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

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Abstract

Triple junctions involving non-subductable plates extend beyond local implications, crucial for studying the geology of convergent plate boundary zones. However, kinematic models overlook Cyprus-Anatolia motion due to limited geodetic constraints. Our study encompasses 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 velocities, con-

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structuring 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 rate ~ 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 3.2 - 4.2 mm/yr. 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. The relative strike-slip motion between Arabia and Anatolia is partitioned between the East Anatolian Fault (slip rates 5.1 - 6.2 mm/yr) and some secondary faults such as Çardak and Malatya faults (slip rates 1.9 - 1.7 mm/yr) 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 which can be defined as the East Anatolian shear zone. A shear partitioning system exists around the Kahramanmaraş triple junction, from Cyprus to southeast Turkey. Strain rates appear relatively small in the Taurus range and Adana/Cilicia basin, transitioning from extensional/transtensional to compressional from east to west. The up component of GNSS velocities on the Taurus karstic plateau reaches 1.2 mm/yr, lower than Quaternary uplift rates on its southern edge. We examine Taurus uplift and Adana/Cilicia basin subsidence, considering slow convergence through earthquake distribution, seismic tomography, and modeling.

1. Introduction

The recent tectonics of the Eastern Mediterranean results from the interaction of three giant tectonic plates, Arabia, Africa and Eurasia (McKenzie et al., 1970; McKenzie, 1972; Şengör, 1979; Şengör et al., 1985). During the middle Miocene, Arabia was separated from Africa along the left-lateral Levant (or Dead Sea) fault zone (e.g., Le Pichon and Gaulier, 1988). The subsequent collision of Arabia with Europe, resulting in gravitational potential build up in Eastern Anatolia, combined with an acceleration of slab rollback in the Hellenic subduction where the northern African slab is subducted (Brun et al., 2016) and a possible contribution from underlying asthenospheric flow, have been driving the westward extrusion of the Anatolian Plate (Özeren and Holt, 2010; Le Pichon and Kreemer, 2010) (Fig. 1a). At present, the boundary between Arabia and Anatolia is essentially a left lateral transform plate boundary, the East Anatolian Fault zone (EAF) (McKenzie, 1976; Şengör et al., 1985). Africa has been divided in the Eastern Mediterranean into a Nubia plate (McKenzie et al., 1970; Le Pichon and Francheteau, 1978) and a Sinai sub-plate (Mahmoud et al., 2005). This Sinai plate thus subducts beneath Anatolia along the Cyprus Arc and moves southward with respect to Arabia along the Levant Fault zone. The Kahramanmaraş triple junction is the junction of the Levant Fault zone, the East Anatolian Fault zone and the Cyprus Arc Subduction (Şengör et al., 1980, 1985; Karig and Kozlu, 1990). This triple junction gives rise to a very complex pattern of deformation in the northeastern Mediterranean because two non-subductable continental plates, namely Arabia and Anatolia, meet here. Triple junctions involving non-subductable plates have more than just local significance. It is therefore of some importance to know their characteristics for studies of the historical geology of the continental convergent plate boundary zones (Fig. 2a)(Şengör et al., 1980). During the final phases of continental collisions (Fig. 2b), the colliding continental plates often fall apart and the resulting pieces tend to move with different velocities with respect to one another (e.g., McKenzie, 1972; Roman, 1973; Dewey, 1977; Molnar and Tapponnier, 1975; Şengör, 1976; Şengör et al., 2019a). In such situations, incompatibility basins inevitably arise (Fig. 2b), as is the case in the Karhova region in eastern Turkey (see especially Şengör, 1979; Şengör et al., 1985, 2019a), and the Adana/Cilicia region between Cyprus and Turkey (Şengör et al., 1980, 1985, 2019a). Additionally, the marine part of the Sinai Plate is formed of thinned continental crust, comprising a thicker region, the Eratosthenes

38 seamount (Fig. 1a), which is currently impinging the Cyprus Arc (Le Pichon
39 et al., 2019). In this incipient collision, the relative motion of Sinai and Ana-
40 tolia is distributed between the Cyprus Arc subduction, the Kyrenia fault
41 running along the Northern Coast of Cyprus, and the Taurus range onshore
42 further north Fig. 1b. In fact, two triple junctions are currently active in
43 the area, namely those of Hatay (Fig. 1b) where the eastward prolongation
44 of the Cyprus arc reaches the Levant Fault, and Kahramanmaraş where the
45 NE prolongation of the Kyrenia fault reaches the EAF (Şengör et al., 2019a;
46 Özkan et al., 2023). However, the motion of Cyprus with respect to Ana-
47 tolia has been ignored so far in regional kinematic models because of a lack
48 of constraints from geodesy, as there were no available data on the Island
49 except for the single NICO station (see for example Mahmoud et al., 2005;
50 Reilinger et al., 2006; Gomez et al., 2020).

51 **Figure1**

52 This paper unveils a refined GNSS (Global Navigation Satellite Sys-
53 tems) velocity field encompassing southern Turkey and Cyprus. Leveraging
54 these data, we construct regional kinematic models that not only illuminate
55 the motion of the study area but also incorporate higher-resolution bound-
56 ary conditions and internal deformation characteristics specific to Cyprus.
57 Through these novel data and models, our aim is to foster a more compre-
58 hensive understanding of the neotectonics of the northeastern Mediterranean.
59 In addition, we will discuss the kinematic context of the major earthquakes
60 that occurred in the Kahramanmaraş triple junction area on February 6,
61 2023: Mw (moment magnitude) 7.8 Pazarcık earthquake on the EAF and
62 Mw 7.6 Elbistan earthquake on Çardak Fault (Barbot et al., 2023; Hussain
63 et al., 2023).

64 **Figure2**

65 Previous geodetic studies established the plate motion and evaluated large
66 scale internal strain of Anatolia (Reilinger et al., 2006; Özeren and Holt, 2010;
67 Cavalié and Jónsson, 2014; England et al., 2016; Weiss et al., 2020; Bletery
68 et al., 2020; Kurt et al., 2022) and Arabia Viltres et al. (2022) or focused on
69 the kinematics of the Levant fault zone (Gomez et al., 2007; Le Beon et al.,
70 2008; Alchalbi et al., 2010; Al Tarazi et al., 2011; Sadeh et al., 2012; Gomez
71 et al., 2020; Hamiel and Piatibratova, 2021) and of the East Anatolian fault
72 zone (Cavalié and Jónsson, 2014; Walters et al., 2014; Aktuğ et al., 2016;
73 Bletery et al., 2020). However, only a few of them take into account the ac-
74 tive deformation of secondary faults such as Malatya and Çardak Faults (also
75 called Sürgü Fault by some authors) (Westaway, 2003; Aktuğ et al., 2013),

76 or the Karataş-Osmaniye Fault (Mahmoud et al., 2013; Özkan et al., 2023).
77 Since vast portions of the region are situated beneath the Mediterranean
78 Sea, observations to measure the kinematics of the Cyprus Arc Subduction
79 are unfeasible. Cyprus, where the GNSS data have been very inadequate
80 so far, is the only place within the Eastern Mediterranean Sea Basin where
81 one can anchor the GNSS-based kinematic deformation models. To remedy
82 this situation, we conducted GNSS surveys in Cyprus and revisited 18 points
83 that have been previously measured in 1998 and 2001. We also incorporated
84 the data from seven permanent GNSS sites in the southern part of the is-
85 land. For the first time, we now have reasonable spatial coverage of space
86 geodetic data in Cyprus enabling us to construct a kinematic model of the
87 easternmost Mediterranean alongside a more detailed understanding of the
88 deformation within Cyprus. Moreover, we also conducted some follow-up sur-
89 veys to several GNSS survey-mode sites in the Turkish mainland to constrain
90 the kinematics of Anatolia with better coverage. We then integrated into our
91 velocity field previously published velocities acquired over the vicinity of the
92 Levant fault and EAF (Gomez et al., 2020; Hamiel and Piatibratova, 2021;
93 Kurt et al., 2022; Viltres et al., 2022). GNSS processing and integration
94 workflow is detailed in section 2.

95 With the combined velocity field as input, we applied two different kine-
96 matic inversion methods. A block model is used to calculate rigid block
97 motions and coupling on the block boundaries that are defined as disloca-
98 tion sources (McCaffrey et al., 2007). The output of this model may thus
99 be interpreted in term of long term slip rates and seismic coupling on major
100 faults. This model also allows internal deformation of the blocks by calcu-
101 lating a unique and uniform strain rate tensor for each block. In parallel,
102 we employed a continuum velocity field interpolation method to calculate the
103 strain rate field of the study area (Haines and Holt, 1993; Beavan and Haines,
104 2001). This strain distribution may be compared with seismicity distribution
105 and tectonic strain regimes indicated by fault maps.

106 From the modeling results, several open questions on the kinematics and
107 tectonics of the area can be addressed. Quantifying the partitioning of defor-
108 mation between the Cyprus Arc Subduction, Kyrenia fault and Taurus range
109 is a primary outcome of the newly acquired data. Then, we evaluate the dis-
110 tribution of deformation around the Kahramanmaraş and Hatay triple junc-
111 tions, notably between the EAF and the Karataş-Osmaniye-Çardak-Malatya
112 fault system and discuss implications for earthquake recurrence intervals.
113 Regarding the Levant fault, the present study is based on fewer velocity

114 vectors than for instance presented in Gomez et al. (2020) and has little to
115 add to their demonstration that slip on the main fault strand is decreasing
116 northward toward the triple junction as part of the motion is diverted
117 offshore. Another important question is the nature of the deformation of
118 the Adana/Cilicia basin. The basin and its frame have been interpreted
119 as elements of a ‘forearc’ (e.g., Aksu et al., 2005; Fernández-Blanco, 2014;
120 Fernández-Blanco et al., 2019, 2020; Aksu et al., 2021, and the extensive literature
121 cited therein), but it has not been made clear how, or even whether,
122 this alleged position has influenced its tectonic evolution. Burton-Ferguson
123 et al. (2005) and Aksu et al. (2021) pointed out the role of the escape of the
124 Anatolian block in inducing a strike-slip component onto the basin evolution.
125 We will examine how the strain distribution in the basin reflects spatial and
126 temporal changes in the boundary conditions. In the Taurus, very high Quaternary
127 uplift rates have been reported (Cosentino et al., 2012; Schildgen
128 et al., 2012, 2014; Cipollari et al., 2013; Radeff et al., 2017; Öğretmen et al.,
129 2018; Racano et al., 2020) and interpreted as a consequence of slab break off
130 or drip tectonics (Duretz and Gerya, 2013; Göğüş et al., 2017). Our results
131 do suggest that the local shortening is indeed insufficient to explain the Quaternary
132 uplift, and we discuss the various processes that may contribute to
133 this effect based on seismic tomography models (Biryol et al., 2011; Abgarmi
134 et al., 2017; Portner et al., 2018; Karabulut et al., 2019; Kounoudis et al.,
135 2020), and also drawing on a comparison with the Alpine orogen, where Quaternary
136 uplift is also out of proportion with crustal shortening (e.g. Sternai
137 et al., 2019).

138 2. GNSS Observations and Analysis

139 This section commences with a thorough exposition of the dataset we
140 acquired, followed by separate treatments of time series assessments for both
141 continuous and survey mode sites. The analysis of continuous stations is
142 based on a well-defined approach, the essence of which we aim to summarize
143 in the main text. However, for a comprehensive understanding of the
144 methodology, we encourage readers to refer to our supplementary document
145 (sections S1-S5). All relevant sections are addressed in the corresponding
146 part of the main text. Concluding this chapter, we integrate our initial velocity
147 field with previously published velocities, resulting in a densified and
148 unified velocity field.

149 *2.1. GNSS Data*

150 We present a GNSS velocity field that unites newly derived with previ-
151 ously published velocities. The raw data of the continuous stations were ob-
152 tained from both international networks (International GNSS Service -IGS
153 hereafter) and regional networks (Turkey Continuous GNSS Network and
154 Cyprus Positioning System) (Fig. 1b). We primarily analyzed the dataset
155 from 2009 to 2021 for continuous stations, although some of them had data
156 gaps during that period. However, we have approximately 10 years of time
157 series for almost every continuous site. The survey mode GNSS sites were
158 selected from the Turkey Fundamental GNSS Network to utilize valuable
159 existing observations and data resources. Each observation was carried out
160 using dual-frequency receivers and a filtering cut-off angle of 10 degrees to
161 minimize atmospheric noise. Each survey mode site has at least 7 different
162 sessions, except for 3 sites in the northern part of Cyprus that were set up in
163 2019, and all sessions have at least 8 hours of observations. The readers can
164 find further detail of the data span of survey mode sites in the supplementary
165 file. In total, we evaluated the raw data of 137 GNSS stations (65 continuous
166 - 72 survey mode) and estimated their velocities.

167 *2.2. Data Evaluation*

168 We performed data assessment using a combination of GAMIT/GLOBK
169 software (Herring et al., 2018, and the extensive literature cited therein)
170 and a stochastic approach. GAMIT/GLOBK integrates the double differ-
171 ences method and carrier phase combinations to eliminate geometric and
172 non-dispersive delays in the solution. We used IGS final orbit and clock
173 products as orbit parameters and the VMF1 (Vienna Mapping Function 1)
174 mapping function to minimize the effect of the tropospheric delay (Boehm
175 et al., 2006). In addition, we incorporated over 20 IGS stations into our net-
176 work to define a well-constrained global network. We processed daily data
177 from 2009 to 2022, while for the period between 1998 and 2009, we only
178 evaluated days with observations for our survey-mode sites. We verified our
179 daily solutions by following the steps outlined in Herring et al. (2018). Once
180 the daily evaluation was successfully performed, we analyzed the time series
181 by treating the survey mode and continuous sites differently.

182 *2.2.1. Continuous GNSS time series*

183 We analyzed continuous GNSS sites, characterized by uniform secular ve-
184 locities and superimposed seasonal signatures. These signals are effectively

185 modeled using linear terms combined with sinusoids of yearly and half-yearly
186 periods. The presence of higher-order harmonics contributing to the seasonal
187 signals is indicated by their asymmetric behavior. To address outlying obser-
188 vations, we adopted a regression approach that incorporates the squares of
189 misfits in the predictions and variances. Full details of our approach are pro-
190 vided in Supplementary Sections S1 and S3. Our starting point was Equ. 5
191 of Bevis and Brown (2014) and, like Serpelloni et al. (2022), we consider only
192 the first two seasonal terms. Other studies raise points we address in section
193 S1 (Johnson and Agnew, 1995; Mao et al., 1999; Bos et al., 2008). A metic-
194 ulous analysis of the residuals, obtained after removing the fitted seasonal
195 contributions, reveals specific sites exhibiting apparent changes in velocity
196 that require special attention. Additionally, a subset of sites presents poten-
197 tial issues due to significant outliers from the regression model, short-duration
198 periods of poor-quality data, or prolonged data gaps. Both horizontal and
199 radial components are considered, with a particular focus on sites where no-
200 ticeable velocity changes occur. Residuals at all sites are shown in Figures
201 S2.1-S2.50 in Supplementary Section S2. These observations align with the
202 findings of previous studies, providing further support and validation to the
203 investigation (Johnson and Agnew, 1995; Mao et al., 1999; Bevis and Brown,
204 2014). Our analysis basically adopts a method considering correlated and
205 dependent GNSS residuals with time following from Johnson and Agnew
206 (1995) and Mao et al. (1999). In a more rigorous way, Bos et al. (2008)
207 utilized spectral indices less than 1 and greater than -1. Spectral indices
208 are dimensionless exponents in power laws relating spectral amplitudes of
209 residuals to the inverse of frequency, and positive and negative values corre-
210 spond to having dominantly low frequencies and dominantly high frequencies
211 respectively. Based on our observations, we employ a simplified approach
212 that attributes residual correlation primarily to seasonal variations. Though
213 numerous other factors contribute to correlations, our spectral analysis men-
214 tioned below (see also Supplementary Sections S1 and S3-S5) confirms that
215 this rough approximation is a good starting point. By assuming that each
216 continuous GNSS time series comprises only two statistically independent
217 observations per year (simplistically viewed as being independently hotter or
218 colder than average summers and winters, or possibly wetter or dryer than
219 average springs and autumns), we applied a correction factor to the velocity
220 variances, resulting in larger velocity standard errors. This correction aligns
221 with the range of values reported in previous studies.

222 In our study, Monte Carlo trials were conducted using 100,000 randomly

223 selected subsets of observations at each site (see S1.2). The subsets had a
224 minimum interval of 6 months between observations and provided insights
225 into velocity standard errors. Spectral analysis complemented this analysis.
226 Velocity estimates were obtained from the subsets in the Monte Carlo trials
227 through straight-line regressions, and despite worse misfits at bad sites, ve-
228 locity standard deviations align with initial estimates. Good sites displayed
229 normal-like statistical distributions of velocities, while bad sites did not. Ir-
230 regular sampling, due to the national lockdown in the course of the COVID
231 pandemic, posed a challenge for Fourier analysis of records at continuous
232 mode sites. To address this, a solution involving linear interpolation between
233 sampling times was utilized. The optimization process yielded eigenfunctions
234 that closely resembled conventional Fourier terms when regular sampling was
235 present. Statistical convenience favored orthogonal expansions in terms of
236 sums over sampling times rather than integrals over time. Modifications were
237 made to the eigenfunctions for irregular sampling to enforce orthogonality in
238 the sum-over-sampling-times sense. Spectral analysis revealed that high-
239 frequency spectra exhibited white noise characteristics, while low-frequency
240 spectra displayed increased amplitudes, particularly at bad sites with appar-
241 ent velocity changes.

242 The spectral behavior at low frequency was analyzed further (section
243 S1.3), indicating peaks around 1 cycle/year in residuals without seasonal
244 terms removed and a steady increase in spectral values toward lower fre-
245 quencies in the case of full residuals. Low frequency behavior is consistent
246 with finite spectral amplitudes at zero frequency. Time domain correlation
247 functions with that property include Gaussian and exponentially decaying
248 variance functions in the spectral domain. Gaussian and exponentially de-
249 caying variances were combined with white noise to match observed spectra.
250 Spectral indices greater than zero were avoided due to their implications of
251 significant correlation between observations extending to infinite time due
252 to infinite spectral variances at zero frequency. Variances of secular velocity
253 were estimated for components that could be fitted in this manner, while
254 a conservative, simplified approach was taken for other components, which
255 were the bad ones with apparent changes in velocity (section S1.4). The
256 agreement between estimates for good components and our estimates from
257 regression and the Monte Carlo trials was found to be satisfactory, with
258 horizontal components showing particularly good results (see figures in the
259 section S1.4).

260 The maximum of all the velocity variance estimates for each component

261 at each site was taken as the final standard error. The further mathematical
262 background of the approach and additional plots pertaining to spectra of the
263 residuals can be found in the supplementary document (sections S3, S4 and
264 S5 respectively).

265 *2.2.2. Survey Mode GNSS time series*

266 The raw position time series of survey mode sites has been assessed with
267 two main steps. We adopted a first-order Gauss Markov Extrapolation (Her-
268 ring et al., 2018), embedded into GAMIT/GLOBK software, whereby we
269 generated the velocities and their raw sigma values for each survey mode
270 site. Once we obtained those, in the second step we followed another route
271 to obtain more realistic standard errors by appropriately scaling them. The
272 scaling was carried out by anchoring the campaign sites to the continuous
273 network by using a block model inversion that involves very small blocks.
274 At that point we would like to refer that this block model does not aim to
275 approach any tectonic problem but rather invert for the poles of rotations
276 for small collections of GNSS sites sufficiently close to each other so that
277 they are almost guaranteed to obey the same rotation. The aim here is to
278 do a grid search (Press et al., 2007) for a scaling factor for the errors of the
279 campaign sites by keeping the errors of the continuous sites constant. The
280 result indicates a necessary increase of errors by a factor of 2.2. A quite
281 similar approach was adopted by Beavan et al. (2016) and they documented
282 a very similar error scaling factor as well.

283 The supplementary document provides access to the NEU (North-East-
284 Up) components of the processed station velocities and their data span (see
285 Table S1, S2, S3).

286 *2.3. Unifying Velocity Fields*

287 After generating an initial velocity field, we combined it with published
288 velocities from previous studies to obtain a GNSS field with higher density
289 (Gomez et al., 2020; Hamiel and Piatibratova, 2021; Viltres et al., 2022;
290 Kurt et al., 2022). To minimize the effect of the some well-known noises
291 such as different data evaluation strategies, pre-defined reference frames from
292 different studies etc., we rotated all these velocity fields individually with
293 respect to our dataset.

294 The rotation is based on a least-square approach that aims to optimize
295 the transformation matrix of common stations for each velocity field pair.

Table 1: Root Mean Square fit of the velocity combination. The first column includes name of the studies and 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

296 Though this approach has been applied by several studies to combine veloci-
 297 ties coming from different evaluations, we made some critical changes to the
 298 weight matrix of the objective function (see Özbey et al., 2021, eq. 4). We
 299 define a new weight parameter r_i to re-weight the covariance matrix C by
 300 $C_i r_i^{-1}$. r_i^{-1} has been constructed as the function of both distance and number
 301 of observation. According to this;

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

302 where D_i is the distance between ith common site pair and n_x and n_y is
 303 the number of observations for the related stations x and y . Our algorithm
 304 allows utilizing a maximum of 5 km distance to decide that two sites are
 305 co-located. It also behaves as if they are exactly the same points for pairs of
 306 stations closer than 1 km. Besides, our approach takes into account the plate
 307 boundaries during its decision-making process as well. If the related station
 308 pair is in different blocks, it directly rejects it. The second parameter is the
 309 number of epochs for each site. Here it is important to note that the number
 310 of observations of permanent sites has been postulated as 365 for a year.
 311 Each velocity field has been rotated separately by taking the velocity field
 312 obtained by this study as the reference system. The statistical outcomes of
 313 these processes are listed in Table 1. The Helmert transformation parameters
 314 of each rotation are also listed in the supplementary document (S4).

315 Fig. 3 shows the final velocity field leveraging in the kinematic models
 316 with respect to the Arabian plate reference frame (Altamimi et al., 2017).
 317 The unified velocities with respect to both the Arabian-fixed and ITRF ref-
 318 erence frames can be found in the supplementary material as Table S5.

319 **Figure3**

320 **3. Modeling**

321 In this section, we present two different modeling approaches to reveal
322 the present-day kinematics around the Kahramanmaraş triple junction and
323 Cyprus. The first model solution is based on a block model and is designed
324 to indicate block motions throughout the boundaries. We suggest a block
325 geometry for the study area and testing this geometry with previously pub-
326 lished models. We then estimate rotation poles for the blocks and derive
327 fault slip rates. In the next section, we introduce a continuum kinematic
328 model and generate a continuum velocity field to monitor the deformation of
329 the region.

330 *3.1. Slip Rate and Locking Distribution Along the Block Boundaries*

331 Our first model aims to determine the kinematic behavior of the Nubia-
332 Cyprus-Anatolia tectonic system in the context of an elastic block-based
333 approach (McCaffrey et al., 2007). Such a block model involves an inverse
334 problem where the unknowns are, Euler vectors for individual blocks, uniform
335 strain rate tensor for each individual block, and coupling ratios on the fault
336 node points. The model can in principle be constrained by GNSS velocities,
337 geological fault slip rates and the azimuth of these rates, and earthquake
338 focal mechanisms. It is worth noting that we here only used GNSS data.

339 The block geometry follows the main active fault zones (Levant fault,
340 Cyprus Arc subduction, Kyrenia fault, East Anatolian fault), which are
341 thought to be critical in shaping the regional tectonics (Fig. 4a). The distri-
342 bution of seismicity is another key feature defining some block boundaries.
343 Our block architecture is comparable with that in previous studies (Reilinger
344 et al., 2006; Gomez et al., 2020) except that they considered Cyprus as part
345 of Anatolia and did not feature the Kyrenia range as a block boundary. This
346 is justifiable as it would not have been possible to constrain the motion of a
347 Cyprus block with the very limited GNSS data available on the island. The
348 Kyrenia arc continues offshore toward the Adana Basin but the Cyprus block
349 probably does not continue further east on-shore. A concentration of mostly
350 extensional focal mechanisms is observed along a N-S trend crossing the east
351 of the Adana/Cilicia basin, 30 km west of the Levant fault. We assumed this
352 trend delineates a block boundary, separating Anatolia and the Cyprus block
353 on its western side from a zone of complex deformation along the Levant and

354 East Anatolian faults. As internal block deformation is taken into account in
355 the model (approximated as a uniform strain field in each block) this deform-
356 ing zone can be defined as a block. The block extends eastward along the
357 East Anatolian fault toward Malatya. The northern boundary of the block
358 is composed of the Çardak and Malatya faults (see Fig. 4a), which are con-
359 sidered active (Westaway, 2003; Sançar et al., 2019; Acarel et al., 2019). An
360 alternate geometry requiring testing is that proposed by Özkan et al. (2023)
361 for the triple junction where the Karataş-Osmaniye Fault (KOF) connects
362 with the East Anatolian Fault following a NE trend, instead of bending to
363 the north toward Çardak Fault. This alternative model is presented in the
364 supplementary material.

365 **Figure4**

366 To the south of Cyprus lies on the Sinai block which is largely offshore.
367 Its motion is crucial for the kinematics of the Cyprus Arc subduction but
368 can only be constrained by velocities along the Levant coast and in Sinai.
369 However, GNSS velocity fields in Levant and in Southern Sinai do not fit in
370 the same rigid block reference frame. The Levant fragment of the Sinai block
371 may be affected by deformation along the Levant fault while south Sinai may
372 be affected by extension around the Gulf of Aqaba. This extension cannot
373 be well accounted for in our model, which simplifies the prolongation of the
374 Levant fault into the Gulf of Aqaba as a vertical fault, and the subduction
375 motion along the northern edge of the block should be better constrained by
376 the northern stations. We thus removed all GNSS rates south of 30°N for
377 the south Sinai. Moreover, previous studies of the Levant Fault kinematics
378 proposed that the NE part of the Sinai microplate is fragmented in order
379 to account for geodetic slip rates decreasing northward on the Levant fault
380 (Gomez et al., 2020). We thus consider an additional block, referred to as the
381 "Latakia" block, extending along the Levant coast (dashed blue line in Fig.
382 4a) north of Israel and compare solutions with and without this additional
383 block. Note that Gomez et al. (2020) considers several blocks west of the
384 Levant Fault, hence our Latakia block should be considered, like the Malatya
385 block as a deforming block.

386 Along the block boundaries, we defined 5 main dislocation sources, ca-
387 pable of accumulating elastic deformation, on which the coupling ratio will
388 be calculated by inversion (Fig. 4a). The Levant and East Anatolian faults,
389 which obey nearly pure strike-slip motion, are modeled as vertical planar
390 sources. The boundary between Anatolia and Malatya block is also simpli-
391 fied as a vertical fault. However, to generate the geometry of dipping faults,

392 such as the Cyprus subduction and Kyrenia fault, we followed published in-
393 terpretations of seismic profiles (Aksu et al., 2005, 2021; Burton-Ferguson
394 et al., 2005; Aksu et al., 2014a; Calon et al., 2005; Hall et al., 2005; Welford
395 et al., 2015; Feld et al., 2017). We utilized, moreover, the seismicity of the
396 region, compiling the earthquakes greater than $M_w = 2.8$. The earthquake
397 locations validate the geometry of the main subduction seismogenic zone be-
398 tween Sinai and Cyprus down to 40 km but do not help define the geometry
399 at depth of Kyrenia fault between Cyprus and Anatolia (Fig. 4b).

400 We conducted a series of synthetic tests to determine the optimal spatial
401 resolution of node points for the slip rate distribution, which was determined
402 by the spatial coverage of the GNSS data along both strike and dip direc-
403 tions. To achieve this, we utilized a checkerboard test, in which we divided
404 the main thrust interface south of Cyprus into planar cells, and monitored
405 the level of recovery of the given slip rate boundary conditions using syn-
406 thetic GNSS velocities at the same geographic locations as our data. We
407 tested two different average cell sizes for the thrust interface: one with an
408 average cell size of 35 km^2 , and the other with an average cell size of 10
409 km^2 . The tests were carried out without any synthetic observation noises.
410 Our results indicated that the test conducted with larger patches had fairly
411 better misfits than the one consisting of finer patch resolution. Fig. S1 in
412 the supplementary displays the checkerboard test solutions.

413 We test inversion results for four different block geometries based on pre-
414 vious publications and compared misfits obtained with these different block
415 models. (Gomez et al., 2020; Özkan et al., 2023). In Model 1, we used the
416 geometry published in Özkan et al. (2023) for south of Anatolia. This model
417 has no Malatya block (see Fig.4a) between Anatolia and the EAF. For the
418 boundary between Cyprus and Anatolia, the Karataş-Osmaniye fault (see
419 Fig.5a) is prolonged to connect to the EAF. Model 2 is based on Model 1
420 with a Latakia block added. Model 3 is the block geometry depicted in Fig.
421 4a without the Latakia block. Model 4 is the six block geometry depicted in
422 Fig. 4a. The solutions for models 3 and 4 have much lower misfits than the
423 first two models, in particular in the southeastern part of the Anatolia block
424 (see Figs. S2 and 5). Moreover, defining the eastern boundary of Cyprus
425 block as illustrated in Fig. 4a notably reduces misfits for the stations in
426 Cyprus. Model 4 has slightly lower misfit than Model 3, but with no reduc-
427 tion of the chi-2 over degree of freedom ratio (Fig.5b). An F-test, which is a
428 powerful statistical method that allows us to assess whether the variability
429 of the variances is significantly different, indicates this improvement is not

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

Model Number	DOF	χ^2	χ_v^2
1	666	4515.48	6.78
2	654	4388.34	6.71
3	632	1813.84	2.87
4	620	1791.80	2.89

430 significant (Table 2). This does not argue against distribution of strain west
 431 of the Levant fault as proposed by Gomez et al. (2020), but indicates that
 432 modeling this as a single added block is probably an oversimplification.

433 **Figure5**

434 Determining robust Euler pole parameters is of utmost importance for
 435 addressing the horizontal motion of the region. This problem is complicated
 436 by the fact that a large part of the Sinai plate is underwater and that the
 437 prolongation of the Sinai plate along the Levant coast (where GNSS stations
 438 are located) may be deforming. Euler poles of Sinai relative to Anatolia and
 439 to Arabia were obtained by the block model inversion. In order to estimate
 440 the Euler pole of the Nubia plate with respect to Anatolia we combined
 441 our determination of the Arabia-Anatolia pole with a Nubia-Arabia pole
 442 calculated in the ITRF No Net Rotation reference frame by Altamimi et al.
 443 (2017). The Nubia poles from this study and Reilinger et al. (2006) are
 444 similar to each other albeit with a slight difference in the rotation rates.
 445 The location of the Euler pole of Reilinger et al. (2006) for Sinai relative
 446 to Anatolia and ours are also close to each other. The rotation rate of the
 447 Reilinger et al. (2006) pole, however, is markedly faster resulting in a slower
 448 subduction velocity in our model. The data we used to constrain the motion
 449 of the Sinai block are essentially the same as in the previous studies, but we
 450 excluded data from South Sinai (below 30°N) as these cannot be fit in the
 451 same rigid reference frame, and this explains in large part the differences.
 452 The pole we determined provides a better fit of GNSS data along the Levant
 453 coast, but a worse fit of the GNSS data in the southern part of Sinai. We
 454 believe that this pole provides a better description of the motion of the
 455 Mediterranean seafloor as it subducts beneath Cyprus (Table 3).

456 After Euler poles and uniform strain rate tensor are estimated for each
 457 block a series of nonlinear inversions such as grid search and simulated an-
 458 nealing (Press et al., 2007) has been run iteratively to solve the coupling ratio

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

Plate Pair	Lat ($^{\circ}$)	Lon ($^{\circ}$)	Ω ($^{\circ}$ /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

459 on each node point. The Green's function that coincide with the location of
 460 the GNSS stations on the surface are determined with a rigorous approach
 461 to discretize the planar fault into rectangular patches (Okada, 1992). For the
 462 parametrization of fault coupling, we express the coupling ratio as constant
 463 between the surface and depth z_1 (an inversion parameter at each node)
 464 and decaying exponentially below z_2 where the fault starts fully slipping, as
 465 proposed by Wang et al. (2003).

466 Fig. 6a represents the block motions along the boundaries defined as
 467 dislocation sources in the model. On the Levant fault, the slip rate decreases
 468 from south to north steadily. It accommodates a 4.7 mm/yr slip rate from
 469 the Gulf of Aqaba to the Dead Sea with an almost purely left lateral strike-
 470 slip regime. However, the fault orients to the Lebanese restraining bend, and
 471 although the slip rate has still a strike-slip domination with a 3.9 mm/yr
 472 rate, it also accommodates a 1.1 mm/yr compressional rate. The Cyprus
 473 arc accommodates 3.5-6.2 mm/yr convergent rates reducing progressively
 474 from west to east. The motion of the Kyrenia fault, on the other hand, is
 475 mainly the left lateral strike-slip from the northwesternmost tip to the east
 476 of the island with rates of 3.2-4.2 mm/yr. Although the slip rates along
 477 the western prolongation of the Kyrenia fault also obey a left lateral strike-
 478 slip behavior, the spatial distribution of our dataset may not be considered
 479 capable of resolving this particular region. Along the boundary between the
 480 Anatolian and Cyprus blocks on one side and the so-called Malatya block on
 481 the other side, the inversion also indicates a ~ 1.3 mm/yr extensional motion,
 482 which is also in agreement with the predominantly extensional style of the
 483 earthquakes (see Fig. 4a). Meanwhile, there are relatively larger velocity

484 residuals on the left side of the boundary, roughly coinciding with Adana
485 Basin, that may represent active deformation not properly modeled with the
486 assumed block geometry. As the residuals we obtained are relatively small,
487 we present the cumulative histogram of the normalized residuals in Fig. 6b.
488 Where the block boundary changes its azimuth from N-S to E-W and along
489 the Çardak fault behaves as an almost left lateral strike-slip behavior with
490 a 1.9 mm/yr rate. The Malatya fault, which extends from the eastern tip
491 of the Çardak fault towards the north, has also left-lateral strike-slip motion
492 accounting for 1.7 mm/yr. The motion on the East Anatolian fault zone, on
493 the other hand, decreases from 6.2 to 5.1 mm/yr from the northernmost tip
494 of the EAF to Kahramanmaraş triple junction where it connects with the
495 Levant fault. Some additional shear is taken up by internal deformation of
496 the Malatya block.

497 **Figure6**

498 The estimated z_1 value for the Levant fault is consistently around 10
499 km. However, the inversion result indicates a depth of approximately 15 km
500 (following the convention of Wang et al. (2003)) for z_2 in the north of the
501 Dead Sea, while it is inverted as 20 km for the south. For the EAF, the
502 z_1 value decreases from 20 to 13 km from south to north, while z_2 remains
503 relatively constant at 25 km. The locking behavior of the Çardak fault is
504 relatively smooth (see Fig. 7a). The inversion estimates a z_1 value around
505 20-25 km depth, but due to the lack of GNSS data for the offshore part, the
506 uncertainties of the coupling coefficient are directly related to the distance
507 between the node points and Cyprus, which is the closest location with data.
508 The coupling distribution drastically decreases towards the west of Kyrenia
509 fault where the dataset becomes sparse (Fig. 7b-c).

510 **Figure7**

511 *3.2. Strain rate field*

512 In this section, we will determine a contemporary strain rate field to
513 characterize deformation styles in the region that comprises northeast Nubia,
514 eastern Mediterranean Sea, Levant fault, Cyprus, Adana/Cilicia basin and
515 neighboring southern Turkey. Our aim is to shed light on its kinematics.
516 This can be useful for future dynamical models as kinematic constraints. In
517 this kinematic continuum model, which is based on the method described
518 by Haines and Holt (1993); Beavan and Haines (2001), we aim to find the
519 minimum strain rate field that best fits the GNSS velocity field for the model
520 region by minimizing the following objective function:

$$\sum_{\text{cells}} \nu \left(\dot{\varepsilon}_{\phi\phi}^2 + 2\dot{\varepsilon}_{\phi\theta}^2 + \dot{\varepsilon}_{\theta\theta}^2 \right) S \quad (2)$$

521 where $\dot{\varepsilon}_{\phi\phi}$, $\dot{\varepsilon}_{\phi\theta}$, and $\dot{\varepsilon}_{\theta\theta}$ are strain rate tensor components with respect to
 522 longitude θ and latitude ϕ for each cell, S corresponds to the surface area of
 523 the related cell. Even though there is a possibility to prescribe the ν value,
 524 which is a weighting factor associated with the rheology of the deforming
 525 material, for each cell individually, we employed a single uniform ν value for
 526 all the cells within the domain. Further details can be found in Beavan and
 527 Haines (2001), Appendix 5.

528 Here, we solely utilized the GNSS velocity field without imposing any
 529 plate motion boundary conditions. To achieve the objective function, we
 530 assigned a uniform ν value. Experiments were made using larger ν values
 531 in the grid cells in SW Cyprus and further offshore where seismic catalogues
 532 show the clustering of earthquakes (see Fig.4b). If these are “damage” zones,
 533 their bulk deformability might be higher than other zones. However these
 534 experiments did not significantly improve the fit to the GNSS velocities even
 535 in the near field sites in southern Cyprus.

536 Fig. 8 shows the second invariant of the strain rate tensor (obeying the
 537 formula $\sqrt{\dot{e}_{xx}^2 + \dot{e}_{yy}^2 + 2\dot{e}_{xy}^2}$ where e_{xx} , e_{xy} , and e_{yy} are the tensor compo-
 538 nents) with seismicity. The solution indicates, in general, small strain rates
 539 within Cyprus, the second invariant rarely exceeding 20 nanostrain per year.
 540 However, there is a clear spatial variability of deformation styles on the is-
 541 land. A transpressive strike slip regime is found along the Kyrenia range
 542 while roughly N-S compression dominates in the southern part on the island
 543 (Fig. 9a). On a larger scale, this strain partitioning within Cyprus seems
 544 to act as a diffuse transition that rotates the predominant compression from
 545 NW-SE in the Sinai block onto NE-SW in the Cilicia basin (see Fig. 8)
 546 immediately to the north of Cyprus. Between Cyprus and Turkey the short-
 547 ening integrated along the principal strain axis between the coasts of Cyprus
 548 and Turkey amounts to a maximum of 0.8 mm/yr. The lack of GNSS data
 549 (Fig. 9b) probably leads us to a strain rate field much smoother than the
 550 reality in Cilicia basin but on the large scale, the solution shows a progressive
 551 transition from compression to strike-slip toward the NE, associated with a
 552 rotation of principle axes to N-S compression and E-W extension, eventually
 553 matching the dominant strain regime found onland in Adana Basin.

554 **Figure8**

555 A swath of higher strain rate (more than 30 nanostrain/yr) over a width
556 of 50-60 km is found east of the Adana basin and extends NE along the north-
557 ern side of the EAF, thus defining a broader East Anatolian shear zone (Fig.
558 8). There, principal strain directions (E-W extension and N-S compression)
559 are consistent with left lateral strike-slip motion. The areal strain ($\dot{\epsilon}_{xx} + \dot{\epsilon}_{yy}$)
560 is positive (see Fig. 9) except at a few locations, indicating transtensive to
561 extensional deformation, consistent with focal mechanisms (Fig. 8). Princi-
562 pal strain orientations retain the same orientation over a broader area, with
563 lower strain rates, that includes Adana basin and the mountains north of
564 it (Aladağlar, see Fig. 9b). Areal strain indicates extension is dominant in
565 these mountains while both mildly transpressive and transtensive styles are
566 found in Adana basin. This may suggest that gravity is influencing strain
567 distribution between topographic highs and basin. The westward limit of this
568 zone of E-W extension coincides with Ecemiş Fault (see Fig. 8). This fault
569 zone has taken up 60 km of left lateral slip since late Eocene and is under
570 transtension since Miocene (Jaffey and Robertson, 2005; Akif Sarıkaya et al.,
571 2015; Yıldırım et al., 2016; Umhoefer et al., 2020). West of Ecemiş fault
572 principal strain axes rotate to NE-SW compression and NW-SE extension,
573 respectively parallel and perpendicular to this part of the Taurus mountain
574 range. Ecemiş fault thus appear to bound the zone of east-west extension
575 related to Anatolian escape. Strain rates within the Taurus range west of
576 Ecemiş fault remain small (less than 10 nanostrain/year), areal strain is dom-
577 inantly positive but changes sign toward the coast in the south-western part
578 of the range. This is the only part of Taurus where compressive strain is
579 currently observed.

580 **Figure9**

581 Along the Levant fault the dominating principal strain orientations pre-
582 sented in Fig. 9a are consistent with left-lateral shear on the fault. The
583 biggest problem is that there GNSS coverage from south of Turkey along the
584 coast towards Israel in particular for the east side of the Levant fault is poor.
585 In Israel where the GNSS coverage is very dense, but still mostly located
586 on the western side of the Levant fault, we see some short wavelength vari-
587 ability of the strain rate field with the compressional axes trending largely
588 NW-SE. The strain rates become less coherent towards the southern tip of
589 Israel. North of Israel the zones of higher extension (positive areal strain)
590 and compression (negative areal strain) do not match the location of the
591 Lebanon restraining bend. This puzzling observation has been reported be-
592 fore (cf. fig. 8 in Gomez et al. (2020)) and was explained by transfer of the

593 compression on offshore faults.

594 Overall, zones of higher strain rate appear to roughly correlate with
595 zone of higher seismic activity in the 0-30 km depth range corresponding
596 to crustal seismicity (Fig. 8). The long-term seismicity catalogue between
597 1905 and 2019 represented on this figure, and also projected on the cross-
598 section in Fig. 10 was compiled from Kandilli Observatory and Earthquake
599 Research Institute's seismicity catalogue between 1905 and 2019 (KOERI,
600 2001; <http://www.koeri.boun.edu.tr>). The magnitude of completeness of the
601 catalogue is $\sim M_c=4$. The mean horizontal location uncertainty is less than
602 5 km in N-S and E-W directions. The mean of the depth uncertainty is ~ 3.5
603 km, varying between 2 and 8 km. We filtered the original catalogue based
604 on the quality factors such as horizontal location uncertainty < 5 km and
605 RMS < 0.5 s. In the East Anatolian shear zone, the distribution of seismicity
606 exhibits a pronounced increase along the sides of the zone, coinciding with
607 the placement of the block boundaries. It also extends westward beneath
608 Adana Basin and north of it where lower strain rates are obtained. The seis-
609 micity within the Taurus is comparatively lower but some concentrations of
610 earthquakes occurs in the prolongation of the Tuz Gölü Fault (Özbey et al.,
611 2022), along Ecemiş fault and between Mersin and Bolkardağ (see Fig. 8 and
612 Fig. 9a). This latter zone also appears as a zone of relatively high strain
613 rate in the GNSS interpolation with positive areal strain indicating exten-
614 sion. However, the orientation and style of the strain tensors determined in
615 this area lack consistency due to relatively higher residuals around the region
616 (Fig. 9b).

617 4. Discussion

618 In this section, we discuss our solutions and make some implications re-
619 garding to our findings by comparing them with previous studies. We men-
620 tion the shear partitioning between the Cyprus subduction and Kyrenia fault
621 in the next subsection. We then refer to the effect of this partitioning sys-
622 tem around the East Anatolian shear zone toward the Kahramanmaraş triple
623 junction in particular and discuss the 6 February 2023 earthquake doublet.
624 In the third subsection, we compare our solution with the previous studies
625 around the Levant fault and discuss the prolongation of distributed defor-
626 mation for the northern part of the Levant fault. We lastly discuss the
627 present-day uplift around the Taurus orogen and Adana/Cilicia basins re-
628 gion by referring to the derived strain rate field of the area and vertical

629 GNSS velocities. Moreover, we employ some published tomographic models
630 and geologic interpretations to depict the discussion with various aspects.

631 *4.1. Cyprus subduction*

632 The slip characteristic both on Cyprus arc and Kyrenia range indicates
633 that an ongoing shear partitioning is the dominant regime for the area. The
634 subduction is still active in spite of the incipient collision with the Eratos-
635 thenes Seamount, with near frontal convergence at a 6.0 mm/yr rate south-
636 west of Cyprus. The locking depth (z_1) extends from the surface to 20 km
637 depth, which is consistent with Welford et al. (2015); Feld et al. (2017). We
638 find a nearly pure left-lateral strike-slip motion on Kyrenia fault with a rate
639 of 3.5-4.2 mm/yr, suggesting a nearly perfect shear partitioning between the
640 subduction and Kyrenia range. Euler poles published by previous studies
641 (Reilinger et al., 2006; Gomez et al., 2020) only predict moderate obliquity
642 on the Cyprus subduction, about 20° south of Cyprus, which corresponds to
643 the critical obliquity threshold for the onset shear partitioning above a sub-
644 duction zone (McCaffrey, 1992). The rotation motion of Anatolia vs. Sinai
645 and the arc shape of the subduction cause a lateral variation of obliquity
646 so that 20° is a minimum value, but shear partitioning above a subduction
647 should not in principle lower slip vector obliquity below $15\text{-}20^\circ$ (McCaffrey,
648 1992). It is thus possible that forces applied on the E and W boundaries of
649 Cyprus block play a role. The Cyprus block interacts with the Malatya block
650 at its NE end and conditions on this boundary are extensional. It is thus
651 possible that the forces applied in this zone near the triple junction influence
652 the motion of the Cyprus block and particularly the amount of strike-slip
653 taken up in Kyrenia range.

654 *4.2. East Anatolian shear zone*

655 In the vicinity of the triple junction the shear between Anatolia and Ara-
656 bia is distributed over a zone that we defined as a block (the Malatya block).
657 On the East Anatolian fault, we obtain 5.1-6.2 mm/yr strike-slip rates that
658 are lower than most previous studies (Aktuğ et al., 2016; Reilinger et al.,
659 2006). However, analyses of a high resolution velocity field obtained combin-
660 ing GNSS and InSAR data (Weiss et al., 2020) found a laterally varying
661 interseismic loading rate on the EAF (Güvercin et al., 2022; Li et al., 2023).
662 The strike-slip rate on the Malatya fault we obtain (1.7 mm/yr) is consistent
663 with previous studies (Aktuğ et al., 2013). The strike-slip rate on the Çardak
664 fault we obtained from the block model is 1.8 mm/yr and is comparable with

665 a 2 mm/yr slip rate calculated from geomorphological offsets (Westaway,
666 2003). In addition, the principal strain orientations between these two faults
667 indicate left-lateral shear co-linear with shear along the East Anatolian fault
668 zone (see Figs. 6 and 9) with an average rate of 35 nanostrain per year and
669 a small extensional component (Fig.8). Assuming simple shear, the internal
670 deformation of the Malatya block over an average width of 50 km amounts to
671 about 1.7 mm/yr. The strike-slip motion between Anatolia and Arabia thus
672 appears to be distributed between the East Anatolian fault, the faults defin-
673 ing the northern boundary of the Malatya block and internal deformation of
674 the block. These three components add up to 8.5-9.7 mm/yr, which is con-
675 sistent with previous estimations of Arabia/Anatolia plate motion (Reilinger
676 et al., 2006; Aktuğ et al., 2016; Bletery et al., 2020). The block boundaries
677 we propose differs from the geometry proposed by Özkan et al. (2023) in that
678 they connect the Karataş-Osmaniye fault to the EAF near Kahramanmaras
679 and thus do not allow shear partitioning east of the triple junction. Their
680 geometry cannot account for the loading of Çardak Fault which was ruptured
681 during the second earthquake of the Feb 6, 2023, earthquake doublet (Toda
682 et al., 2023; Barbot et al., 2023). Our solution with a N-S transtensional
683 boundary connecting to Çardak fault has a lower misfit and also better rep-
684 resents mapped active faults (Emre et al., 2018)(Figure 1b). We conclude
685 that part of the EAF motion is partitioned from the main fault in a broader
686 zone around the triple junction, resulting in decreased interseismic loading
687 rates on the main strand of the EAF.

688 During the Feb 6, 2023 sequence ruptures occurred on both the southern
689 and the northern boundaries of the Malatya block. The main shock (Mw 7.8)
690 occurred on the East Anatolian and Levant faults while the large Mw 7.6 af-
691 tershock occurred on Çardak Fault, corresponding to a moment magnitude
692 about half of that of the main shock (Toda et al., 2023; Hussain et al., 2023).
693 However preliminary estimates of coseismic slip from finite fault models and
694 from optical image correlation indicate that the smaller earthquake has in
695 fact larger displacements but over a smaller rupture length (Toda et al., 2023;
696 Barbot et al., 2023; Li et al., 2023; Melgar et al., 2023). The occurrence of
697 these events shows that both boundaries are seismically active and present
698 a high seismic hazard but also suggest that recurrence interval is very dif-
699 ferent on these two faults. Estimates of surface slip from Sentinel-2 image
700 correlation are 4 m in average over a large part of the main shock rupture
701 with a local maximum of about 7 m, and 6 m in average for the aftershock
702 with a maximum of 8-9 m (Barbot et al., 2023; Hussain et al., 2023). Using

703 our interseismic backslip estimates, recurrence intervals of 750 to 1500 year
704 are inferred for the East Anatolian Fault and from 3000 to 5000 years on the
705 Çardak Fault. It thus appears that triggering of the Çardak Fault does not
706 occur each time a large earthquake occurs on the East Anatolian Fault, and
707 probably less than once every three cycle on the EAF. Moreover the Mw 7.8
708 earthquake is a multi-segment rupture (Barbot et al., 2023) and such events
709 have longer recurrence interval than those estimated for characteristic earth-
710 quakes on individual segments. Estimates from single segments range from
711 100 years to about 900 years along the East Anatolian Fault with the longest
712 intervals and largest maximum magnitude (Mw 7.4) in the triple junction
713 area (Güvercin et al., 2022). It is important to note that this study took into
714 account a westward decrease of interseismic loading rates along the EAF
715 segments. The duration of seismic cycles involving a multi-segment rupture
716 is even longer. Their estimation depends on complex scenarios that com-
717 bine multi-segment and single segment ruptures and ranges from 700 to 2500
718 years (Karabulut et al., 2023). Shear partitioning in the Kahramanmaraş
719 triple junction is thus one of the factors contributing to very long earthquake
720 cycles on the EAF. Moreover, the earthquake hazard on secondary faults
721 must not be ignored even though large events on these slower faults may
722 have even longer recurrence intervals.

723 *4.3. Levant fault zone*

724 Block-based model inversion indicates that the Levant fault accommo-
725 dates a 3.5-4.7 mm/yr slip rate, and it decreases, slightly but steadily, from
726 south to north. This result is consistent with previous studies such as
727 Al Tarazi et al. (2011); Sadeh et al. (2012); Gomez et al. (2020); Hamiel and
728 Piatibratova (2021). Gomez et al. (2020) find a decreasing motion north-
729 ward from 5.0 mm/yr to 2.5-3.5 mm/yr as they consider two additional
730 block boundaries transferring part of the Levant fault motion to hypotheti-
731 cal offshore structures. However, the northward decrease of the slip rate of
732 the Levant fault found by previous studies is not well explained by a single
733 Latakia block as this block is likely deforming. The presence of the Latakia
734 block is crucial for delineating the zone of distributed deformation in the
735 vicinity of the triple junction. It is nevertheless likely that a significant part
736 of the motion on the Levant Fault is transferred to faults running along the
737 margin (see Figs. 1 and 10). These fault then connect offshore to the Cyprus
738 Arc subduction, which in this zone mostly accommodates strike-slip motion.
739 Our results are thus fully consistent with previous studies.

740 *4.4. Central Taurus and Adana/Cilicia Basin*

741 In this section we address the possible causes of the fast recent uplift
742 rates of Taurus and their relationship with the strain distribution within
743 the Adana/Cilicia basin and the Cyprus arc. The present day shortening
744 within the Taurus seems unable to explain its uplift, but one should keep
745 in mind that Taurus is part of an orogen that has been active in several
746 phases since the closure of the Inner Tauride Ocean in Late Eocene (Şengör
747 et al., 2019a). Understanding present day tectonics requires knowledge of
748 crustal and mantle structure and taking into account the evolution of Taurus
749 and Adana/Cilicia basin since the onset of Arabia/Eurasia collision in the
750 Miocene. Fig. 10a is a geological map showing only the rocks and structures
751 younger than the Oligocene. All blank areas on land are pre-Miocene rocks
752 and structures. The submarine areas are also left blank. Fig. 10b shows a
753 simplified structural N-S cross-section at 34°E across Central Anatolia and
754 Cyprus (Şengör et al., 2019b). For the upper mantle structure, we extracted
755 a cross-section from a new high-resolution tomographic model of the mantle
756 beneath it (Karabulut et al., 2019). This model is calculated by utilizing 860
757 broadband seismic stations to provide an improved image of the upper mantle
758 structure in the Aegean-Anatolia domain. The model mainly exhibits major
759 discontinuities of subducting slabs from Hellenic to Cyprus subduction zones,
760 the readers may look at further details from Karabulut et al. (2019). We here
761 point out that the fast uplifting part of Taurus is above cold lithosphere while
762 hot mantle is found north of the Inner Tauride structure. This assertion is
763 also supported by other tomographic images (Biryol et al., 2011)(Portner
764 et al., 2018) (Kounoudis et al., 2020) and by receiver functions imaging a
765 subhorizontal positive anomaly at 70 km depth beneath Taurus that may
766 correspond to the top of a flat Cyprus slab (Abgarmi et al., 2017).

767 **Figure10**

768 Several studies have investigated the uplift dynamics of the Central Tau-
769 rus in the light of a multi-phased uplift scenario since the Miocene (Cosentino
770 et al., 2012; Schildgen et al., 2012, 2014; Cipollari et al., 2013; Radeff et al.,
771 2017; Öğretmen et al., 2018; Racano et al., 2020) involving lithospheric man-
772 tle delamination, slab roll-back and break-off, and consequent asthenospheric
773 upwelling. These studies relied on cosmogenic exposure ages of gravels from
774 the Göksu River terraces (Schildgen et al., 2012), micropaleontological data
775 from the marine deposits in Mut and Adana basins (Cosentino et al., 2012;
776 Schildgen et al., 2012; Cipollari et al., 2013; Öğretmen et al., 2018), Miocene-
777 aged fluvial conglomerates (Radeff et al., 2017), and abandoned marine plat-

778 forms (Racano et al., 2020). Cipollari et al. (2013) placed the maximum age
779 of the surface uplift to ~ 8 My based on calcareous nanoplankton ages from
780 the Mut Basin. Radeff et al. (2017) interpreted the Upper Messinian-Lower
781 Pliocene (5.45-5.33 My) fluvial conglomerate deposits of the Adana Basin
782 as uplift-related and resulting in ~ 4 mm/yr uplift. The latest uplift-phase
783 was later revised by Öğretmen et al. (2018) through detailed biostratigraphic
784 age and paleodepth reconstructions from the Early-Middle Pleistocene aged
785 marine deposits found at ~ 1 km asl in the Mut Basin pointing to ~ 3.2 - 3.4
786 mm/yr uplift rate since 0.46 My (Fig. 10b). Marine terraces developed after
787 the deposition of these marine deposits yielded similar uplift rates from
788 3.8-3.4 mm/yr to 1.6-1.1 mm/yr for the present-day (Racano et al., 2020).

789 For comparison, we extracted the vertical velocities of some particular
790 GNSS stations. Data history and monument type are the key criteria for
791 our selection. In order to ensure data quality and avoid potential biases we
792 only chose stations that have at least 7 years of data span and eliminated the
793 stations settled on building roofs. Although the vertical component of GNSS
794 velocity vectors is less reliable than horizontal components, the up velocities
795 of chosen GNSS sites indicate an uplift for the Taurus Range, ranging from
796 0.30-1.20 mm/yr and 0.8 mm/yr in Northern Cyprus (Kyrenia range). The
797 GNSS up velocities are thus slower than the geologic estimates reported
798 above. These differences can be in part due to the temporal scale differences
799 between the GNSS data and geological findings. They may also be related
800 to spatial variations of uplift rates. It is possible that the highest geological
801 uplift rates are enhanced by erosion as they are measured near rivers that
802 incise the southern slope of the Taurus plateau at a very high rate (Racano
803 et al., 2020). Moreover the rapid incision of the Göksu river in the Mut Basin
804 may feed back on the uplift rates obtained by Öğretmen et al. (2018).

805 While the Adana/Cilicia basin may be considered as in a fore-arc po-
806 sition with respect to the Cyprus subduction, its position with respect to
807 the Taurus orogen is, at least in the early stages, that of a flexural fore-
808 land basin, analogous to the Molasse basin in the Alpine orogen (Şengör
809 et al., 2019a). In addition, the Adana Basin and the eastern extremity of
810 the Cilicia Basin has been affected by transtensional tectonics since the in-
811 ception of the Kahramanmaraş triple junction (Şengör et al., 1985; Karig
812 and Kozlu, 1990). The stretching event induced some mafic magmatism in
813 the eastern part of the basin and along the Amanos segment of the East
814 Anatolian Fault (Polat et al., 1997; Parlak et al., 1998; Cosca et al., 2020).
815 Indeed, we showed that the present day strain distribution indicates different

816 deformation regimes: Cilicia Basin undergoes slow NNE-SSW compression
817 while Adana Basin is deforming under left lateral shear along a NE-SW di-
818 rection. However, several studies have proposed that the subsidence of both
819 the Adana and Cilicia basins since Mid-Miocene is in large part related to
820 flexural bending, with only limited contribution from lateral shortening of
821 extension (Fernández-Blanco et al., 2019; Ergin and Aktar, 2018; Williams
822 et al., 1995). Fernández-Blanco et al. (2020) further suggested a monoclinial
823 flexural system driven by lower crustal flow could explain both Taurus uplift
824 and Cilicia Basin subsidence. However, they state that their model does not
825 account for the uplift rates documented by Öğretmen et al. (2018).

826 The continuum deformation field (Fig. 9a) obtained in and around the
827 Taurus mountain range shows little shortening in the upper crust (less than 1
828 mm/yr across the western part of Cilicia Basin). Moreover, Cyprus/Anatolia
829 motion in the block model is dominantly strike-slip. The Anatolia-Cyprus
830 pole we calculated would predict pure strike-slip relative motion on a fault
831 running along the coast, which nearly follows a small circle for this pole. In
832 fact, this strike slip-motion is dominantly taken up along the Kyrenia fault
833 but residuals of the block model suggest left lateral strike-slip motion may
834 be taking place along the coast of Cilicia Basin in the prolongation of Kozan
835 Fault (see Fig. 1b). This fault had been proposed to move at rates of 4
836 to 8 mm/yr based on sediment depocenter migration (Aksu et al., 2014b),
837 However the rates estimated from GNSS are barely above noise level at about
838 one mm/yr. An analogy with the Alps may here be considered regarding
839 convergence and uplift rates. Convergence has ceased in the Western Alps
840 and is less than 1 mm/yr along the Central Alps cross section here considered
841 (Walpersdorf et al., 2018; Serpelloni et al., 2016). Yet, uplift rates of 1 mm/yr
842 to 2.5 mm/yr are observed in the core of the Alps and the widely accepted
843 view is that post-glacial rebound and erosion cannot fully explain them,
844 suggesting an involvement of the mantle (Sternai et al., 2019). The possibility
845 of a recent slab break-off below the Western Alps has been proposed, but is
846 disputed (Lippitsch et al., 2003; Zhao et al., 2016). Nevertheless slab break-
847 off is unlikely to provide a satisfactory explanation for the Central Alps where
848 a continuous lithospheric slab is well imaged.

849 Let us now examine how the present day distribution of uplift in the
850 Taurus orogen, with maximum rates in the outer part of Taurus above cold
851 lithosphere, could be explained by mechanical models of slab break off. In
852 some models with weak lower crustal rheology, lithosphere delamination and
853 slab retreat open a wide asthenospheric window beneath the domain being

854 uplifted (Duretz and Gerya, 2013; Burov et al., 2014). This is not the case
855 for Taurus where the zone of hot mantle lies north of the ophiolitic suture
856 and not below the zone of present day fast uplift. However, this situation
857 may correspond to model cases involving an eduction mechanism, that is the
858 extrusion of a slice of crustal material between a thrust and an extensional
859 detachment (Duretz and Gerya, 2013; Duretz et al., 2011; Burov et al., 2014).
860 In these models the eduction process is driven by the combined buoyancy of
861 hot asthenosphere and of crustal material previously shoved into the subduc-
862 tion. However, the velocity field we obtain is not compatible with an eduction
863 system as this should imply active extension within or north of the uplifting
864 domain and, likely, higher convergence between Taurus and Cyprus than our
865 $\simeq 1$ mm/yr estimate. For instance, the model proposed to explain the high
866 uplift rates in Öğretmen et al. (2018) involves a fast horizontal displacement
867 of the educted block, in the cm/yr range (Duretz and Gerya, 2013). Never-
868 theless, the apparent decoupling of uplift, upper crustal strain distribution
869 and upper mantle buoyancy implies some kind of lower crustal flow. For in-
870 stance, lower crustal channel flow giving rise to localized uplift and erosion at
871 the edge of a plateau of thickened crust may occur without involving asteno-
872 spheric upwelling (Beaumont et al., 2004). On the other hand, the forearc
873 uplift model proposed by Fernández-Blanco et al. (2020) may be insufficient
874 to explain the uplift rates, but this model did not fully take into account
875 that the basement of the whole Eastern Mediterranean south of Cyprus is,
876 probably, thinned continental crust (Le Pichon et al., 2019). This domain
877 has been stretched in an E-W direction during the opening of the Neothetis
878 and the northern extent of this thinned continental lithosphere is unknown.
879 Possibly, it has been underthrust as far as beneath Central Taurus where
880 the Moho of the subducting plate has been imaged. Drawing again on the
881 comparison with the Alps, this situation may be analogous with the under-
882 thrusting (followed by its exhumation) of the Briançonnais in the Oligocene
883 (e.g. Jolivet et al., 2003). In this context, it seems difficult to resolve the re-
884 lative contributions to the Taurus uplift of crustal buoyancy and of processes
885 involving lithospheric slabs and the asthenosphere.

886 5. Conclusion

887 Acquisition of new GNSS data on Cyprus and southern Turkey brings
888 new insight into the deformation of the region around the Kahramanmaraş
889 triple junction. It shows that the present-day deformation of Cyprus may

890 be understood as a shear partitioning system between the Cyprus arc sub-
891 duction and the Kyrenia fault, which appears to be a dominantly strike-slip
892 boundary. Thus, the incipient collision with the Eratosthenes Seamount may
893 not have yet perturbed much the kinematics of the Cyprus subduction. On
894 the other hand, the northeast continuation of the shear partitioning system
895 toward the Anatolia/Arabia collision zone brings further complexity to the
896 Kahramanmaraş triple junction.

897 In the Anatolia-Arabia plate boundary our study demonstrates that part
898 of the motion on the East Anatolian Fault is distributed away from the main
899 fault in the vicinity of the triple junction, as was previously showed for the
900 Levant fault in the Arabia-Nubia plate boundary (Gomez et al., 2020). Thus,
901 the EAF is not the only deformation source in the East Anatolian shear zone
902 as deformation is also distributed on secondary faults such as Çardak and
903 Malatya faults. The earthquake sequence that occurred on February 6 2023
904 emphasizes the earthquake hazard presented by secondary faults in complex
905 plate boundary zones. In the study area the kinematics of faults offshore
906 of the Levant and Hatay coasts still need consideration. On land the slip
907 rates calculated on the faults bounding Malatya block result in very long
908 earthquake cycles of 750-2000 years for the part of the EAF which ruptured
909 recently and probably 3000-5000 years for Çardak Fault. How such rare
910 events may be taken into account in hazard assessment poses questions.

911 We also showed that the part of the Taurus east of the Ecemiş Fault
912 is subject to E-W extension related to Anatolian extrusion. On the other
913 hand the Western part of Taurus and Cilicia Basin is under mild compression
914 related to Cyprus arc subduction. However, the high uplift rates observed in
915 the Taurus cannot be explained by upper crustal shortening. A combination
916 of processes, involving lower crustal flow and mantle are needed to explain
917 this uplift.

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1430 **Figure Captions**

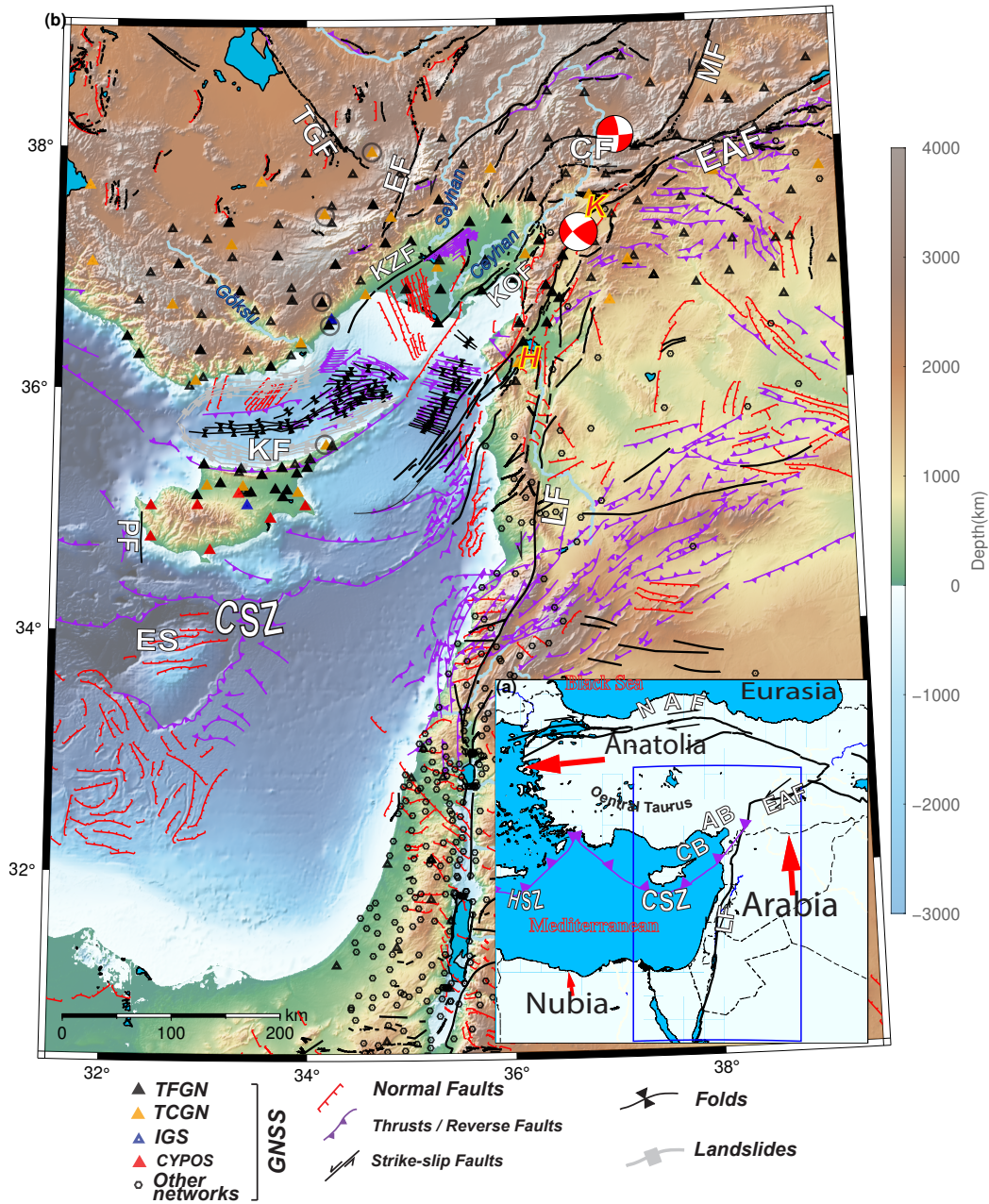


Figure 1: a) Tectonics of the Eastern Mediterranean and fundamental features in the scope of this study. Abbreviations: EAF: East Anatolian Fault, NAF: North Anatolian Fault, LF: Levant Fault, CSZ: Cyprus Subduction Zone, HSZ: Hellenic Subduction Zone, AB: Adana Basin, CB: Cilicia Basin b) Tectonic structures 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 stations enclosed within ellipses correspond to the sites discussed in the uplift context outlined in section 4.4. Focal mechanisms belong to 06 Feb 2023 Mw=7.8 and Mw=7.6 Kahramanmaraş Pazarçık and Elbistan earthquakes. 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 point to the studies that have published the data.

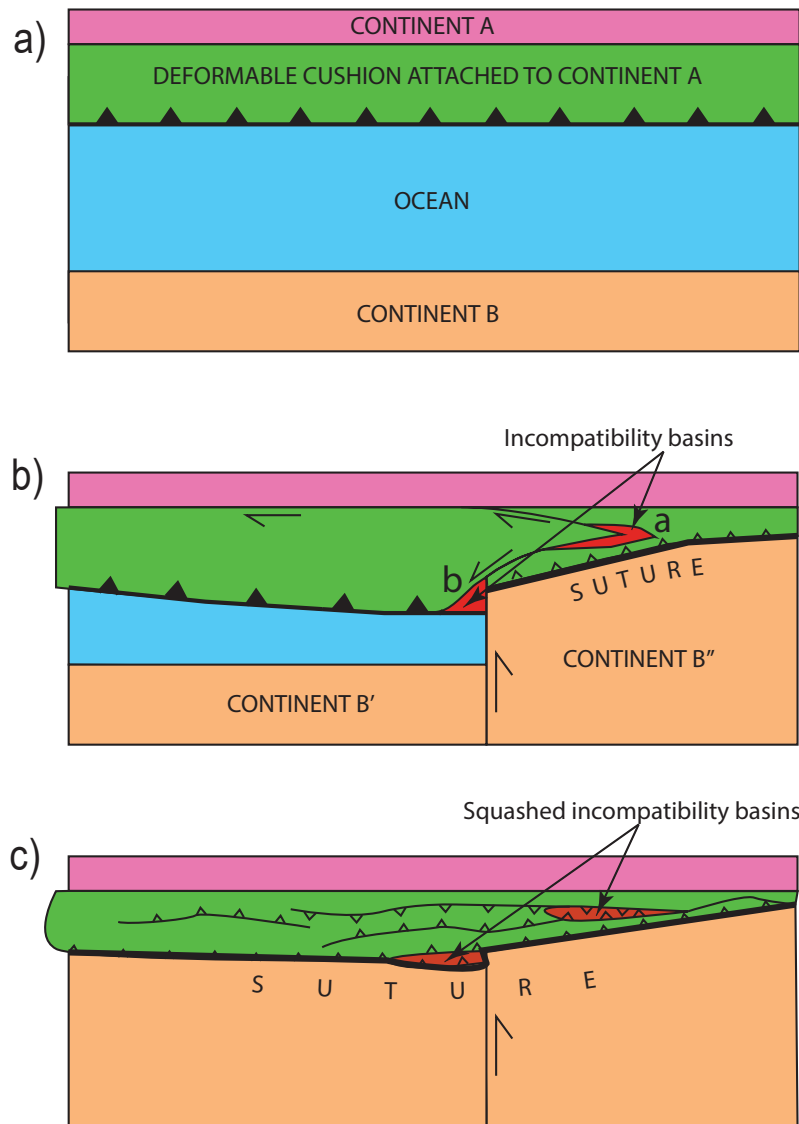


Figure 2: A sketch in map view depicts incompatibility basins arising from triple junctions and their fate: a) Continent A and continent B are approaching at the expense of the intervening ocean, which is being consumed beneath continent A creating an easily deformable cushion at its margin. b) Continent B is divided into two pieces, B' and B'' by a north-south striking transform fault. When continent B'' collides with continent A's easily deformable part of A is expelled westward. This leads to the formation of a Karhova-type incompatibility basin at a, and an Adana/Cilicia-type incompatibility basin at b. c) When full collision occurs following the elimination of all ocean between the two approaching continents, the previously formed incompatibility basins will also be squashed and obliterated out of recognition, except by careful local geological studies.

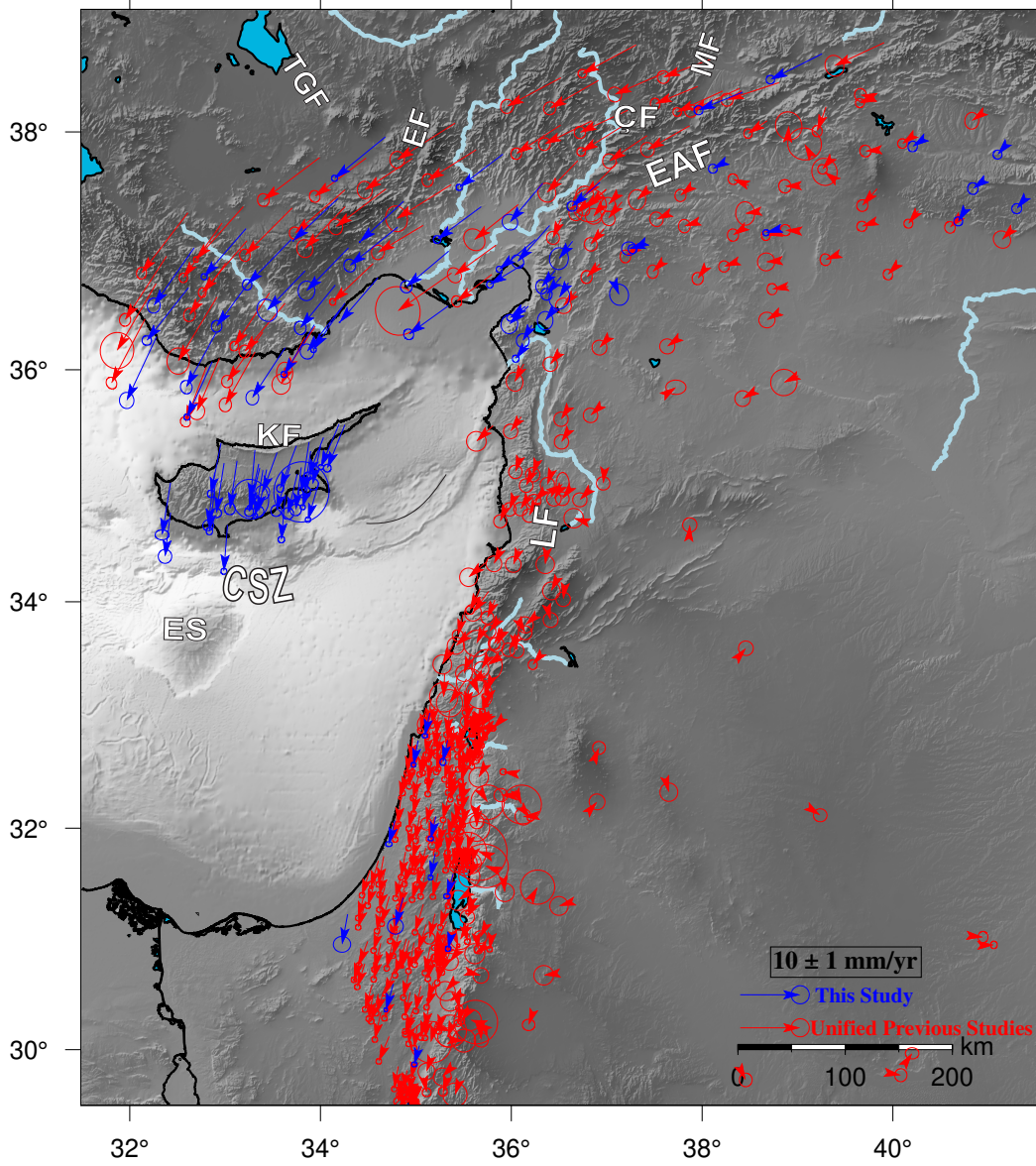


Figure 3: Unified GNSS velocity field with respect to the Arabian fixed reference frame. Blue arrows represent the newly derived rates and red arrows show previous studies previously-published rates.

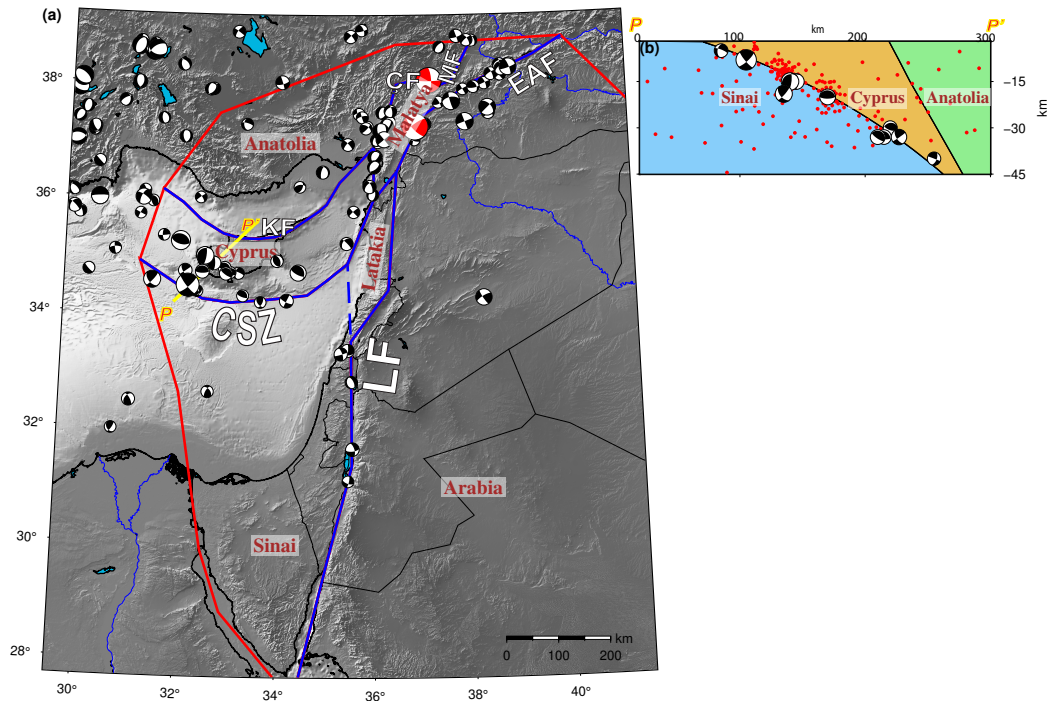


Figure 4: a) Block geometry and seismic activity around the region. Blue lines represent the boundaries defined as dislocation sources, red lines correspond to the other block boundaries which do not accumulate elastic strain. Focal mechanisms represent the earthquakes $M_w \geq 4.5$ between 1976-2022 (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 coincide with the domain of the cross section, were projected onto the section.

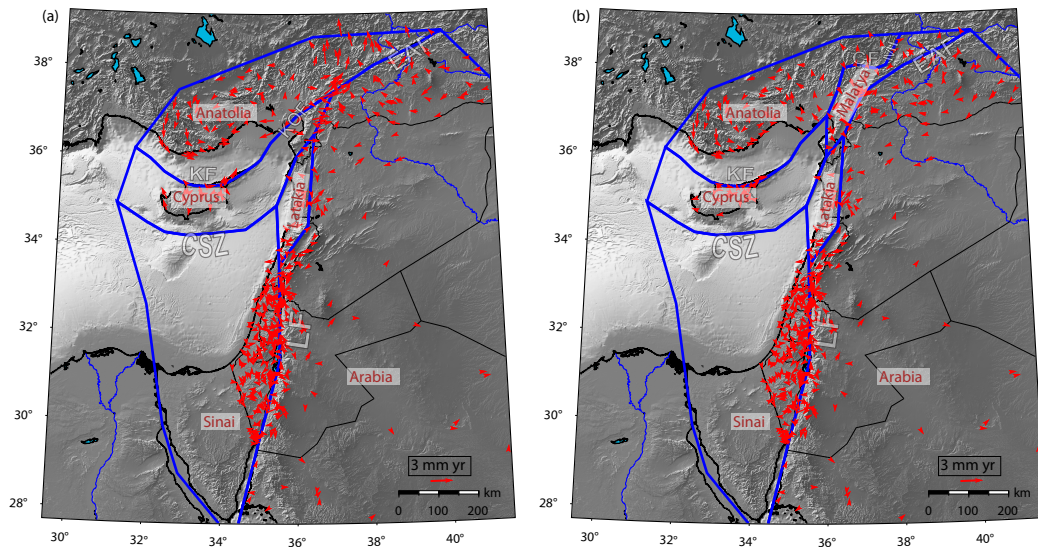


Figure 5: Comparing Diverse Block Geometries: a) This model adheres to the fault geometries proposed by Özkan et al. (2023) for Anatolia, without considering the Malatya block. b) Implementing the geometry as depicted in Fig.4a. The red arrows signify the residual velocities for each respective model.

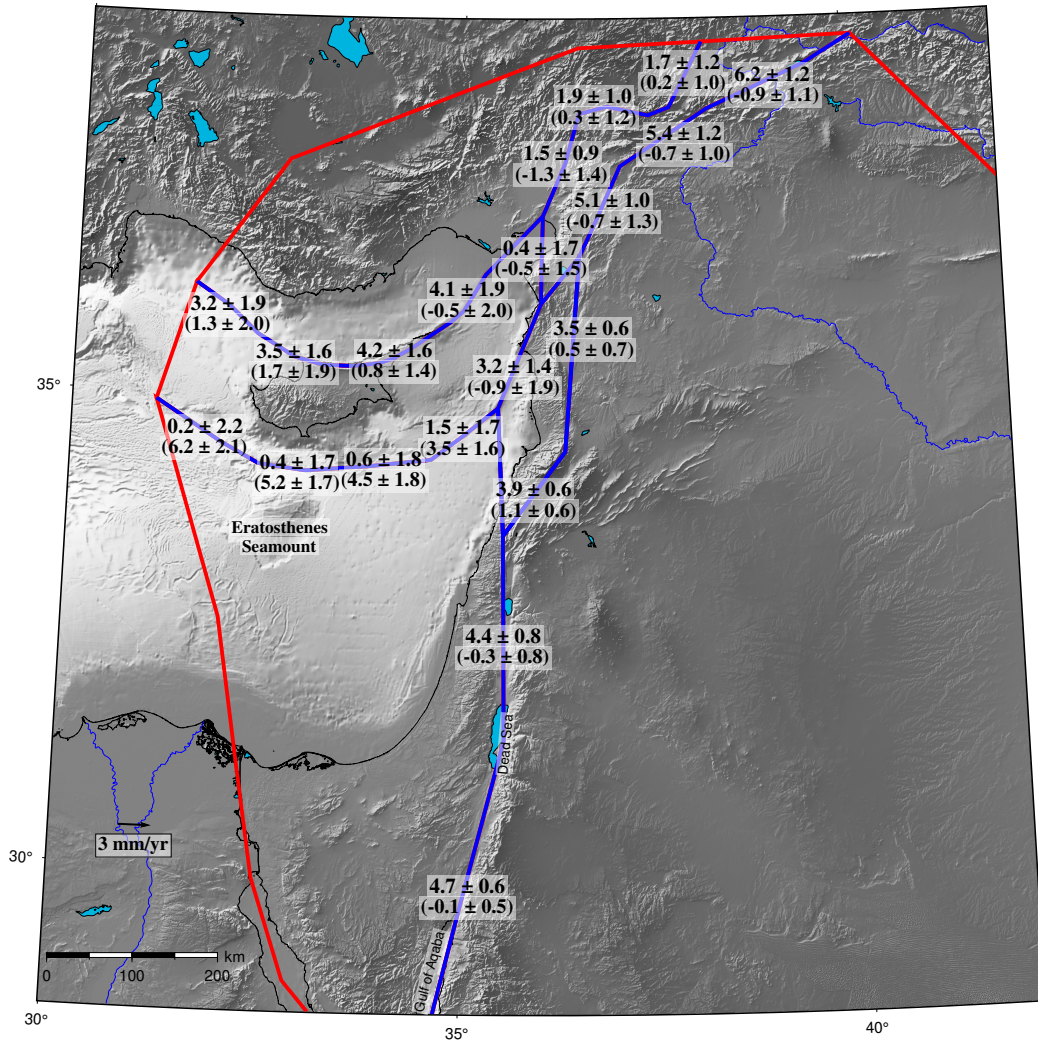


Figure 6: a) Modeled fault slip rates and residual velocities. The values with no parentheses are the strike-slip rates (Positive means left lateral) and the slip rates within the parentheses are convergence rates (positive means compression). Red arrows are the strain rate crosses for each block.

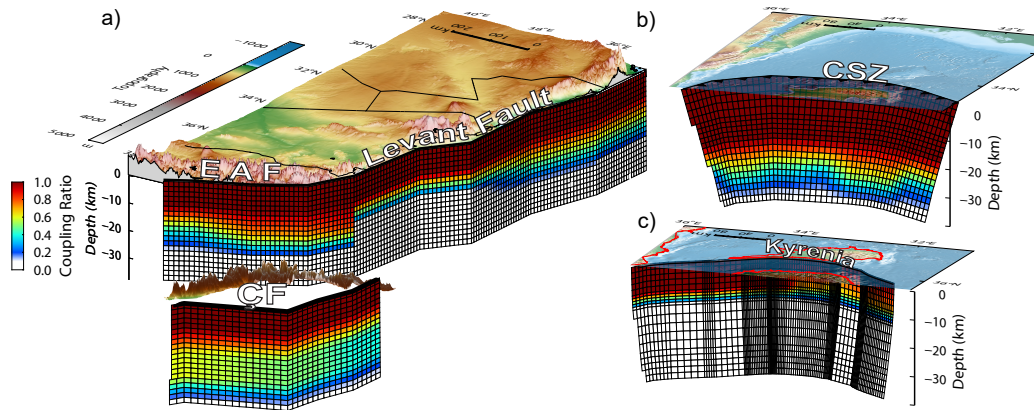


Figure 7: The distribution of locking on the dislocation sources within the block model. a) Levant, East Anatolian, and Çardak Faults (and the prolongation of the northwestern boundary of the Malatya block), b) Cyprus Subduction Zone, and c) Kyrenia fault.

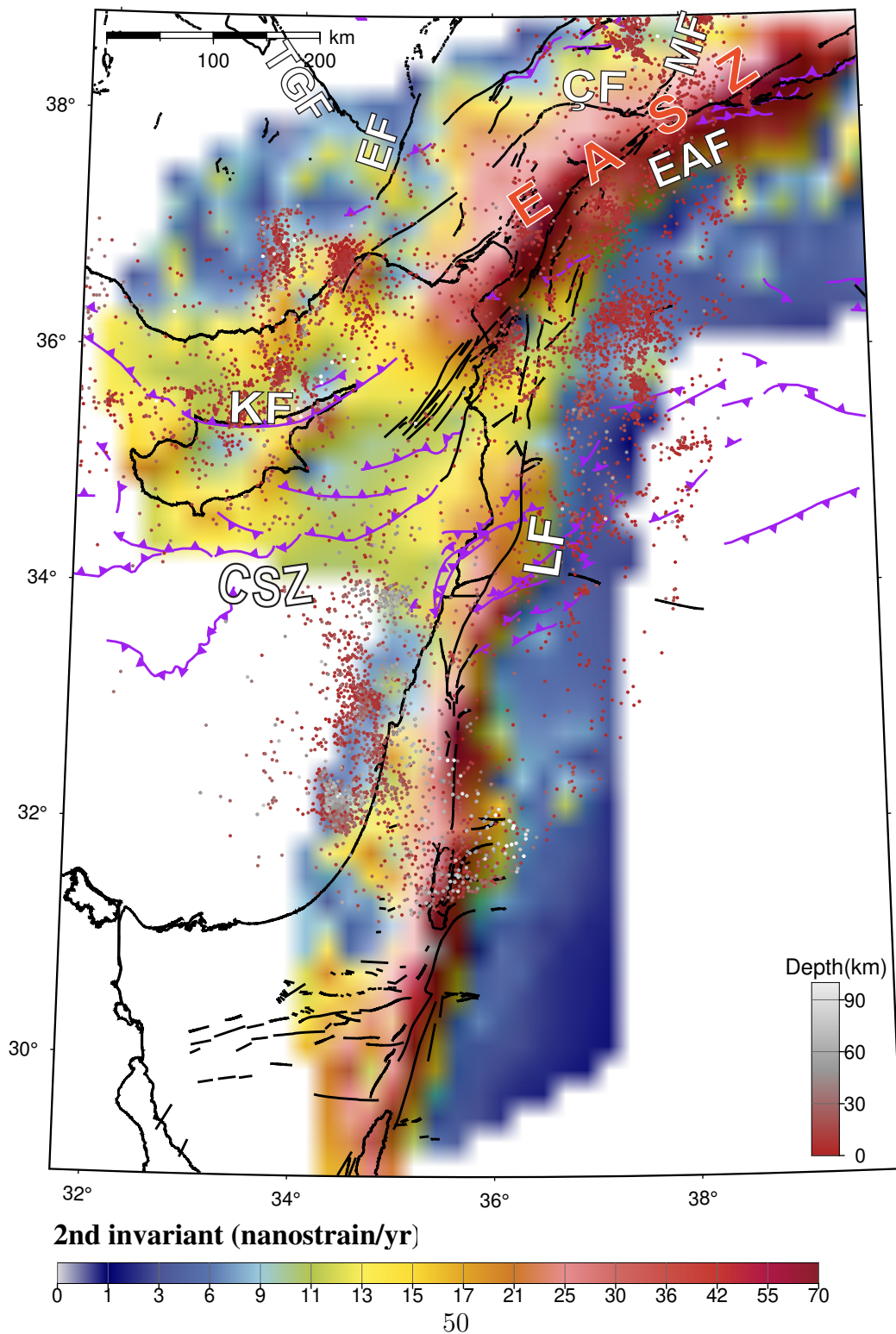


Figure 8: Seismicity, color-coded by depth, and the second invariant of the strain rate tensor. Seismicity catalog was taken from (KOERI, 2001; <http://www.koeri.boun.edu.tr>). EASZ: East Anatolian Shear Zone

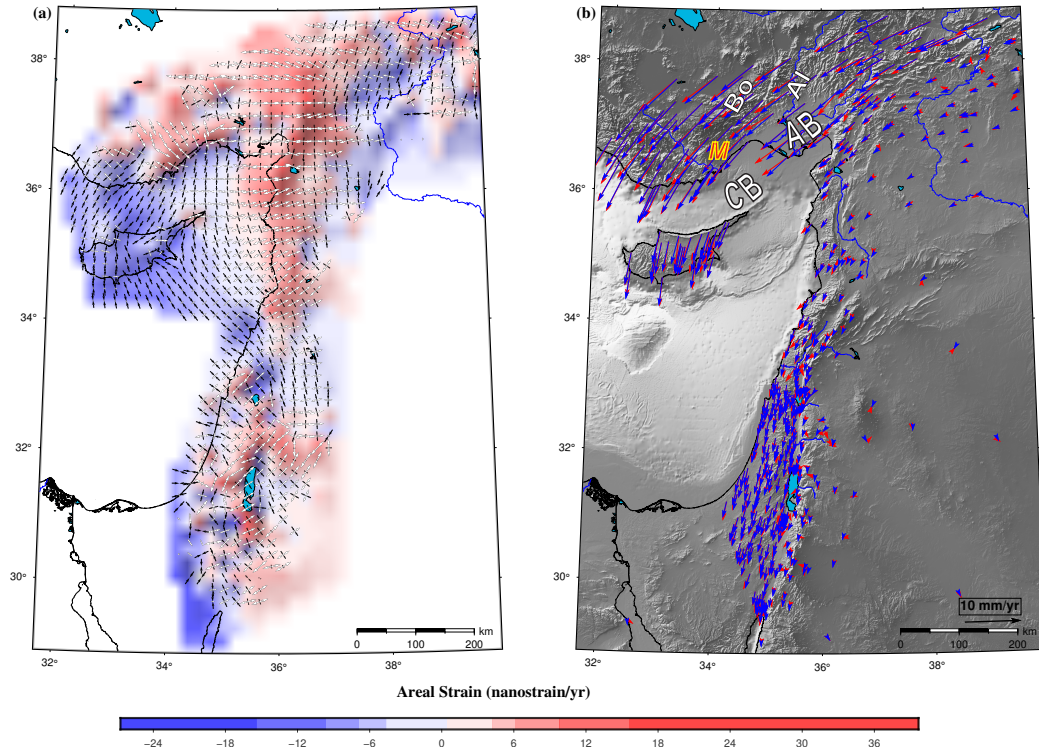


Figure 9: a) Strain rate field of the area. Arrow crosses are the principal strain rate tensor components. Black arrow belongs to the compression component of each tensor while white ones are the extensional component. Magnitudes of the principal rate crosses were normalized. The grid represents the 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). b) Observed (red) and predicted (blue) GNSS velocities. Bo: Bolkardağ, Al: Aladağlar.

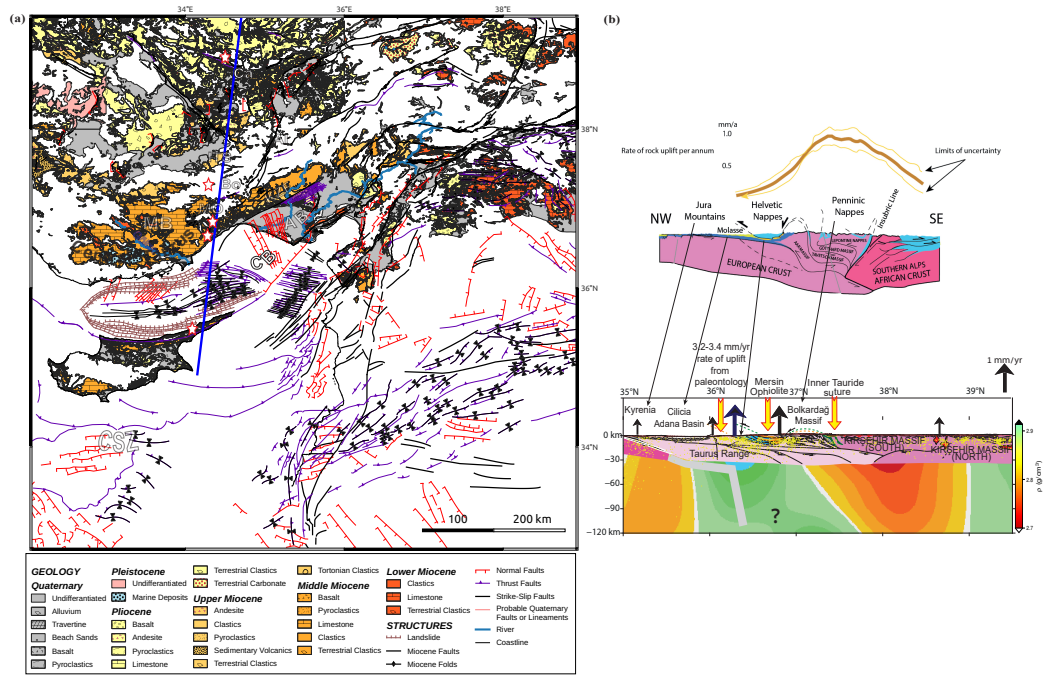


Figure 10: a) Tectonic formations and structures younger than Oligocene. Geologic formations, digitized from (Ed. Senel, 2002, Geological Map of Turkey, Adana), (Ed. Ulu, 2002, Geological Map of Turkey, Konya), and some formations were updated according to Ögretmen et al. (2018, fig. 2). Tectonic structures were compiled from Emre et al. (2013, 2018); Şengör and Zabcı (2019); Aksu et al. (2005); Burton-Ferguson et al. (2005); Aksu et al. (2014a, 2021, and cited studies therein). The solid blue line corresponds to the location of the cross-section displayed in panel (b). GNSS stations are shown as white stars. MB: Mut Basin, Bo: Bolkardağ, Al: Aladağlar, ITS: Inner Tauride Suture, MO: Mersin Ophiolite, Ca: Cappadocia. b) A cross-section from the southeast of Cyprus to Central Anatolia, with a comparative analysis involving the Alps. The upper portion comprises geological interpretations extracted from (Şengör et al., 2019b), while the lower part displays a density model derived from tomography (Karabulut et al., 2019). Black arrows indicate the GNSS uplift rates from stations labeled with stars in panel a). The analogy suggests that the Kyrenia Range corresponds to the Jura Mountains, and the Adana/Cilicia Basin serves as an equivalent to the Alpine molasse basin, with the Taurus Range and Bolkardağ Massif resembling the Helvetic Nappes and Lepontine Nappes, respectively. Long-term seismicity data were projected onto the section (KOERI, 2001; <http://www.koeri.boun.edu.tr>), and the tomography aligns with the 34°N generated from Karabulut et al. (2019).