAFZ, smaller-scale features are also observed such as the high-velocity anomaly south of the Hazar Lake whose location coincides with a local Cretaceous ophiolitic unit. Another high-velocity anomaly down to 6 km is located to the south of the Palu segment where the Ophiolitic Melanges are observed.

The sensitivity test shows that the selected inversion parameters do not introduce significant artifacts for the expected sizes of the anomalies. However, the velocities to the NE of the model close to the EAFZ could be even higher considering the result of the checkerboard tests. Although the observed high velocity anomaly to the south of the study region is located within the fairly resolved parts of the model, the increased velocities in those areas are well correlated with the volcanic rocks of the Arabian foreland.

The final 3D velocity model is utilized to improve the initial locations of the earthquakes. The mean residual of the new hypocenter locations of 3885 earthquakes is 0.09 s after relocation with the 3D model. The improved final earthquake catalog is projected to the 8 NW-SE vertical profiles perpendicular to the EAFZ (Figure 7a). The observed 3D crustal structure and the distribution of the earthquakes put new constraints on the vertical geometry of the EAFZ. From SW to NE profiles 1 to 8 demonstrate the changing dip angles along the strike. Although the resolution is relatively low at the SW of the fault zone, along Erkenek segment, profiles 1, 2, and 3 display a clear north dipping fault plane in tomographic images (Figure 7b).

Profiles 4, 5, and 6 are cross the Pütürge segment. The cross-sections of seismicity and the tomographic images along profiles 4 and 5 demonstrate that the dip angle along the Pütürge segment is slightly shallower towards the north compared to the dip angles observed along the Erkenek segment. The cross section along Profile 6 displays a steeper angle compared to its SW (Figure 7b).

Profiles 7 and 8 demonstrate the vertical geometry of EAFZ along the Palu segment. These cross sections demonstrate a different dip angle which is the steepest along EAFZ (Figure 7b).
Figure 5. The input Checkerboard pattern and inversion results (a) True sinusoidal checkerboard patterns with 20 km in EW and 15 km in NS directions with a maximum 10% perturbation. (b). Colors represent positive and negative velocity perturbations. Black solid contours bound the area with cells with HC > 1500. The pink solid line is the contour of DWS = 1000.
4. Discussion

The V_p velocity model presented in this study is dominated by Bitlis and Pütürge massifs along with ophiolitic rocks and Flysches in between, revealing a clear velocity contrast across the surface trace of the EAFZ. The seismic tomography model of Mevged et al. (2021) demonstrates a low-velocity zone making a boundary between the Arabian plate and Eastern Anatolia. This observation is well correlated with the 3D upper crustal structure having lower velocities to the north of the Bitlis Suture Zone. The increased velocities on the north of the EAFZ are also consistent with the previous studies which illustrate the crystalline basement (e.g., Delph et al., 2015). These observations and fault morphology are coherent (Emre et al., 2013). In addition, some of the small-scale features in the study region are manifested by the variations of the seismic velocities obtained in this study.

The cross-sections reveal that the EAFZ dips to the north with varying angles. The dip appears to change at short distance scales such as 30–40 km. The steepest section of the

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**Figure 6.** Map views of the P wave velocity perturbations. The changes are displayed with the color scale below the figure. At the upper left panel (4 km), Pütürge Metamorphic Massif, ophiolites, and Flysches are represented by circles, dashes, and crosses, respectively. Faults are shown by black lines (Emre et al. 2013). The earthquakes relocated using the 3D velocity model are displayed by black circles. Regions located outside the HC = 1500 contour are masked. The pink solid line represents DWS = 1000 and bounds the reliable zones of the model. Black dashed lines mark segment boundaries. The locations of the profiles are demonstrated by pink marks along the gray bar above panels. Ç = Çelikhan, H = Lake Hazar, P = Palu.
EAFZ is the Palu segment with a dip angle of ~80°. To the SW, the average fault dip angle along the Pütürge segment is previously suggested to be between 65°–70° (Güvercin et al., 2022; Konca et al., 2021). The velocity contrast at the cross-sections along the Pütürge Segment also displays similar dip angles. The dip angle observed along the Pütürge segment is also consistent with the relocated locations. Along the western tip of the model, the fault interfaces appear with a steeper angle along the Erkenek segment which is also compatible with the distribution of the relocated locations.

The observed dips are consistent with the previous studies suggesting a north-dipping fault plane (Güvercin et al., 2022). It is possible that the changing direction of plate motion and the existence of crustal materials with different shear strengths played a role in the dip angle variations along the EAFZ.

At depths greater than 6 km along the eastern profile crossing the Palu segment, there is a sharp velocity change from low to high. The lower velocity zone at the center of the Palu segment extends from 4 km to 12 km. This
zone of lower velocities also divides the seismically active parts of the segment. Correspondingly, none of the major earthquakes that occurred in this segment ruptured the whole segment, leaving the central part quiescent in the interseismic period.

5. Conclusion
The tomographic images obtained in this study provide more accurate knowledge of the crustal structure beneath the EAFZ. The model exhibits significant perturbations of the crustal velocities across the EAFZ along Palu, Pütürge, and Erkenek segments. The short wavelength variations of the velocity model are consistent with the local geology consisting of metamorphic massifs and ophiolitic units. The two sides of the EAFZ along strike are represented by high and low velocities making a clear contrast across the surface trace of the fault. The relocated hypocenters with 3D velocity model and the crustal tomographic model imply a north dipping fault. However, the results indicate that dip angle of the EAFZ is not uniform along the strike.

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Figure S1. The comparison of the 1D velocity model obtained in this study and the 1D velocity models from Pousse-Beltran et al., (2020) and Medved et al., (2021). Red thick lines represent the P and S velocities obtained in this study.
Figure S2. The distribution of DWS in the study area. DWS variations are demonstrated by the color scale next to the figure. Faults are displayed by bold black lines (Emre et al., 2013).
Figure S3. The distribution of Hit Count (HC) in the study area. HC variations are demonstrated by the color scale next to the figure. Faults are displayed by bold black lines (Emre et al., 2013).