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Kinematics of the Kahramanmaraş triple junction and of Cyprus : evidence of shear partitioning

Volkan Özbey^{1,2,*}, Ali Mehmet Celâl Şengör^{3,4}, Pierre Henry², Mehmet Sinan Özeren⁵, A. John Haines⁶, Elliot C. Klein⁷, Ergin Tari¹, Cengiz Zabcı³, Konstantinos Chousianitis⁸, Sezim Ezgi Güvercin⁹, Nazik Öğretmen⁵

Abstract

Triple junctions involving convergent plate boundaries extend beyond local implications, which is crucial for studying the geology of convergent plate boundary zones. However, kinematic models overlook Cyprus-Anatolia motion due to limited geodetic constraints. Our study area comprises Cyprus, southern Turkey, and the Levant coast, focusing on the Kahramanmaraş triple junction, where a destructive earthquake sequence occurred on February 6, 2023. We present precise positioning data merged with published ve-

*Corresponding author

Email address: ozbeyv@itu.edu.tr (Volkan Özbey)

¹Istanbul Technical University, Department of Geomatics Engineering, 34469, Maslak, Istanbul, Turkey

²Aix-Marseille Universite, CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France

³Istanbul Technical University, Department of Geology, 34469, Maslak, Istanbul, Turkey

⁴Center for Global Tectonics, School of Earth Sciences, State Key Lab for Geological Processes and Mineral Resources, Badong National Observatory and Research Station for Geohazards, China University of Geosciences, Wuhan

⁵Istanbul Technical University, Eurasia Institute of Earth Sciences, 34469, Maslak, Istanbul, Turkey

⁶GNS Science - Institute of Geological and Nuclear Sciences, (emeritus), New Zealand

⁷FM Global, Research Division, Norwood, MA, United States

⁸Institute of Geodynamics, National Observatory of Athens, Lofos Nymfon, Athens, Greece

⁹Yıldız Technical University, Department of Geomatics Engineering, 34349, İstanbul, Turkey

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locities, constructing an up-to-date velocity field for the interseismic period. Employing two kinematic approaches, we analyze its tectonic implications. In Cyprus, we find the relative motion of Africa (Sinai Plate) and Anatolia is partitioned between convergence in the Cyprus subduction, with a rate of 3.5-6.2 mm/yr, progressively decreasing from west to east and left-lateral transpressive Kyrenia fault, situated along the northern coast of Cyprus, with rate 3.3-4.2 mm/yr. The relative strike-slip motion between Arabia and Anatolia is partitioned between the East Anatolian Fault (slip rates 5.2-6.2 mm/yr) and some secondary faults such as Çardak and Malatya faults (slip rates 2.0-1.7 mm/yr respectively) and causes distributed deformation for a 50-60 km wide region. The largest second invariant strain rate tensors from the continuum kinematic model also coincide with the same region, the East Anatolian shear zone. A shear partitioning system exists around the Kahramanmaraş triple junction, from Cyprus to southeast Turkey. The Levant Fault has a 3.5-4.7 mm/yr left-lateral slip rate, decreasing northward as part of it is transferred to offshore faults. Strain rates appear relatively small in the Taurus range and Adana/Cilicia basin, transitioning from extensional/transtensional to compressional from east to west.

Résumé

La déformation associée aux jonctions triples impliquant des plaques convergentes s'étend régionalement et influe sur l'activité sismique et l'évolution tectonique des frontières de plaque. Notre étude de la jonction triple de Kahramanmaraş — où une séquence de tremblements de terre destructeurs s'est produite le 6 février 2023 — englobe Chypre, le sud de la Turquie et la côte du Levant. Nous fusionnons de nouvelles données de positionnement GNSS avec les champs de vitesses publiées, construisant ainsi un champ de vitesse intersismique incluant Chypre — où les données disponibles étaient jusqu'à présent très limitées. Ce champ de vitesse est analysé d'une part avec un modèle de blocs élastiques et d'autre part avec une méthode d'interpolation continue. Nous montrons que le mouvement relatif de l'Afrique (plaque Sinäi) et de l'Anatolie est partitionné entre la subduction de Chypre, avec un taux de convergence de 3,5 à 6,2 mm/an diminuant progressivement d'ouest en est, et la faille transpressive de Kyrenia, situé le long de la côte nord de Chypre, avec une vitesse de décrochement senestre 3,3 à 4,2 mm/an. Ce système de partitionnement se prolonge à terre où le mouvement de décrochement entre l'Arabie et

l'Anatolie est réparti dans une zone de cisaillement de 50 à 60 km de large. Dans la zone des séismes du 6 février ce mouvement est distribué entre la Faille Est Anatolienne (taux de glissement 5,2-6,2 mm/an) et certaines failles secondaires telles que les failles Çardak et Malatya (taux de glissement 2,0-1,7 mm/an). Entre les plaques Arabie et Sinaï, la faille du Levant a un taux de glissement senestre de 3,5 à 4,7 mm/an, diminuant vers le nord ou une partie de la déformation est transférée en mer. Il apparait ainsi que le mouvement sur chacune des frontières de plaques formant la jonction triple de Kahramanmaraş est réparti sur plusieurs failles. En revanche, les taux de déformation sont relativement faibles dans la chaîne du Taurus et dans le bassin d'Adana/Cilicie où le style de déformation change progressivement d'extensif/transtensif à l'est à transpressif à l'ouest.

1. Introduction

2 The recent tectonics of the Eastern Mediterranean result from the inter-
3 action of the Arabia, Africa, and Eurasia plates since Miocene (McKenzie
4 et al., 1970; McKenzie, 1972; Şengör, 1979; Şengör et al., 1985) (Fig. 1a).
5 During the middle Miocene, Arabia was separated from Africa along the left-
6 lateral Levant (or Dead Sea) fault zone (e.g., Le Pichon and Gaulier, 1988).
7 The subsequent collision of Arabia with Europe, resulting in gravitational
8 potential build-up in Eastern Anatolia, combined with an acceleration of
9 slab rollback in the Hellenic subduction where the northern African slab is
10 subducted (Brun et al., 2016) and a possible contribution from underlying
11 asthenospheric flow, have been driving the westward extrusion of the Anato-
12 lian Plate (Özeren and Holt, 2010; Le Pichon and Kreemer, 2010). Currently,
13 the boundary between Arabia and Anatolia is a left lateral transform plate
14 boundary, the East Anatolian Fault zone (EAF) (McKenzie, 1976; Şengör
15 et al., 1985). Africa has been divided in the Eastern Mediterranean into a
16 Nubia plate (McKenzie et al., 1970; Le Pichon and Francheteau, 1978) and
17 a Sinai sub-plate (Mahmoud et al., 2005). The Sinai plate thus subducts
18 beneath Anatolia along the Cyprus Arc and moves southward concerning
19 Arabia along the Levant Fault zone. The Kahramanmaraş triple junction is
20 the junction of the Levant Fault zone, the East Anatolian Fault zone (EAF),
21 and the Cyprus Arc Subduction (Şengör et al., 1980, 1985; Karig and Ko-
22 zlu, 1990) (Fig. 1b). This triple junction also gives rise to a very complex
23 pattern of deformation in the northeastern Mediterranean because of the

24 convergence of the two continental plates, namely Arabia and Anatolia. Ad-
25 ditionally, the marine part of the Sinai Plate is formed of thinned continental
26 crust, comprising a thicker region, the Eratosthenes seamount, which is cur-
27 rently impinging the Cyprus Arc (Le Pichon et al., 2019). In this incipient
28 collision, the relative motion of Sinai and Anatolia is distributed between the
29 Cyprus Arc subduction, the Kyrenia fault running along the Northern Coast
30 of Cyprus, and the Taurus range onshore further north. In fact, two triple
31 junctions are currently active in the area, namely those of Hatay (see Fig.
32 1b) where the eastward prolongation of the Cyprus arc reaches the Levant
33 Fault, and Kahramanmaraş where the NE prolongation of the Kyrenia fault
34 reaches the EAF (Şengör et al., 2019; Özkan et al., 2023). However, the mo-
35 tion of Cyprus with respect to Anatolia has been ignored so far in regional
36 kinematic models because of a lack of constraints from geodesy, due to insuf-
37 ficient data on the island (see for example Mahmoud et al., 2005; Reilinger
38 et al., 2006; Gomez et al., 2020).

39 **Figure1**

40 This paper presents a refined GNSS (Global Navigation Satellite Sys-
41 tems) velocity field encompassing southern Turkey and Cyprus. Leveraging
42 these data, we construct regional kinematic models that not only illuminate
43 the motion of the study area but also incorporate higher-resolution bound-
44 ary conditions and internal deformation characteristics specific to Cyprus.
45 Through these novel data and models, we foster a more comprehensive un-
46 derstanding of the neotectonics of the northeastern Mediterranean. In ad-
47 dition, we will discuss the kinematic context of the major earthquakes that
48 occurred in the Kahramanmaraş triple junction area on February 6, 2023:
49 Mw (moment magnitude) 7.8 Pazarcık earthquake on the EAF and Mw 7.6
50 Elbistan earthquake on Çardak Fault (Barbot et al., 2023; Hussain et al.,
51 2023).

52 Previous geodetic studies either measured Arabia and Anatolia plate mo-
53 tion and deformation (Reilinger et al., 2006; Özeren and Holt, 2010; Cavalie
54 and Jónsson, 2014; England et al., 2016; Weiss et al., 2020; Bletery et al.,
55 2020; Kurt et al., 2022; Viltres et al., 2022) or focused on the kinematics
56 of the Levant fault zone (Gomez et al., 2007; Le Beon et al., 2008; Alchalbi
57 et al., 2010; Al Tarazi et al., 2011; Sadeh et al., 2012; Gomez et al., 2020;
58 Hamiel and Piatibratova, 2021) and of the East Anatolian fault zone (Cavalié
59 and Jónsson, 2014; Walters et al., 2014; Aktuğ et al., 2016; Bletery et al.,
60 2020). However, only a few studies account for the active deformation of
61 secondary faults such as Malatya and Çardak Faults (also called Sürgü Fault

62 by some authors) (Westaway, 2003; Aktuğ et al., 2013), or the Karataş-
63 Osmaniye Fault (Mahmoud et al., 2013; Özkan et al., 2023). Ascertaining
64 the kinematics of the Cyprus Arc Subduction using land-based GNSS obser-
65 vations has proven to be a difficult task since much of the subduction arc is
66 expressed beneath the Mediterranean Sea. The Island of Cyprus is the only
67 place within the Eastern Mediterranean Basin where the Cyprus Arc Sub-
68 duction kinematics can be studied using onshore geodetic constraints. Still,
69 the data have been too sparse to date. We thus conducted new GNSS surveys
70 in Cyprus between 2019 and 2021, along with data from permanent GNSS
71 sites, providing comprehensive spatial coverage for constructing a kinematic
72 model of the eastern Mediterranean. Our velocity field includes follow-up
73 surveys in the Turkish mainland and velocities published by previous stud-
74 ies. In section 2 we present our GNSS processing strategy and integration
75 workflow details.

76 We applied two kinematic inversion methods with our combined velocity
77 field as input. On the one hand, we employed a continuum velocity field in-
78 terpolation method to calculate the strain rate field of the study area (Haines
79 and Holt, 1993; Beavan and Haines, 2001). This strain distribution may be
80 compared with seismicity distribution and tectonic strain regimes indicated
81 by fault maps. This information also contributes to the definition of bound-
82 aries for a block model. The block model calculates rigid block motions and
83 coupling on the block boundaries defined as dislocation sources (McCaffrey
84 et al., 2007). The output of this model may thus be interpreted in terms of
85 long-term slip rates and seismic coupling on major faults. This model also
86 allows for the internal deformation of the blocks by calculating a unique and
87 uniform strain rate tensor for each block. In parallel,

88 Our newly acquired data and model results help us to address several
89 important questions regarding the kinematics and active tectonics of the
90 Eastern Mediterranean region. We quantify the partitioning of deforma-
91 tion among the Cyprus Arc Subduction, Kyrenia fault, and Taurus range.
92 We evaluate the distribution of deformation around the Kahramanmaraş and
93 Hatay triple junctions, notably between the EAF and the Karataş-Osmaniye-
94 Çardak-Malatya fault system and discuss implications for earthquake recur-
95 rence intervals. Regarding the Levant fault, the present study is based on
96 fewer velocity vectors than, for instance, presented in Gomez et al. (2020)
97 and has little to add to their demonstration that slip on the main fault strand
98 is decreasing northward toward the triple junction as part of the motion is
99 diverted offshore.

100 **2. GNSS Observations and Analysis**

101 *2.1. GNSS Data*

102 We present a GNSS velocity field that unites newly derived with previ-
103 ously published velocities. We conducted GNSS surveys in Cyprus between
104 2019 and 2021 and revisited 18 points that had been previously measured in
105 1998 and 2001. We also incorporated the data from seven permanent GNSS
106 sites in the southern part of the island. For the first time, we now have
107 reasonable spatial coverage of space geodetic data in Cyprus. This enables
108 us to construct a kinematic model of the easternmost Mediterranean that,
109 in turn, provides us with a more detailed picture of the deformation within
110 Cyprus. We also conducted some follow-up surveys at several GNSS survey-
111 mode sites in the Turkish mainland to further constrain the kinematics of
112 Anatolia with better coverage. We then integrated into our velocity field
113 previously published velocities acquired over the vicinity of the Levant fault
114 and EAF.

115 The raw data of the continuous stations were obtained from both inter-
116 national networks (International GNSS Service -IGS hereafter) and regional
117 networks (Turkey Continuous GNSS Network and Cyprus Positioning Sys-
118 tem) (Fig. 1b). We primarily analyzed the dataset from 2009 to 2021 for
119 continuous stations, although some of them had data gaps during that pe-
120 riod. However, we have approximately 10 years of time series for almost
121 every continuous site. The survey mode GNSS sites were selected from the
122 Turkey Fundamental GNSS Network to utilize valuable existing observations
123 and data resources. Each observation was carried out using dual-frequency
124 receivers and a filtering cut-off angle of 10 degrees to minimize atmospheric
125 noise. Each survey mode site has at least 7 different sessions, except for 3
126 sites in the northern part of Cyprus that were set up in 2019, and all sessions
127 have at least 8 hours of observations. The readers can find further details of
128 the data span of survey mode sites in the supplementary file. We evaluated
129 the raw data of 137 GNSS stations (65 continuous - 72 survey modes) and
130 estimated their velocities.

131 *2.2. Seismicity*

132 The long-term seismicity catalogue between 1905 and 2019 represented
133 in this figure was compiled from Kandilli Observatory and Earthquake Re-
134 search Institute's seismicity catalogue between 1905 and 2019 (KOERI, 2001;

135 <http://www.koeri.boun.edu.tr>). The magnitude of completeness of the cat-
136 alogue is $\sim M_c=4$. The mean horizontal location uncertainty is less than 5
137 km in N-S and E-W directions. The mean of the depth uncertainty is ~ 3.5
138 km, varying between 2 and 8 km. We filtered the original catalogue based
139 on quality factors such as horizontal location uncertainty < 5 km and RMS
140 < 0.5 s. This dataset does not include the February 2023 earthquakes and
141 their aftershocks. In the East Anatolian shear zone, this data set emphasizes
142 seismic activity on the Malatya Fault (MF), between the Çardak Fault (CF)
143 and Karatas-Osmaniye Fault (KOF), and south of Hatay but displays rela-
144 tively little activity along and on the recently ruptured segments of Çardak
145 fault and the EAF (Fig.3). A concentration of earthquakes observed south
146 of Cyprus is largely associated with the subduction plane of the Cyprus Arc
147 and will here be used to constrain its geometry.

148 *2.3. Data Evaluation*

149 We performed data processing using a combination of GAMIT/GLOBK
150 software (Herring et al., 2018a, and the extensive literature cited therein)
151 and a stochastic approach. GAMIT/GLOBK integrates the double differ-
152 ences method and carrier phase combinations to eliminate geometric and
153 non-dispersive delays in the solution. We used IGS final orbit and clock
154 products as orbit parameters and the VMF1 (Vienna Mapping Function 1)
155 mapping function to minimize the effect of the tropospheric delay (Boehm
156 et al., 2006). In addition, we incorporated over 20 IGS stations into our net-
157 work to define a well-constrained global network. We processed daily data
158 from 2009 to 2022, while for the period between 1998 and 2009, we only eval-
159 uated days with observations for our survey-mode sites. We verified our daily
160 solutions by following the steps outlined in Herring et al. (2018a). Once daily
161 solutions were obtained for each station, combinations were carried out using
162 a Global Kalman filter approach (Herring et al., 2018b). This approach facil-
163 itates the sequential estimation of parameters, providing an advantage over
164 other estimation methods due to its ability to define the state vector and its
165 stochastic model for future measurement times (Herring et al., 1990). Global
166 network solutions from various institutions were integrated into the evalua-
167 tion to create a comprehensive network encompassing the existing regional
168 one. The time series for all sites were generated relative to the International
169 Terrestrial Reference Frame 2014 (ITRF14) (Altamimi et al., 2016).

170 The time series analysis was carried out in three main steps. Firstly,
171 outliers were detected and removed, with a particular emphasis on permanent

172 sites due to their extensive data. Secondly, efforts were made to acquire
 173 more realistic sigma values for each site. To achieve this, a first-order Gauss-
 174 Markov Extrapolation was implemented. Given the substantial differences
 175 in data quantity between continuous and survey-mode sites, these steps were
 176 executed with multiple approaches. Random walk noise of 0.02 mm/yr was
 177 added to all permanent sites' horizontal and vertical components. Conversely,
 178 the random walk noise added to survey-mode sites was five times greater.
 179 The subsequent step involved generating velocities for each site. The velocity
 180 field was determined with respect to the Arabian plate fixed reference frame,
 181 utilizing Euler pole parameters from Altamimi et al. (2017).

182 Station velocities and uncertainties for each component (North, East, Up)
 183 and time span The supplementary document provides the corresponding time
 184 series in Tables S1 to S3.

185 *2.4. Unifying Velocity Fields*

186 After generating an initial velocity field, we combined our resulting GNSS
 187 velocity field with published velocities from previous studies (Gomez et al.,
 188 2020; Hamiel and Piatibratova, 2021; Viltres et al., 2022; Kurt et al., 2022;
 189 Özkan et al., 2023). To minimize the effect of some well-known sources of
 190 noise such as those stemming from different data evaluation strategies and
 191 pre-defined reference frames from different studies, we rotated all velocity
 192 fields individually with respect to our dataset.

193 The rotation is based on a least-square approach that aims to optimize
 194 the transformation matrix of common stations for each velocity field pair.
 195 Though this approach has been applied in several studies, we made some
 196 critical changes to the weight matrix of the objective function (see Özbey
 197 et al., 2021, eq. 4). The weight parameter r_i has been constructed as the
 198 function of both distance D_i between the i th common site pair, and the
 199 number of observations n_x and n_y for the two related stations x and y (Eq.
 200 1).

$$r_i = \begin{cases} e^{-D_i^2/n_x*n_y}, & 1 < D_i \leq 5 \\ e^{-1/n_x*n_y}, & D_i \leq 1 \end{cases} \quad (1)$$

201 Stations with a distance closer than 5 km are considered to be co-located
 202 while stations with a distance closer than 1 km are considered to be the
 203 same points. In addition, our approach takes into account the plate and

Table 1: Root Mean Square fit of the velocity combination. The first column includes the name of the studies and the second column indicates the initial reference frame of each velocity field. The third column shows the number of common station pairs.

Study	Reference Frame	N. of Common Stations	RMS (mm/yr)
Gomez et al. (2020)	ITRF08	20	0.96
Hamiel and Piatibratova (2021)	ITRF14	27	0.46
Kurt et al. (2022)	EURA_I14	65	0.57
Viltres et al. (2022)	ARAB_I14	13	0.22
Özkan et al. (2023)	EURA_I14	23	0.93

204 block boundaries during its decision-making process. If the related station
 205 pair is located on different blocks or plates, the algorithm rejects it. The
 206 second parameter that is taken into account is the number of epochs for
 207 each site. Here it is important to note that the number of observations of
 208 permanent sites has been postulated as 365 for a year. Each velocity field has
 209 been rotated separately by taking the velocity field obtained by this study as
 210 the reference system. The statistical outcomes of these processes are listed
 211 in Table 1.

212 Fig. 2 shows the final velocity field leveraging in the kinematic mod-
 213 els. The unified velocities with respect to both the Arabian-fixed and ITRF
 214 reference frames, defined from Altamimi et al. (2017), can be found in the
 215 supplementary material as Table S4.

216 **Figure2**

217 3. Modelling

218 We present two different modelling approaches to reveal the present-day
 219 kinematics around the Kahramanmaraş triple junction and Cyprus. We first
 220 introduce a continuum kinematic model and generate a continuum velocity
 221 field to monitor the deformation of the region. We then introduce a block
 222 model that describes the rates of interseismic block motions occurring along
 223 the block boundaries. We suggest a block geometry for the study area and
 224 testing this geometry with previously published models including our own
 225 (Klein et al., 2022) that we developed prior to the two devastating earth-
 226 quakes of February, 2023. Once the best-fitting geometry is determined,

227 we present rotation poles for each block, slip rates, and coupling ratios for
 228 the faults. It is important to note that the block model geometry presented
 229 herein was defined before 2023 (Klein et al., 2022).

230 3.1. Strain rate field

231 Here, we generate a contemporary strain rate field to characterize de-
 232 formation styles in the region that comprises northeast Nubia, the east-
 233 ern Mediterranean Sea, the Levant fault, Cyprus, Adana/Cilicia basin, and
 234 neighbouring southern Turkey. We aim to shed light on the kinematics of the
 235 region therein. This can be useful for future dynamical models as kinematic
 236 constraints or for future seismic hazard models as geodetically inferred mo-
 237 ment constraints. Our kinematic continuum model is based on the method
 238 described by Haines and Holt (1993); Beavan and Haines (2001).

239 The method is essentially a least-squares fit to the GNSS data. The
 240 horizontal velocity field in the interpolation domain is derived from a vector
 241 function $\mathbf{W}(\mathbf{r})$:

$$\mathbf{v} = \mathbf{W}(\mathbf{r}) \times \mathbf{r} \quad (2)$$

242 The function $\mathbf{W}(\mathbf{r})$, in Eq.2, is defined at the knotpoints of a quadrilaterals
 243 mesh on the spherical earth surface and interpolated with bicubic spline
 244 functions (Haines and Holt, 1993; Beavan and Haines, 2001). The $\mathbf{W}(\mathbf{r})$
 245 values at knotpoints are inverted in order to minimize a penalty function,
 246 which in our application case is of the form:

$$\sum_{\text{points}} \sum_{\alpha, \beta} (v_{\alpha}^{\text{fit}} - v_{\alpha}^{\text{obs}}) V_{\alpha, \beta}^{-1} (v_{\beta}^{\text{fit}} - v_{\beta}^{\text{obs}}) + \sum_{\text{cells}} \nu \left(\bar{\bar{\epsilon}}_{\phi\phi}^2 + 2\bar{\bar{\epsilon}}_{\phi\theta}^2 + \bar{\bar{\epsilon}}_{\theta\theta}^2 \right) S \quad (3)$$

247 where $V_{\alpha, \beta}$ represent the data variance-covariance matrices for the geode-
 248 tic velocity measurements \mathbf{v}^{obs} with subscripts α, β , ranging over longitude
 249 ϕ and latitude θ . The $\bar{\bar{\epsilon}}_{\phi\phi}$, $\bar{\bar{\epsilon}}_{\phi\theta}$, and $\bar{\bar{\epsilon}}_{\theta\theta}$ are strain rate tensor components
 250 for each cell, S corresponds to the surface area of the related cell. The first
 251 double summation of the penalty function is the misfit to the observed GNSS
 252 velocity field subject to observational errors. The second double summation
 253 represents an a priori constraint to minimize strain. The weighting factor
 254 ν determines the relative weight of velocity data and the minimal strain as-
 255 sumption in the penalty function, and thus the amount of smoothing in the
 256 interpolation.

257 Here, we solely utilized the GNSS velocity field without imposing any
 258 plate motion boundary conditions. We also assigned a uniform ν value to
 259 achieve the objective function. Experiments were made using lower ν values
 260 in the grid cells in SW Cyprus and further offshore, where seismic catalogues
 261 show the clustering of earthquakes. If these are “damage” zones, their bulk
 262 deformability might be higher than other zones. However, these experiments
 263 did not significantly improve the fit to the GNSS velocities even in the near
 264 field sites in southern Cyprus justifying our decision not to include laterally
 265 varying ν values.

266 Fig. 3 shows the second invariant of the strain rate tensor (obeying the
 267 formula $\sqrt{\dot{e}_{\phi\phi}^2 + \dot{e}_{\theta\theta}^2 + 2\dot{e}_{\phi\theta}^2}$ where $\dot{e}_{\phi\phi}$, $\dot{e}_{\phi\theta}$, and $\dot{e}_{\theta\theta}$ are the tensor components)
 268 overlain by the seismicity of the region. The solution indicates, in general,
 269 low strain rates within Cyprus, where the second invariant rarely exceeds
 270 20 nanostrain/yr. However, in (Fig. 4), deformation styles indicate a clear
 271 spatial variability of deformation in the island. A transpressive strike-slip
 272 regime is found along the Kyrenia range, while roughly N-S compression
 273 dominates in the southern part of the island (Fig. 4). On a larger scale, this
 274 strain partitioning within Cyprus seems to act as a diffuse transition that
 275 rotates the predominant compression from NW-SE in the Sinai block onto
 276 NE-SW in the Cilicia basin immediately to the north of Cyprus. Between
 277 Cyprus and Turkey, the shortening integrated along the principal strain rate
 278 axis between the coasts of Cyprus and Turkey amounts to a maximum of 0.8
 279 mm/yr. The lack of GNSS data probably leads us to a strain rate field that
 280 is much smoother than reality in the Cilicia basin. Despite this, the solution
 281 shows a progressive transition from compression to strike-slip toward the
 282 NE, associated with a rotation of principle axes to N-S compression and E-
 283 W extension, eventually matching the dominant strain regime found on land
 284 in the Adana Basin.

285 **Figure3**

286 A swath of higher strain rate (more than 30 nanostrain/yr) over a width
 287 of 50-60 km is found east of the Adana basin and extends NE along the north-
 288 ern side of the EAF, thus defining a broader East Anatolian shear zone (Fig.
 289 3). The principal strain directions (E-W extension and N-S compression) are
 290 consistent with left-lateral strike-slip motion. The areal strain ($\dot{e}_{\phi\phi} + \dot{e}_{\theta\theta}$)
 291 is positive (see Fig. 4) except for at a few locations, indicating transten-
 292 sive to extensional deformation, consistent with focal mechanisms (Fig. 3).
 293 Principal strain rate orientations retain the same orientation over a broader

294 area, with lower strain rates, that include the Adana basin and the moun-
295 tains north of it (Aladağlar, see Fig. 5). Areal strain indicates extension is
296 dominant in these mountains while both mildly transpressive and transten-
297 sive styles are found in the Adana basin. This may suggest that gravity
298 influences strain distribution between topographic highs and the basin. The
299 westward limit of this zone of E-W extension coincides with the Ecemiş Fault
300 (see Fig. 4). This fault zone has taken up 60 km of left lateral slip since late
301 Eocene and has been under transtension since Miocene (Jaffey and Robert-
302 son, 2005; Akif Sarıkaya et al., 2015; Yıldırım et al., 2016; Umhoefer et al.,
303 2020). The principal strain rate axes rotate to NE-SW compression and NW-
304 SE extension west of the Ecemiş fault, which are respectively parallel and
305 perpendicular to this part of the Taurus mountain range. The Ecemiş fault
306 thus appears to bound a zone of east-west extension related to the escape
307 of the Anatolian plate. Strain rates within the Taurus range, west of the
308 Ecemiş fault, are low (less than 10 nanostrain/year), and areal strain there is
309 dominantly positive, but changes sign toward the coast in the south-western
310 part of the range. This is the only part of Taurus where compressive strain
311 is currently observed.

312 **Figure4**

313 Along the Levant fault, the dominating principal strain orientations (see
314 Fig. 4) are consistent with left-lateral shear on the fault. The GNSS cover-
315 age, however, provides poor kinematic constraints in the region from south
316 of Turkey along the coast towards Israel and, in particular, along the east
317 side of the Levant fault where station coverage is sparse. Some short wave-
318 length variability of the strain rate field, with compressional axes trending
319 largely NW-SE, is evident within Israel, where the GNSS coverage is dense
320 but mostly located on the western side of the Levant fault. The strain rates
321 become less coherent towards the southern tip of Israel. North of Israel the
322 zones of higher extension (positive areal strain) and compression (negative
323 areal strain) do not match the location of the Lebanon restraining bend. This
324 puzzling observation has been reported previously (cf. fig. 8 in Gomez et al.,
325 2020) and was possibly explained by the transfer of the compression onto off-
326 shore faults. Overall, zones of higher strain rate appear to roughly correlate
327 with zones of higher seismic activity in the 0-30 km depth range correspond-
328 ing to crustal seismicity (Fig. 3). We already mentioned that the recently
329 ruptured segments of Çardak Fault and the EAF have been relatively silent
330 before the earthquakes. On the other hand, the zone of E-W extension north
331 of Karatas-Osmaniye Fault (KOF) and east of Çardak Fault (CF) displays

332 relatively high seismic activity. A cluster of seismic activity between Mersin
333 and Bolkardağ also appears as a zone of relatively high strain rate in the
334 GNSS interpolation with positive areal strain indicating extension (see Fig.
335 3 and Fig. 4). However, the orientation and style of the strain tensors de-
336 termined in this area lack consistency and velocities present relatively higher
337 interpolation residuals (Fig. 5). On the other hand, distributed compressive
338 to transpressive deformation between northern Cyprus and the Anatolian
339 coast may explain seismicity beneath the Cilicia basin. Clusters of seismic
340 activity are also present within the Arabian plate and offshore Lebanon in
341 zones of apparently low strain rates, but these areas on the edges of GNSS
342 data coverage are not well constrained in the continuum model interpolation.

343 **Figure5**

344 *3.2. Block Model*

345 Our second modelling effort aims to determine the kinematic behaviour
346 of the Nubia-Cyprus-Anatolia tectonic system in the context of an elastic
347 block-based approach (McCaffrey et al., 2007). Such a block model involves
348 solving an inverse problem where the unknowns are Euler vectors for indi-
349 vidual blocks, uniform strain rate tensor for each block, and coupling ratios
350 on the fault node points. The model can, in principle, be constrained by
351 GNSS velocities, geological fault slip rates and the azimuth of these rates,
352 and earthquake focal mechanisms. Here we only used GNSS data.

353 The block geometry follows the main active fault zones (Levant fault,
354 Cyprus Arc subduction, Kyrenia fault, East Anatolian fault), which are
355 thought to be critical in shaping the regional tectonics (Fig. 6a). The distri-
356 bution of seismicity is another key feature defining some block boundaries.
357 The main differences in block architecture with previous studies result from
358 the definition of a Cyprus block. On one hand, large-scale studies considered
359 Cyprus to be a part of Anatolia and did not feature the Kyrenia range as a
360 block boundary (Reilinger et al., 2006; Gomez et al., 2020). This is justifiable
361 as it would not have been possible to constrain the motion of a Cyprus block
362 with the very limited GNSS data available on the island at that time. On
363 the other hand, a detailed kinematic study of the Hatay triple junction pro-
364 posed connecting the Kyrenia arc to the EAF along the KOF (Özkan et al.,
365 2023) and this implies considering the area between Hatay and KOF as part
366 of the Cyprus block. Inversion results obtained with this block geometry
367 are presented in the appendix and we will show that this assumption results
368 in large misfits. An alternate solution may be drawn taking into account

369 a concentration of mostly extensional focal mechanisms along an N-S trend
370 to the east of the Adana/Cilicia basin, 30 km west of the Levant fault. We
371 assume this trend delineates a block boundary, separating Anatolia and the
372 Cyprus block on its western side from a zone of complex deformation along
373 the Levant and East Anatolian faults (the East Anatolian Shear Zone, Fig.
374 3). As internal block deformation is taken into account in the model (approx-
375 imated as a uniform strain rate field in each block) this deforming zone can
376 be defined as a block that stretches eastward along the East Anatolian fault
377 toward Malatya (Klein et al., 2022). Defining part of the northern bound-
378 ary of this block along Çardak fault appears as an obvious hypothesis after
379 the February 6 earthquakes. Moreover, Çardak (sometimes also called Surgu
380 Fault) and Malatya faults (see Fig. 6a) are known to be active and have been
381 included in previous tectonic models of the triple junction (Westaway, 2003;
382 Sançar et al., 2019; Acarel et al., 2019).

383 **Figure6**

384 To the south of Cyprus lies the Sinai block which is largely offshore. Its
385 motion is crucial for the kinematics of the Cyprus Arc subduction but can
386 only be constrained by velocities along the Levant coast and in the Sinai
387 Peninsula. However, GNSS velocity fields in the Levant and in Southern
388 Sinai do not fit in the same rigid block reference frame. Previous studies of
389 Levant Fault kinematics proposed that the NE part of the Sinai microplate is
390 fragmented in order to account for geodetic slip rates decreasing northward
391 on the Levant fault (Gomez et al., 2020). We thus consider an additional
392 block, referred to as the "Latakia" block, to extend along the Levant coast
393 (dashed blue line in Fig. 6a) north of Israel and compare solutions with
394 and without this additional block. Note that Gomez et al. (2020) considers
395 several blocks west of the Levant Fault. Hence, our Latakia block should
396 be considered, like the Malatya block, as a deformable block. Moreover,
397 south Sinai may be affected by extension around the Gulf of Aqaba but this
398 extension cannot be well accounted for in our model, which simplifies the
399 prolongation of the Levant fault into the Gulf of Aqaba as a vertical fault.
400 We thus removed all GNSS rates south of 30°N for the south Sinai.

401 Along the block boundaries, we defined 5 main dislocation sources, ca-
402 pable of accumulating elastic deformation, on which the coupling ratio will
403 be calculated by inversion (Fig. 6a). The Levant and East Anatolian faults,
404 which obey nearly pure strike-slip motion, are modelled as vertical planar
405 sources. The boundary between the Anatolia and Malatya blocks is simpli-
406 fied as a vertical fault. However, to generate the geometry of dipping faults,

407 such as the Cyprus subduction and Kyrenia fault, we followed published in-
408 terpretations of seismic profiles (Aksu et al., 2005, 2021; Burton-Ferguson
409 et al., 2005; Aksu et al., 2014a; Calon et al., 2005; Hall et al., 2005; Welford
410 et al., 2015; Feld et al., 2017). In addition, we utilized the seismicity of
411 the region to compile earthquakes greater than $M_w = 2.8$. The earthquake
412 locations validate the geometry of the main subduction seismogenic zone be-
413 tween Sinai and Cyprus down to a depth of 40 km but do not help define the
414 geometry at the depth of Kyrenia fault between Cyprus and Anatolia (Fig.
415 6b).

416 We conducted a series of synthetic tests to determine the optimal spatial
417 resolution of node points for the slip rate distribution, which was determined
418 by the spatial coverage of the GNSS data along both strike and dip directions.
419 To achieve this, we utilized a checkerboard test, in which we divided the
420 main thrust interface south of Cyprus into planar cells, and monitored the
421 level of recovery of the given slip rate boundary conditions using synthetic
422 GNSS velocities at the same geographic locations as our data. We tested
423 two different average cell sizes for the thrust interface: one with an average
424 cell size of 35 km^2 , and the other with an average cell size of 10 km^2 . The
425 tests were carried out without any synthetic observation noises. Our results
426 indicated that the test conducted with larger patches had slightly better
427 misfits than the one consisting of finer patch resolution. Fig. S1 in the
428 supplementary displays the checkerboard test solutions.

429 We evaluate inversion results using three different block geometries. It is
430 crucial to emphasize that the models were inverted employing the same veloc-
431 ity field. In Model 1, we employed the geometry introduced by (Özkan et al.,
432 2023) around the triple junction. This model does not include a Malatya
433 block between Anatolia and the East Anatolian Fault (EAF). Additionally,
434 the Karataş-Osmaniye fault (see Fig. 7a) connects northeastward with the
435 EAF, extending the boundary between Anatolia and Cyprus, and adding
436 part of Hatay to the Cyprus block. Model 3 is the block model illustrated
437 in Fig. 6a. It includes a Latakia block in an attempt to account for the
438 fragmentation of the Sinai plate Gomez et al. (2020). Model 2 is based on
439 Model 3, without a Latakia block, the extent of which is here considered part
440 of the Sinai plate. As indicated in Table 2, the residuals exhibit a substan-
441 tial improvement in Models 2 and 3, which consider a Malatya block. This
442 notable improvement is primarily attributed to larger misfits in Model 1 for
443 stations in the Hatay region and Cyprus when these stations are forced to
444 be part of the same block.

Table 2: Results of inversions for different block models. χ_v^2 is the reduced chi-square (χ^2 divided by the number of Degrees of Freedom (DOF)).

Model Number	DOF	χ^2	χ_v^2
1	696	4219.25	6.06
2	662	1868.62	2.82
3	650	1761.52	2.71

445 However, the improvement associated with the assumption of a Latakia
 446 block is subtle. Model 3 has a slightly lower misfit than Model 2 but with
 447 a small reduction of the chi-2 over the degree of freedom ratio (Table 2).
 448 An F-test, which is a powerful statistical method that allows us to assess
 449 whether the variability of the variances is significantly different, indicates
 450 this improvement is not significant (Table 2).

451 **Figure7**

452 Determining robust Euler pole parameters is of utmost importance for
 453 addressing the horizontal motion of the region. This problem is complicated
 454 by the fact that a large part of the Sinai plate is underwater and that the
 455 prolongation of the Sinai plate along the Levant coast (where GNSS stations
 456 are located) may be deforming. Euler poles of Sinai relative to Anatolia and
 457 to Arabia were obtained by the block model inversion. In order to estimate
 458 the Euler pole of the Nubia plate with respect to Anatolia we combined
 459 our determination of the Arabia-Anatolia pole with a Nubia-Arabia pole
 460 calculated in the ITRF No Net Rotation reference frame by Altamimi et al.
 461 (2017). The Nubia poles from this study, and Reilinger et al. (2006) are
 462 similar to each other, albeit with a slight difference in the rotation rates.
 463 The location of the Euler pole of Reilinger et al. (2006) for Sinai relative
 464 to Anatolia and ours are also close to each other. The rotation rate of the
 465 Reilinger et al. (2006) pole, however, is markedly faster resulting in a slower
 466 subduction velocity in our model. The data we used to constrain the motion
 467 of the Sinai block are essentially the same as in the previous studies, but we
 468 excluded data from South Sinai (below 30°N) as these cannot be fit in the
 469 same rigid reference frame, and this explains in large part the differences.
 470 The pole we determined provides a better fit of GNSS data along the Levant
 471 coast, but a worse fit of the GNSS data in the southern part of Sinai. We
 472 believe that this pole provides a better description of the motion of the
 473 Mediterranean seafloor as it subducts beneath Cyprus (Table 3).

474 After an Euler pole and a uniform strain rate tensor are estimated for each

Table 3: Euler pole parameters estimated by this study and those from previous studies.

Plate Pair	Lat (°)	Lon (°)	Ω (°/Myr)	Reference
SIN - AN	31.77	37.91	-0.591	this study
SIN - AN	31.99	36.01	-1.185	Reilinger et al. (2006)
CY - AN	37.61	32.73	0.717	this study
NU - AN	31.67	34.83	-1.205	Reilinger et al. (2006)
NU - AN	31.69	34.88	-1.021	this study Altamimi et al. (2017)

Abbreviations: SIN: Sinai, AN: Anatolia, NU: Nubia, CY: Cyprus

475 block, a series of nonlinear inversions (i.e., grid search and simulated anneal-
 476 ing (Press et al., 2007)) has been run iteratively to solve the coupling ratio
 477 on each node point. The Green’s function that coincides with the location of
 478 the GNSS stations on the surface is determined with a rigorous approach to
 479 discretize the planar fault into rectangular patches (Okada, 1992). For the
 480 parametrization of fault coupling, we express the coupling ratio as constant
 481 between the surface and depth z_1 (an inversion parameter at each node)
 482 and decaying exponentially below z_2 where the fault starts fully slipping, as
 483 proposed by Wang et al. (2003).

484 Fig. 8a represents the block motions along the boundaries defined as
 485 dislocation sources in Model 3. As the residuals we obtained are relatively
 486 small, we present histogram of both the north and east residuals in Fig. 8b.
 487 On the Levant fault, the slip rate decreases steadily from south to north. It
 488 accommodates a 4.7 ± 0.6 mm/yr slip rate from the Gulf of Aqaba to the Dead
 489 Sea with an almost purely left lateral strike-slip regime. At the Lebanese
 490 restraining bend, slip remains dominantly strike-slip at a 3.0 ± 6 mm/yr rate,
 491 with a poorly constrained 0.8 ± 0.7 mm/yr compressional rate. The Cyprus
 492 arc accommodates 3.5-6.2 mm/yr convergent rates reducing progressively
 493 from west to east. The motion of the Kyrenia fault, on the other hand, is
 494 mainly left lateral strike-slip from the northwesternmost tip to the east of
 495 the island with rates of 3.2-4.2 mm/yr. Although the slip rate along the
 496 western prolongation of the Kyrenia fault also obeys a left lateral strike-
 497 slip behaviour, the spatial distribution of our dataset may not be considered
 498 capable of resolving this particular region. Along the boundary between the
 499 Anatolian and Cyprus blocks on one side and the so-called Malatya block on
 500 the other side, the inversion indicates a significant ~ 1.3 mm/yr extensional

501 motion, which is in agreement with the predominantly extensional style of
502 the earthquakes (see Fig. 6a). Meanwhile, there are relatively larger velocity
503 residuals on the left side of the boundary, roughly coinciding with Adana
504 Basin, that may represent active deformation not properly modelled with
505 the assumed block geometry. Where the block boundary changes its azimuth
506 from N-S to E-W and along the Çardak fault, the slip rate is an almost left
507 lateral strike-slip behaviour with a 2.0 ± 1.0 mm/yr rate. The Malatya fault,
508 which extends from the eastern tip of the Çardak fault towards the north, has
509 also left-lateral strike-slip motion accounting for 1.7 ± 1.2 mm/yr. The motion
510 on the East Anatolian fault zone, on the other hand, decreases from 6.2 ± 1.2
511 to 5.2 ± 1 mm/yr from the northernmost tip of the EAF to Kahramanmaraş
512 triple junction where it connects with the Levant fault. Some additional shear
513 is taken up by internal deformation of the Malatya block. Furthermore, the
514 block motions for the two alternative model scenarios are provided in the
515 supplementary document (Figs. S2 and S3).

516 **Figure8**

517 Most block boundaries inverted for dislocation sources appear fully locked
518 down the depth z_1 . The only notable exception is the western part of the
519 Kyrenia fault in Cyprus, but this result may not be reliable because of the
520 distribution of velocity data, all located south of the fault with few points
521 near the fault zones. The estimated z_1 value for the Levant fault is con-
522 sistentlly around 10 km. However, the inversion result indicates a depth of
523 approximately 15 km (following the convention of Wang et al. (2003)) for z_2
524 at the segments north of the Dead Sea, while it is 20 km at the segments south
525 of it. For the EAF, the z_1 value decreases from 20 to 13 km from south to
526 north, while z_2 remains relatively constant at 25 km. The locking behaviour
527 of the Çardak fault is homogeneous along strike with $z_1=8$ km and $z_2= 20$
528 km (see Fig. 9a). On the Cyprus arc subduction the inversion estimates a
529 z_1 value around 20-25 km depth, but due to the lack of GNSS data for the
530 offshore part, the uncertainties of the coupling coefficient increase with the
531 distance between the node points and Cyprus (Fig. 9b-c).

532 **Figure9**

533 **4. Discussion**

534 We discuss our solutions and describe some implications of them including
535 (1) the shear partitioning between the Cyprus subduction and Kyrenia fault;
536 (2) the effect of this partitioning system around the East Anatolian shear zone

537 toward the Kahramanmaraş triple junction; (3) a comparison of our solution
538 with the previous studies around the Levant fault and the prolongation of
539 distributed deformation for the northern part of the Levant fault; and (4) the
540 results of our interseismic fault coupling model and coseismic slip behaviour
541 of the 2023 Kahramanmaraş earthquakes.

542 *4.1. Cyprus subduction, Kyrenia range and Taurus*

543 The slip characteristics on both the Cyprus arc and Kyrenia range indi-
544 cate that ongoing shear partitioning is the dominant regime for the area. The
545 subduction is still active despite an incipient collision with the Eratosthenes
546 seamount southwest of Cyprus, with near frontal convergence at a 6.0 mm/yr
547 rate. The continuum deformation field (Fig. 4) obtained in and around the
548 Taurus mountain range shows little shortening in the upper crust and, off-
549 shore, convergence between Taurus and Cyprus across the western part of
550 the Cilicia basin is less than 1 mm/yr. The dominantly left-lateral strike-slip
551 motion we find on the Kyrenia fault with a rate of 3.5-4.2 mm/yr, suggests a
552 nearly perfect shear partitioning between the subduction and Kyrenia range.
553 However, the distribution of seismicity in the area suggests the Kyrenia Fault
554 may not be the only fault system involved. The Anatolia-Cyprus pole we cal-
555 culated would also predict pure strike-slip relative motion on a fault running
556 along the coast (the coast nearly follows a small circle for this pole) in the
557 prolongation of The Kozan fault. This fault has been proposed to move
558 at rates of 4 to 8 mm/yr based on sediment depocenter migration (Aksu
559 et al., 2014b). However, the GNSS residuals (although consistent in orien-
560 tation with left-lateral motion along the coast, see Fig. 5) are barely above
561 noise level at about 1 mm/yr. Most probably, the strike-slip motion between
562 Cyprus and Anatolia is dominantly taken up along the Kyrenia fault and its
563 NE prolongation (the KOF).

564 The Euler poles published by previous studies (Reilinger et al., 2006;
565 Gomez et al., 2020) only predict moderate obliquity on the Cyprus subduc-
566 tion, at about 20° south of Cyprus, which corresponds to the critical obliquity
567 threshold for the onset shear partitioning above a subduction zone (McCaf-
568 frey, 1992). The rotation motion of Anatolia vs. Sinai and the arc shape of
569 the subduction cause a lateral variation of obliquity so that 20° is a minimum
570 value, but shear partitioning above subduction should not, in principle, lower
571 slip vector obliquity below 15-20° (McCaffrey, 1992). It is thus possible that
572 forces applied on the E and W boundaries of the Cyprus block play a role.

573 The Cyprus block interacts with the Malatya block at its NE end and kine-
574 matic conditions on this boundary are extensional. It is thus possible that
575 the forces applied in this zone near the triple junction influence the motion
576 of the Cyprus block and particularly the amount of strike-slip taken up by
577 the Kyrenia fault.

578 The fault coupling model of the Cyprus arc subduction is characterized by
579 full locking from the surface to 20 km, which is consistent with Welford et al.
580 (2015); Feld et al. (2017), transitioning to partial locking between 20 and
581 30 km. The seismic activity during the instrumental period aligns with our
582 coupling model, with the majority of earthquakes occurring within the 12-20
583 km depth range of the Cyprus subduction zone (see Fig. 6b). Conversely,
584 the Kyrenia fault exhibits a distribution of locking extending from 0 to 7
585 km, transitioning to freely slipping behaviour beyond that depth. However,
586 seismic activity on this fault is too low to provide an independent constraint
587 on the depth range of the seismogenic zone.

588 *4.2. East Anatolian shear zone*

589 In the vicinity of the triple junction the shear between Anatolia and Ara-
590 bia is distributed over a zone that we defined as a block (the Malatya block).
591 On the East Anatolian fault, we obtain 5.1-6.2 mm/yr strike-slip rates that
592 are lower than most previous studies (Aktuğ et al., 2016; Reilinger et al.,
593 2006). However, analyses of a high-resolution velocity field obtained by com-
594 bining GNSS and InSAR data (Weiss et al., 2020) found a laterally varying
595 interseismic loading rate on the EAF (Güvercin et al., 2022; Li et al., 2023).
596 The strike-slip rate on the Malatya fault we obtained (1.7 mm/yr) is consis-
597 tent with previous studies (Aktuğ et al., 2013). The strike-slip rate on the
598 Çardak fault we obtained from the block model is 1.8 mm/yr and is com-
599 parable with a 2 mm/yr slip rate calculated from geomorphological offsets
600 (Westaway, 2003). In addition, the principal strain rate orientations between
601 these two faults indicate left-lateral shear co-linear with shear along the East
602 Anatolian fault zone (see Figs. 8 and 4) with an average rate of 35 nanostrain
603 per year and a small extensional component (Fig.3). Assuming simple shear,
604 the internal deformation of the Malatya block over an average width of 50 km
605 amounts to about 1.7 mm/yr. The strike-slip motion between Anatolia and
606 Arabia thus appears to be distributed between the East Anatolian fault, the
607 faults defining the northern boundary of the Malatya block and the internal
608 deformation of the block. These three components add up to 8.5-9.7 mm/yr,

609 which is consistent with previous estimations of Arabia/Anatolia plate mo-
610 tion (Reilinger et al., 2006; Aktuğ et al., 2016; Bletery et al., 2020). The
611 block boundaries we propose differ from the geometry proposed by Özkan
612 et al. (2023) in that they connect the Karataş-Osmaniye fault to the EAF
613 near Kahramanmaraş and thus do not allow shear partitioning east of the
614 triple junction. Their geometry cannot account for the loading of Çardak
615 Fault which was ruptured during the second earthquake of the Feb 6, 2023,
616 earthquake doublet (Toda et al., 2023; Barbot et al., 2023). Our solution with
617 an N-S transtensional boundary connecting to Çardak fault has a lower misfit
618 and also better represents mapped active faults (Emre et al., 2018)(Figure
619 1b). We conclude that part of the EAF motion is partitioned from the main
620 fault in a broader zone around the triple junction, resulting in decreased
621 interseismic loading rates on the main strand of the EAF.

622 *4.3. Levant fault zone*

623 Block-based model inversion indicates that the Levant fault accommo-
624 dates a 3.5-4.7 mm/yr slip rate, and it decreases slightly but steadily from
625 south to north. This result is consistent with previous studies such as
626 Al Tarazi et al. (2011); Sadeh et al. (2012); Gomez et al. (2020); Hamiel and
627 Piatibratova (2021); Li et al. (2024). Gomez et al. (2020) found a decreasing
628 motion northward from 5.0 mm/yr to 2.2 ± 0.5 mm/yr as they consider two
629 block boundaries transferring part of the Levant fault motion to hypothet-
630 ical offshore structures. Our inversion results find less transfer of motion
631 to offshore faults. For instance, only 0.7 ± 0.7 mm/yr are transferred to the
632 western boundary of the Latakia block compared to 1.5 ± 0.5 mm/yr for the
633 corresponding block boundary in Gomez et al. (2020). However, uncertain-
634 ties are large so that inversion results remain compatible. Several factors may
635 contribute to a lower velocity on the offshore block boundary and a higher
636 uncertainty in our results. Our data set is different and possibly with a higher
637 noise level as it combines several different studies, a different inversion code
638 is used that allows internal block deformation, and block boundaries also
639 differ.

640 *4.4. Interseismic fault coupling model and 2023 Kahramanmaraş earthquake* 641 *doublet*

642 During the Feb 6, 2023 sequence, ruptures occurred on the southern and
643 northern boundaries of Malatya block. The main shock (Mw 7.8) occurred
644 on the East Anatolian and Levant faults while the large Mw 7.6 aftershock

645 occurred on Çardak Fault (CF), corresponding to a moment magnitude about
646 half of that of the main shock (Toda et al., 2023; Hussain et al., 2023). The
647 occurrence of these events shows that both boundaries are seismically active
648 and present a high seismic hazard. Our interseismic coupling inversion results
649 find both faults are fully and homogeneously locked down to at least 10 km
650 depth, but we cannot exclude that heterogeneities may be present but not
651 resolvable with the GNSS data set we used. Based on InSAR and seismicity
652 distributions, previous studies found shallow locking depth and aseismic creep
653 on the EAF east of E038.5° longitude (Bletery et al., 2020; Konca et al.,
654 2021; Cakir et al., 2023). Moreover, the depth of locking near the bend
655 between EAF and Levant Fault (Fig. 9a) may be overestimated because of
656 the simplified geometry of the block boundary where two faults branches are
657 in fact present (the Nurdaği-Pazarcık Fault and the Pazarcık segment of the
658 EAF). Several research groups worked on the coseismic slip distributions on
659 both EAF and CF using seismological records, SAR interferometry, optical
660 (Sentinel-2) images, and coseismic GNSS data and various inversions and
661 joint inversions have been published using these data (Barbot et al., 2023; Li
662 et al., 2023; Melgar et al., 2023; Jia et al., 2023; Toda and Stein, 2024; Chen
663 and Zhou, 2024). The average distribution of coseismic slip with depth is
664 consistent with a locking depth of 10-15 km for both faults with a progressive
665 transition down to 20 km (Jia et al., 2023). These coseismic slip models
666 also find that the smaller earthquake has, in fact, larger displacements but
667 over a smaller rupture length. This implies, taking into account interseismic
668 loading rates, that the recurrence interval is very different on these two faults.
669 Estimates of surface displacement from Sentinel-2 image correlation are 4 m
670 on average over a large part of the main shock rupture with a local maximum
671 of about 7 m and 6 m on average for the aftershock with a maximum of 8-9
672 m (Barbot et al., 2023; Hussain et al., 2023). Using our interseismic backslip
673 estimates, recurrence intervals of 750 to 1500 years are inferred for the East
674 Anatolian Fault and from 3000 to 5000 years on the Çardak Fault. It thus
675 appears that triggering of the Çardak Fault does not occur each time a large
676 earthquake occurs on the East Anatolian Fault, and probably does so less
677 than once every three cycles on the EAF. Moreover, the Mw 7.8 earthquake
678 is a multi-segment rupture (Barbot et al., 2023), and such events have longer
679 recurrence intervals than those estimated for characteristic earthquakes on
680 individual segments. Estimates from single segments range from 100 years
681 to about 900 years along the East Anatolian Fault with the longest intervals
682 and largest maximum magnitude (Mw 7.4) in the Kahramanmaraş triple

683 junction area (Güvercin et al., 2022). It is important to note that that study
684 took into account a westward decrease of interseismic loading rates along
685 the EAF segments. The duration of seismic cycles involving a multi-segment
686 rupture is even longer. Their estimation depends on complex scenarios that
687 combine multi-segment and single-segment ruptures and ranges from 700 to
688 2500 years (Karabulut et al., 2023). We conclude that shear partitioning
689 in the Kahramanmaraş triple junction is one of the factors contributing to
690 very long earthquake cycles on the EAF. Moreover, the earthquake hazard
691 on secondary faults must not be ignored even though large events on these
692 slower faults may have even longer recurrence intervals.

693 5. Conclusion

694 Acquisition of new GNSS data on Cyprus and southern Turkey brings
695 new insight into the deformation of the region around the Kahramanmaraş
696 triple junction. It shows that the present-day deformation of Cyprus may
697 be understood as a shear partitioning system between the Cyprus arc sub-
698 duction and the Kyrenia fault, which appears to be a dominantly strike-slip
699 boundary. Thus, the incipient collision with the Eratosthenes Seamount may
700 not have yet perturbed much the kinematics of the Cyprus subduction. On
701 the other hand, the northeast continuation of the shear partitioning system
702 toward the Anatolia/Arabia collision zone brings further complexity to the
703 Kahramanmaraş triple junction.

704 In the Anatolia-Arabia plate boundary, our study demonstrates that part
705 of the motion on the East Anatolian Fault is distributed away from the main
706 fault in the vicinity of the triple junction, as was previously shown for the
707 Levant fault in the Arabia-Nubia plate boundary (Gomez et al., 2020). Thus,
708 the EAF is not the only deformation source in the East Anatolian shear zone
709 as deformation is also distributed on secondary faults such as Çardak and
710 Malatya faults. The earthquake sequence that occurred on February 6 2023
711 emphasizes the earthquake hazard presented by secondary faults in complex
712 plate boundary zones. In the study area, the kinematics of faults offshore
713 of the Levant and Hatay coasts still need consideration. On land, the slip
714 rates calculated on the faults bounding the Malatya block result in very long
715 earthquake cycles of 750-2000 years for the part of the EAF that ruptured
716 recently and probably 3000-5000 years for Çardak Fault. How such rare
717 events may be considered in hazard assessment poses questions.

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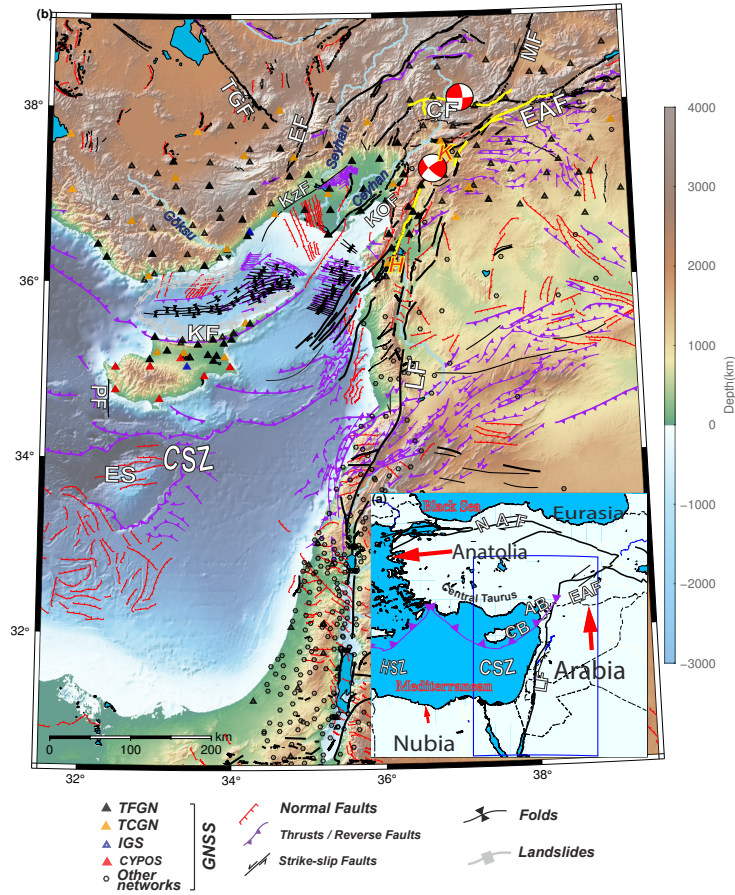


Figure 1: a) Tectonics of the Eastern Mediterranean and fundamental features in the scope of this study. Abbreviations: EAF: East Anatolian Fault, NAF: North Anatolian Fault, LF: Levant Fault, CSZ: Cyprus Subduction Zone, HSZ: Hellenic Subduction Zone, AB: Adana Basin, CB: Cilicia Basin b) Tectonic structures and GNSS sites around the region. Structures digitized from Emre et al. (2013, 2018); Şengör and Zabcı (2019), the structures around Adana/Cilicia basins are taken from Aksu et al. (2005); Burton-Ferguson et al. (2005); Aksu et al. (2014a, 2021, and cited studies therein). The main boundaries are represented with thicker lines. Focal mechanisms belong to 06 Feb 2023 $M_w=7.8$ and $M_w=7.6$ Kahramanmaraş Pazarcık and Elbistan earthquakes. The surface rupture geometry, shown in yellow lines, is taken from the U.S. Geological Survey (USGS) with Data Release (doi: 10.5066/P985I7U2). Abbreviations: K=Kahramanmaraş triple junction, H=Hatay triple junction, KF: Kyrenia Fault, ÇF: Çardak Fault, MF: Malatya Fault, EF: Ecemiş Fault, KOF: Karataş-Osmaniye Fault, TGF: Tuz Gölü Fault, KZF: Kozan Fault, PF: Paphos Fault, ES: Eratosthenes seamount, IGS: International GNSS Service, TCGN: Turkey Continuous GNSS Network, TFGN: Turkey Fundamental GNSS Network, CYPOS: Cyprus Positioning System. We consistently employ the same abbreviations throughout all figures in this text, adhering to those presented in this figure, as necessary.

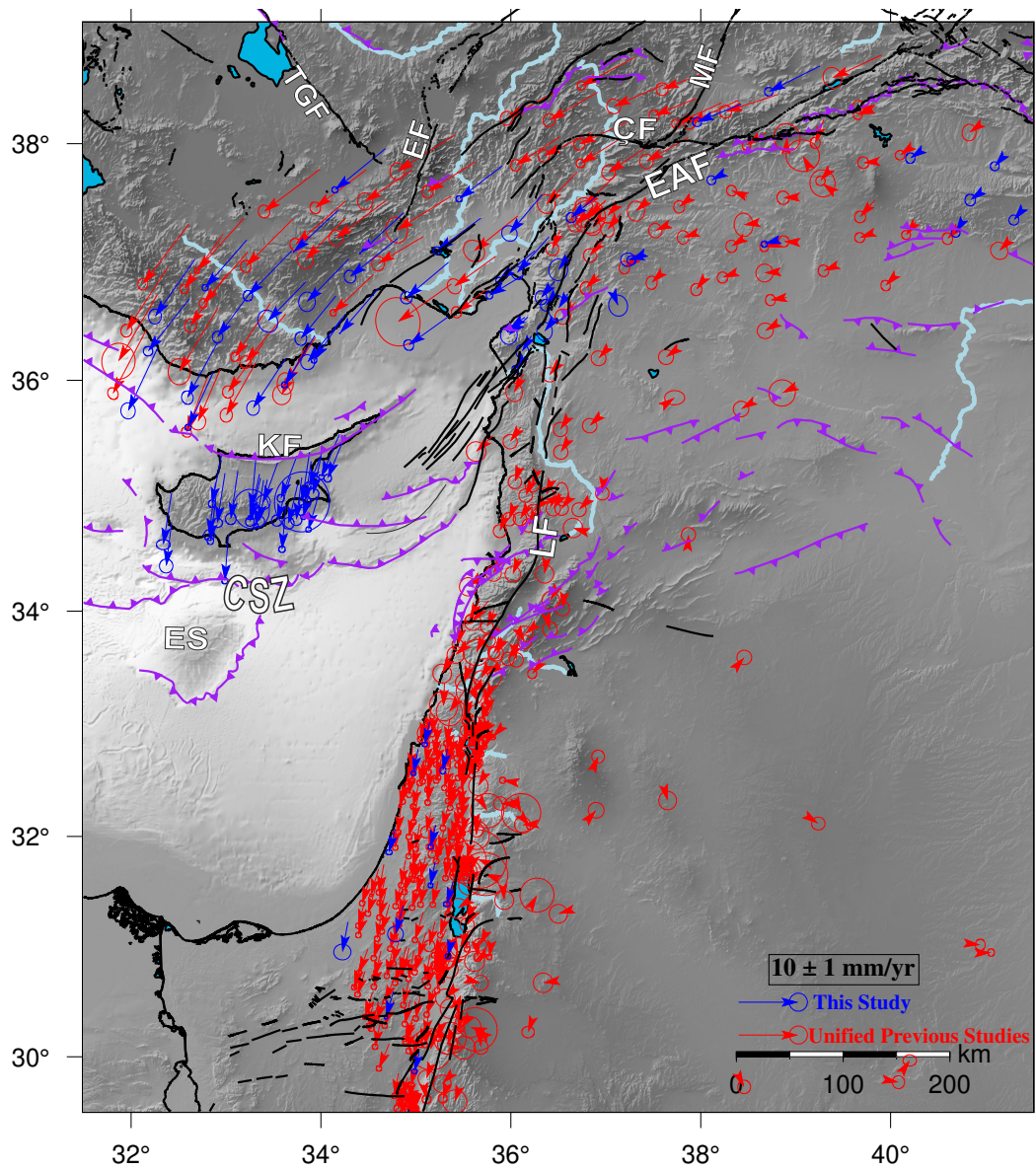


Figure 2: Unified GNSS velocity field with respect to the fixed Arabian frame. Newly derived rates are depicted by blue arrows, while red arrows indicate rates from previous studies.

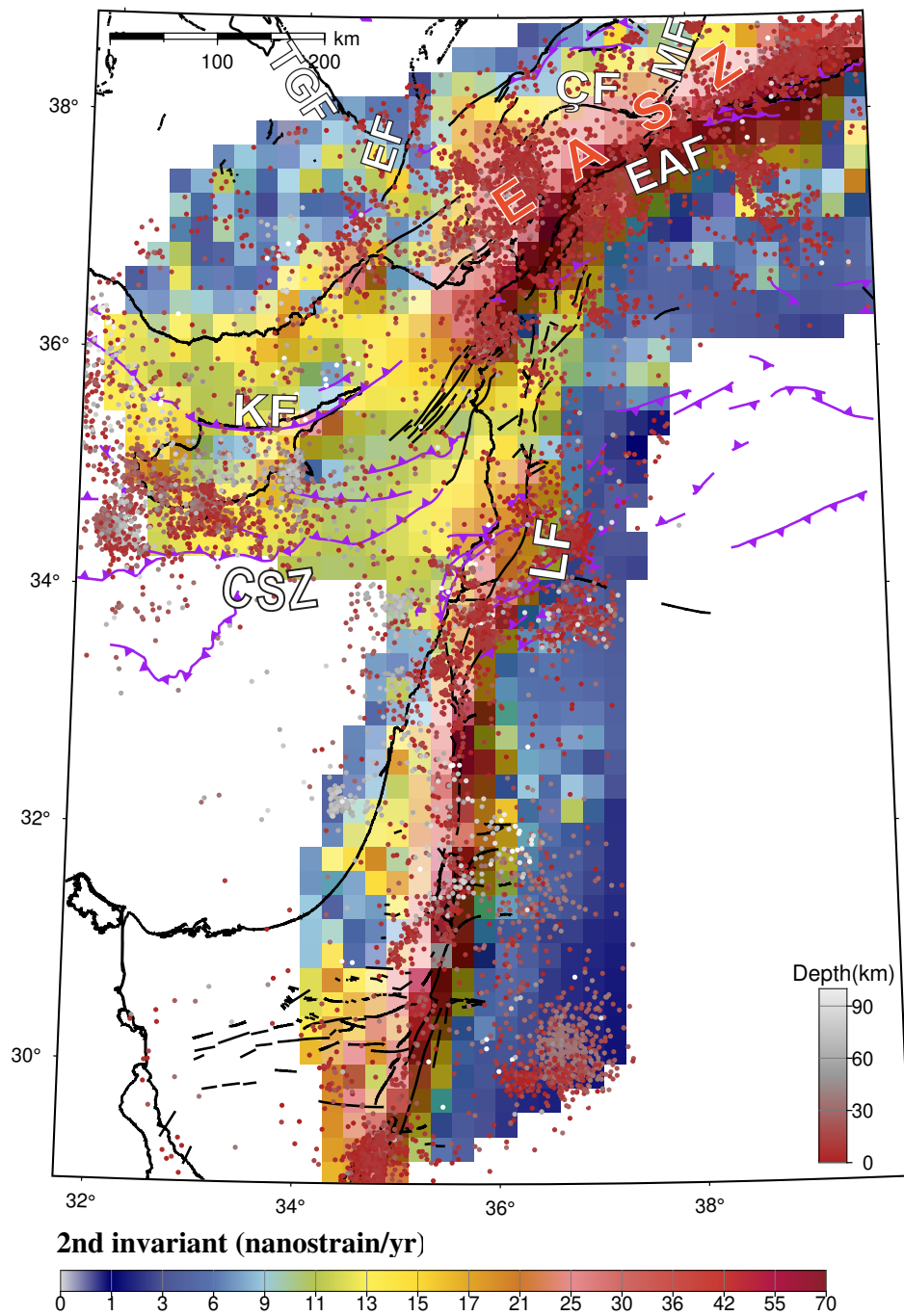


Figure 3: Seismicity, colour-coded by depth, and the second invariant of the strain rate tensor. The seismicity catalogue was taken from (KOERI, 2001; <http://www.koeri.boun.edu.tr>). EASZ: East Anatolian Shear Zone

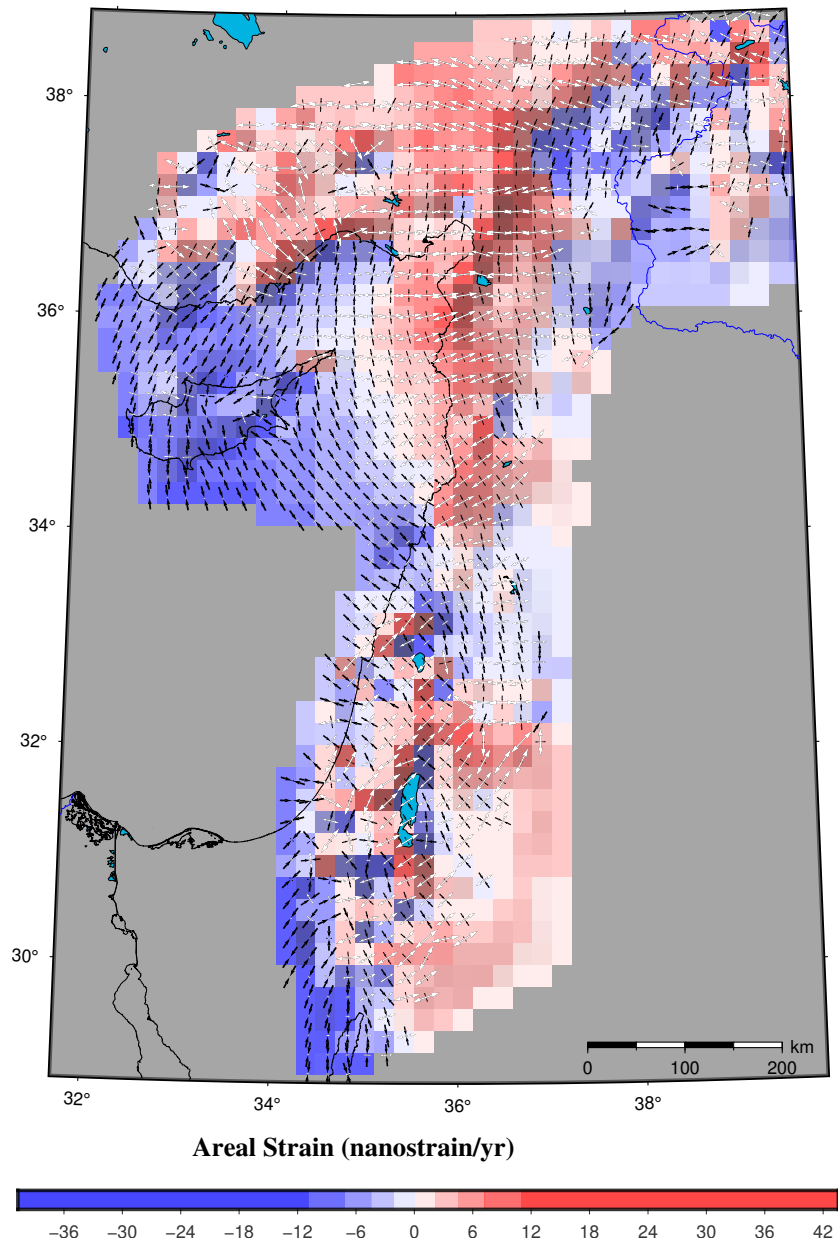


Figure 4: Strain rate field of the area. Arrow crosses are the principal strain rate tensor components. The black arrow belongs to the compression component of each tensor while the white ones are the extensional component. Magnitudes of the principal rate crosses were normalized. The grid represents the areal strain change that accounts for the trace of the tensor for each cell (Blue means that the dominant force of the cell is compression, while red implies extension).

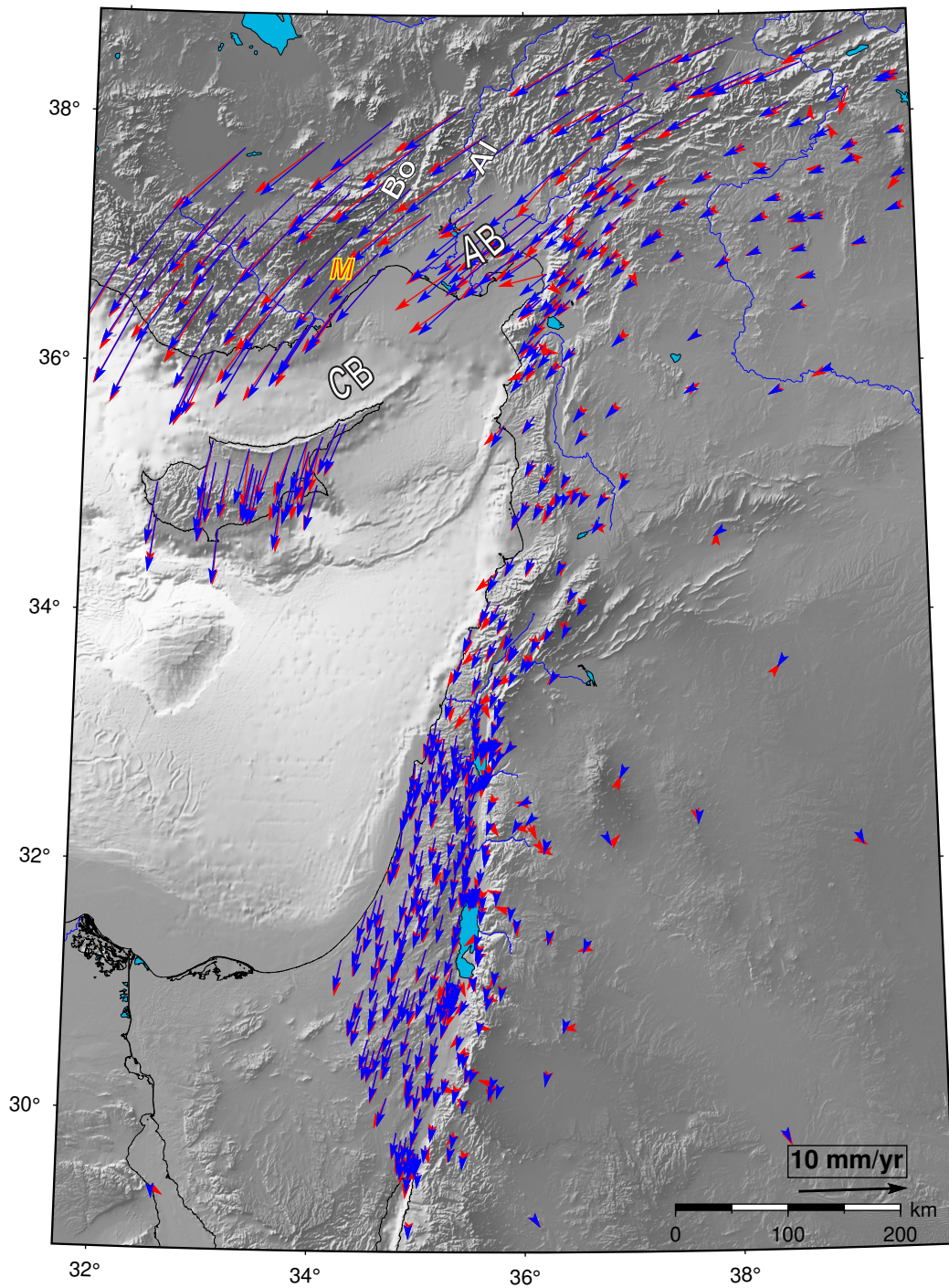


Figure 5: Observed (red) and predicted (blue) GNSS velocities coming from continuum kinematic model inversion. Abbreviations: Bo: Bolkardağ, Al: Aladağlar.

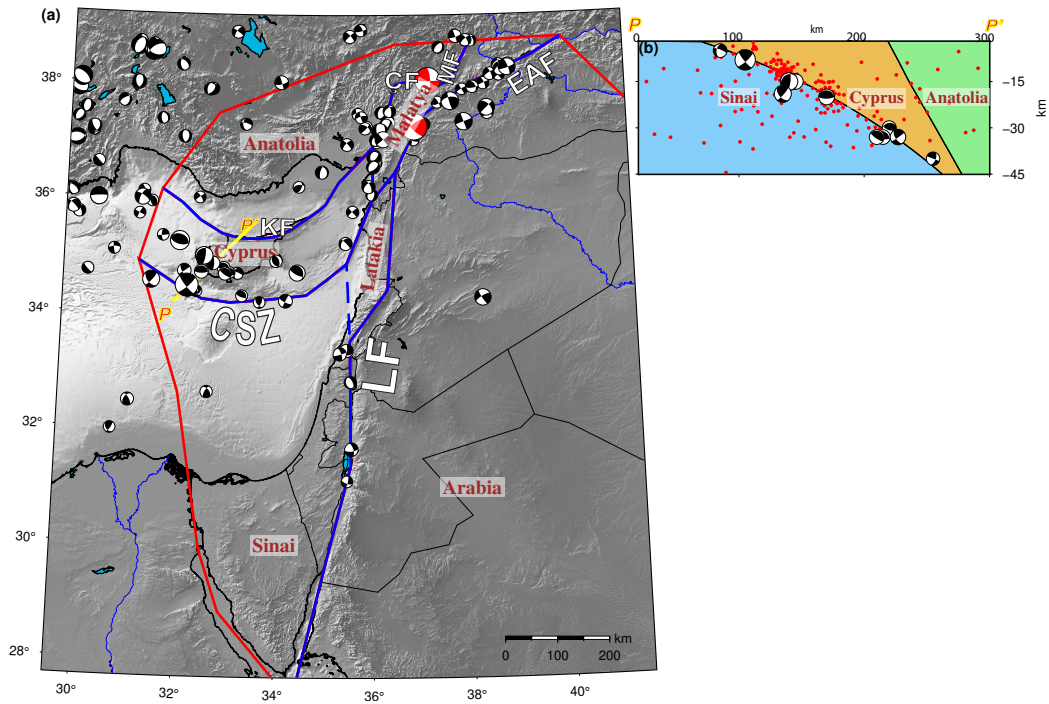


Figure 6: a) Block geometry and seismic activity around the region. Blue lines represent the boundaries defined as dislocation sources, red lines correspond to the other block boundaries which do not accumulate elastic strain. Focal mechanisms represent the earthquakes $M_w \geq 4.5$ between 1976-2022 (Ekström and Nettles, 1997) (the Feb 6 2023 earthquakes are highlighted in red). They were scaled according to their magnitudes. b) The cross-sectional view (marked as P-P' in the map) from the northern tip of the Cyprus Arc to the Kyrenia range (~ 35 km width). Focal mechanisms (Ekström and Nettles, 1997) and red dots (KOERI, 2001; <http://www.koeri.boun.edu.tr>), which are the earthquakes that coincide with the domain of the cross-section, were projected onto the section.

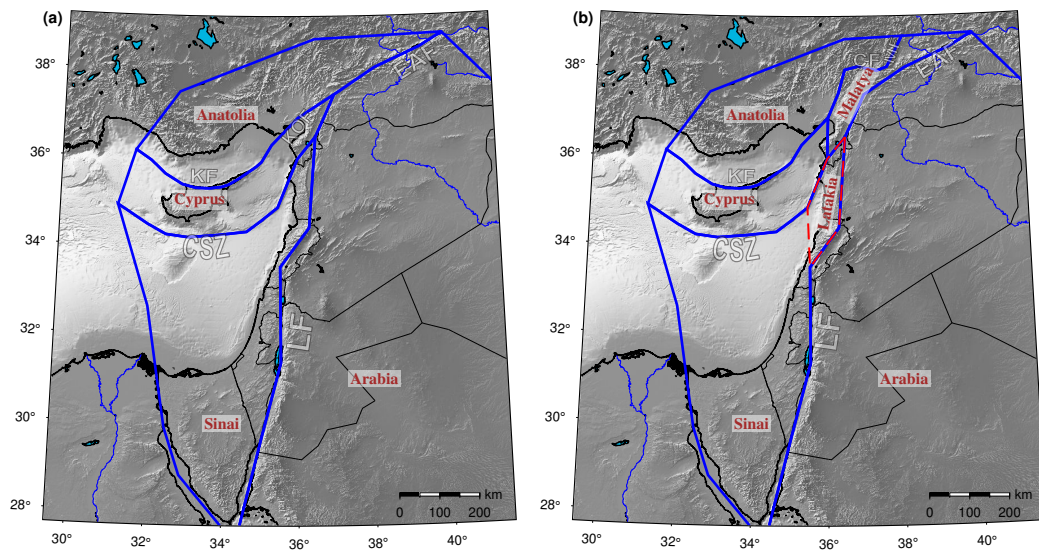


Figure 7: Comparing Diverse Block Geometries: a) This model adheres to the fault geometries proposed by Özkan et al. (2023) for Anatolia, without considering the Malatya block. b) The blue solid lines delineate the block geometry consisting of five blocks (Model 2), while the red dashed line illustrates the inclusion of the Latakia block in Model 3, respecting the primary boundaries outlined in Model 2.

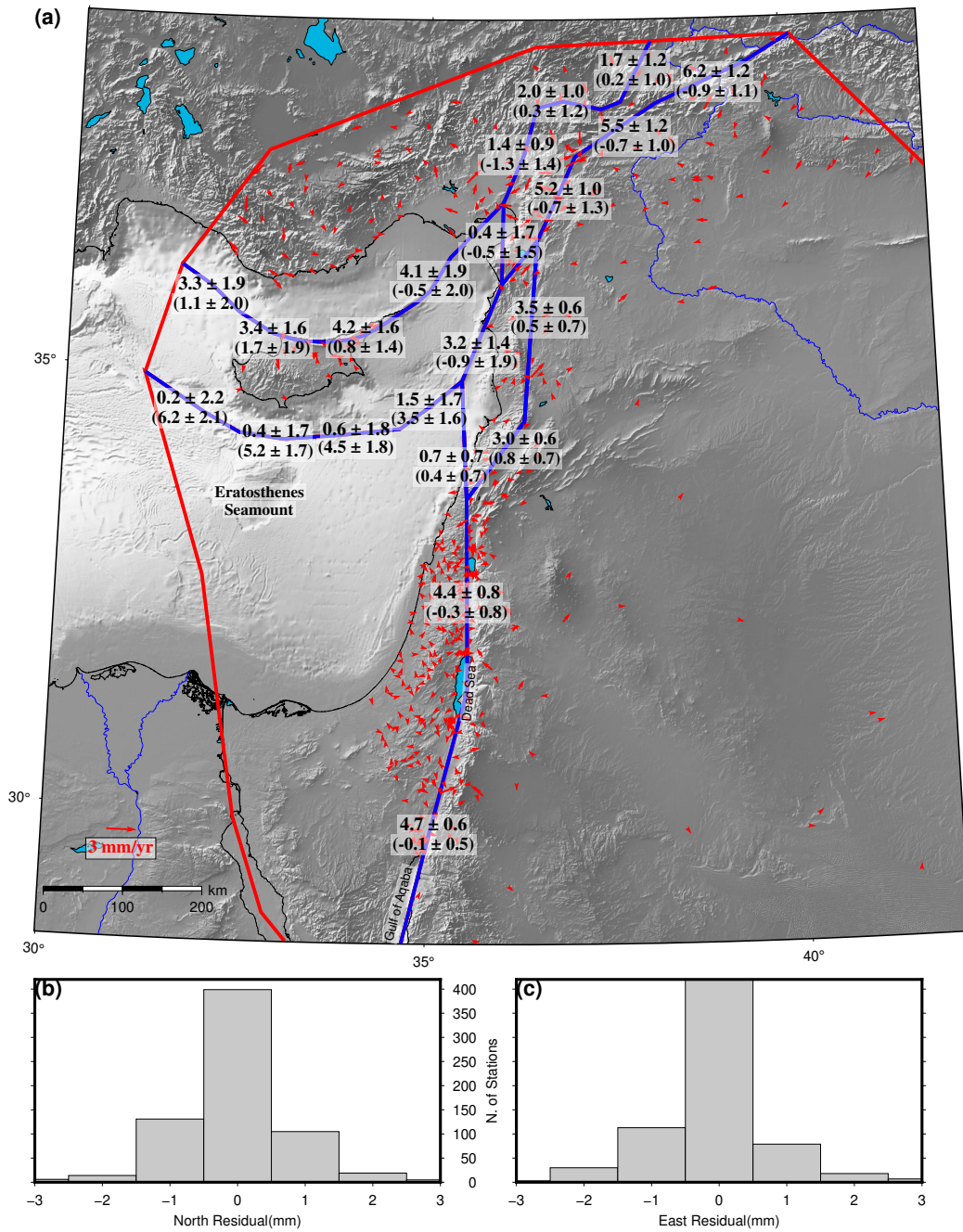


Figure 8: a) Block motions and residual velocities. The values with no parentheses are the strike-slip rates (Positive means left lateral) and the slip rates within the parentheses are convergence rates (positive means compression). The red arrows are the residual velocities coming from model 3(best-fitting model). b) and c) panels show the histogram view of the north and east velocity components residuals.

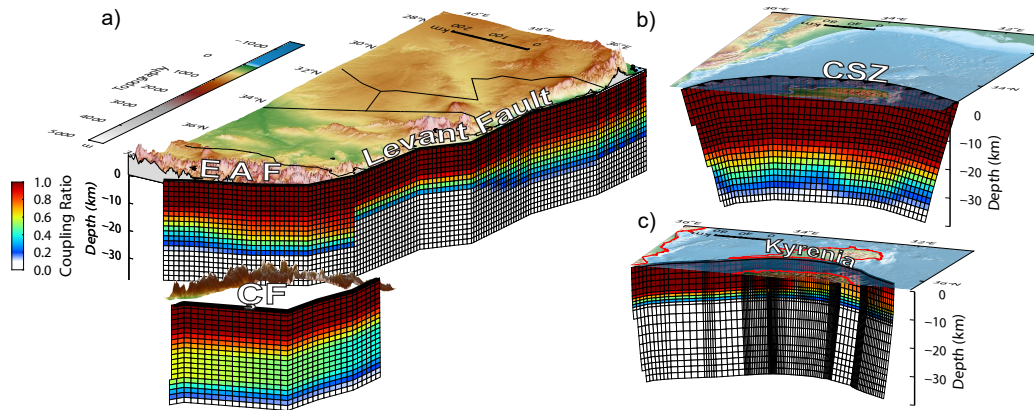


Figure 9: The locking distribution on the dislocation sources within the block model. a) Levant, East Anatolian, and Çardak Faults (and the prolongation of the northwestern boundary of the Malatya block), b) Cyprus Subduction Zone, and c) Kyrenia fault.