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A stochastic view of the 2020 Elazığ M_w 6.8 earthquake (Turkey)

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Key Points:

- We infer a stochastic model for the distribution of subsurface fault slip associated with the 2020 Elazığ earthquake
- We account for uncertainties in both the depth-dependence of the assumed elastic structure and the location and geometry of the fault
- Our models are characterized by two primary patches of fault slip where distribution appears to be controlled by geometrical complexities

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Abstract

Until the M_w 6.8 Elazığ earthquake ruptured the central portion of the East Anatolian Fault (EAF, Turkey) on January 24, 2020, the region had only experienced moderate magnitude ($M_w < 6.2$) earthquakes over the last century. We use geodetic data to constrain a model of subsurface fault slip. We adopt an unregularized Bayesian sampling approach relying solely on physically justifiable prior information and account for uncertainties in both the assumed elastic structure and fault geometry. The rupture of the Elazığ earthquake was mostly unilateral, with two primary disconnected regions of slip. This rupture pattern may be controlled by structural complexity. Both the Elazığ and 2010 M_w 6.1 Kovancılar events ruptured portions of the central EAF that are believed to be coupled during interseismic periods, and the Palu segment is the last portion of the EAF showing a large fault slip deficit which has not yet ruptured in the last 145 years.

Plain Language Summary

The Elazığ earthquake ruptured the central portion of the East Anatolian Fault (EAF), a major strike-slip fault in eastern Turkey, on January 24, 2020. Before this event, the region had only experienced moderate magnitude earthquakes over the last century. We aim at understanding the rupture of this earthquake, and how it relates to the historical ruptures of the EAF. To do so, we use measurements of displacement at the surface to image the subsurface slip on the fault that occurred during the earthquake. As the characteristics of the crust are poorly known, we make realistic assumptions on the fault geometry and Earth structure, and build on novel approaches to account for the possible biases of our assumptions and to characterize the uncertainties of the imaged slip. We suggest that the Elazığ earthquake rupture may be controlled by structural complexity of the fault, and that two main regions of slip surround a fault bend acting as a barrier to rupture propagation. We also suggest that the fault segment located between Lake Hazar and the city of Palu is the last portion of the central EAF, showing a large deficit of the fault slip, which has not yet ruptured in the last 145 years.

1 Introduction

A large portion of Turkey is located on the Anatolian Plate (AP), which is slowly extruding westward as a result of the north-south collision between the Arabian and Eurasian tectonic plates (e.g., Mckenzie, 1970; McKenzie, 1972; McClusky et al., 2000). The west-

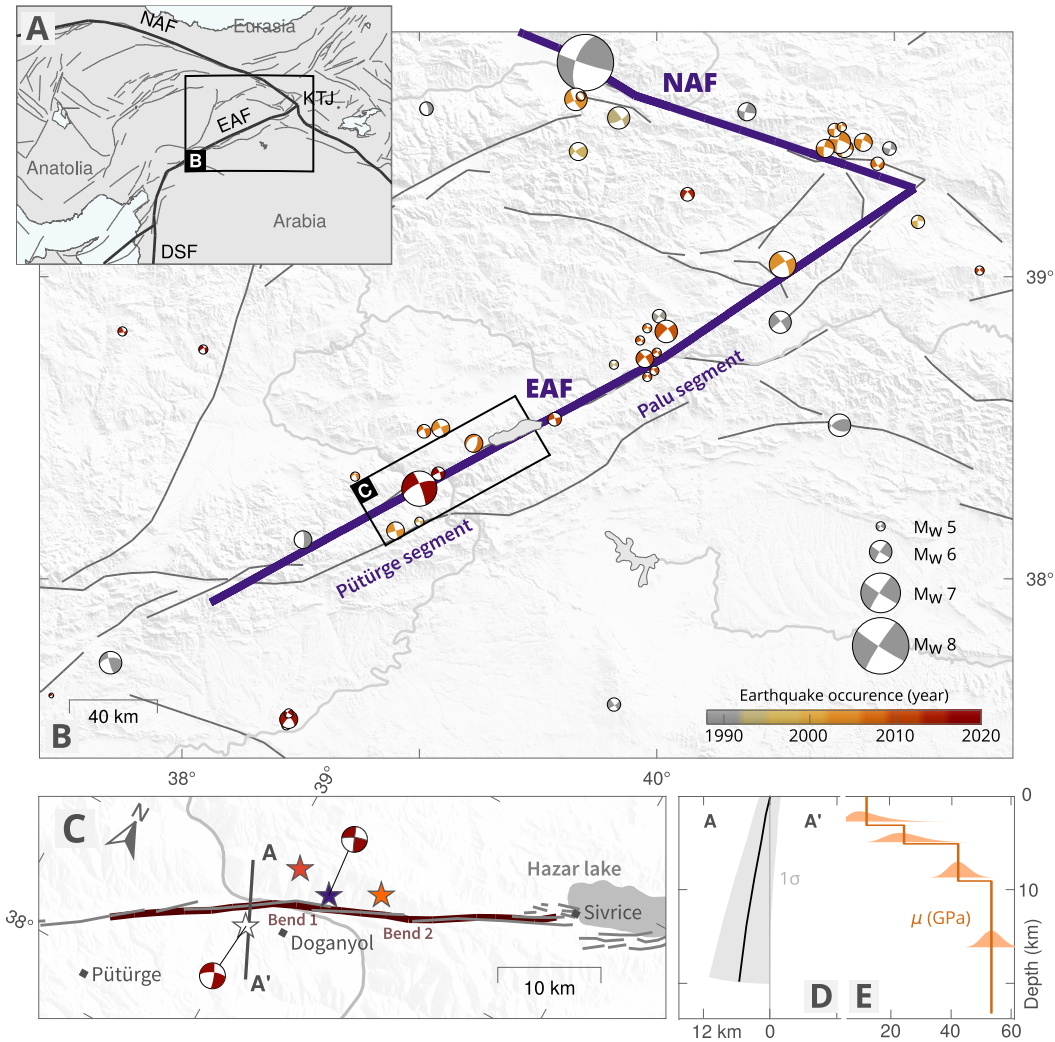


Figure 1. Tectonic setting and assumed characteristics for the Elazığ earthquake. (a) Tectonic setting of the area, plate boundaries are shown in thick black lines. East and North Anatolian Faults are labelled (EAF and NAF), as well as the Dead Sea fault (DSF) and Karlıova Triple Junction (KTJ). (b) Active fault traces (Basilic et al., 2013) and seismicity since 1976 (GCMT, Dziewonski et al., 1981) around the EAF and NAF. The Elazığ earthquake focal mechanism (GCMT) is in red. (c) Details of assumed (dark red) and mapped (gray) fault trace at the surface. Two structural bends of the causative fault geometry are highlighted. Possible epicenters are shown with white, red, purple and orange stars (from left to right on the map), respectively from GCMT, Jamalreyhani et al. (2020), KOERI and AFAD (2020). (d) Assumed fault geometry at depth and associated uncertainty (standard deviation of 5° around the assumed dip and 1 km around the fault surface trace). (e) Assumed shear moduli with depth (derived from Maden, 2012; Ozer et al., 2019) and associated uncertainties.

ward motion of the AP is predominantly accommodated along the North and East Anatolian faults (NAF and EAF, Fig. 1). The NAF experienced a sequence of destructive earthquakes that struck within the last eighty years (e.g., A. Barka, 1996; Stein et al., 1997; Armijo et al., 1999; Şengör et al., 2005). In contrast, the EAF is generally assumed to be less active, and has only experienced small to moderate events over the last century, although large ($M > 7$) earthquakes have occurred in the historical record (e.g., Ambraseys, 1970; Ambraseys & Jackson, 1998; Hubert-Ferrari et al., 2020).

The EAF is a left-lateral 600-km-long strike-slip fault linking the Dead Sea fault (DSF, Fig. 1) to the Karlova Triple Junction (KTJ, Fig. 1) where it intersects with the right-lateral NAF (e.g., Yilmaz et al., 2006; Duman & Emre, 2013). The EAF has a complex geometry divided into several main segments, each of them characterized by bends, pull-apart basins or compressional structures (e.g., Duman & Emre, 2013), and also comprises multiple secondary sub-parallel and seismically active structures delineating a 50-km-wide fault zone (e.g., Bulut et al., 2012). The EAF accommodates a displacement of 9 to 15 mm/yr (Cetin et al., 2003; Reilinger et al., 2006; Cavalíé & Jónsson, 2014; Aktug et al., 2016; Bletery et al., 2020), with creep dominantly at depths greater than 5 km (Cavalíé & Jónsson, 2014; Bletery et al., 2020). As a comparison, the NAF shows creep rates around 20-25 mm/yr below a locking depth of 7-25 km (e.g. Cakir et al., 2014a; Hussain et al., 2018; Kaneko et al., 2013; Walters et al., 2011; Wright et al., 2001). Shallower portions of the EAF are characterized by an highly varying inter-seismic slip deficit, some portions being fully coupled while others appear to be at least partially creeping (Bletery et al., 2020).

The January 24 2020 M_w 6.8 earthquake ruptured the EAF between the Hazar Pull-apart Basin and the city of Pütürge (Fig. 1). In the area, the main fault has been mapped, from the interpretation of aerial photos and field studies, as a sinuous trend interrupted by bends and step-overs whose widths do not exceed a kilometer (Duman & Emre, 2013). Coseismic surface rupture does not show a significant horizontal component and is probably mostly gravitational (Tatar et al., 2020). In this study, we investigate the subsurface rupture of the Elazığ earthquake and its relationship to fault geometry and inter-seismic slip deficit. While assuming a fault structure with a realistic geometry, we also account for its inherent uncertainties, as well as uncertainties related to assumptions on the crustal structure. We adopt a Bayesian sampling approach which allows us to sample a large panel of possible slip models and to estimate the posterior uncertainty on the

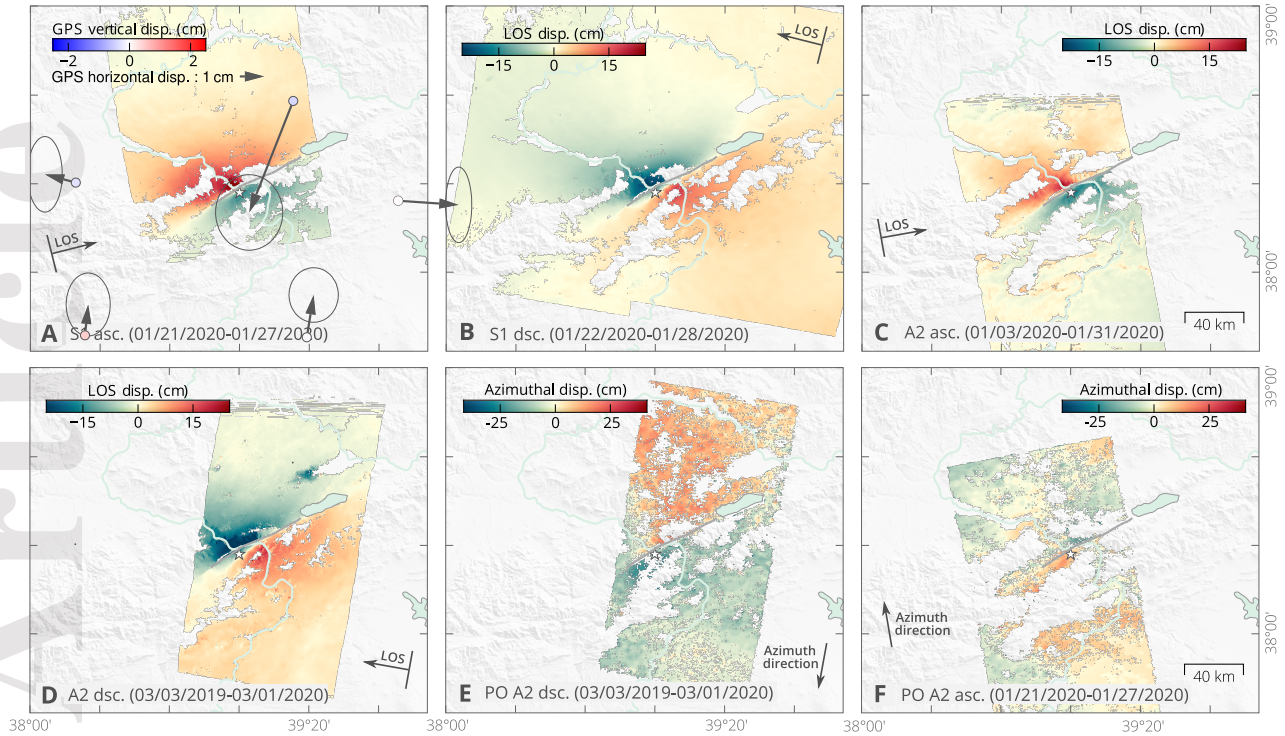


Figure 2. Observations used in this study. (a) Surface displacement in the satellite line-of-sight (LOS) direction from a Sentinel-1 (S1) ascending (asc.) interferogram, overlaid with coseismic GNSS offsets (Melgar et al., 2020). (b) Surface displacement from a Sentinel-1 descending (dsc.), (c) an ALOS-2 (A2) ascending interferogram, and (d) an ALOS-2 descending interferogram. (e) Pixel-offset (PO) surface displacement in the satellite along-track (azimuth) direction from the ALOS-2 descending pair, and (f) from the ALOS-2 ascending pair. The surface projection of the satellite LOS direction is positive in the ground-to-satellite direction.

79 inverted slip distribution. This approach allows us to describe the rupture of the Elazığ
 80 in detail, while discussing how it may have been driven by structural complexity. Finally,
 81 we also provide an updated interpretation of the seismic budget for the central EAF.

82 2 Bayesian Inference framework

83 2.1 Data

84 We derive the earthquake surface displacement from four Synthetic Aperture Radar
 85 (SAR) interferometric pairs and two SAR pixel offsets images (summarized in Table S2,
 86 Figs 2 and S1 for a closer view on the deformation). We computed two ALOS-2 ascend-
 87 ing and descending interferograms, and two Sentinel-1 ascending and descending inter-

88 ferograms. Copernicus Sentinel-1 data have been acquired by the European Space Agency
89 (ESA) and processed with the NSBAS software (Doin et al., 2012). ALOS-2 data are
90 collected by the Japan Aerospace Exploration Agency (JAXA) and have been processed
91 using the InSAR Scientific Computing Environment (ISCE) software (Rosen, 2012) aug-
92 mented with an additional module for processing ALOS-2 data (Liang & Fielding, 2017a).

93 We also applied pixel offset tracking analysis to ALOS-2 images on both tracks (Liang
94 & Fielding, 2017b). Resulting surface displacements have lower precision and higher noise
95 than LOS measurements, but provide useful information on the deformation along the
96 satellite track (azimuthal) direction. Due to snowy conditions in January, both L-band
97 ALOS-2 and C-band Sentinel-1 data decorrelate at higher topographic elevations. Note
98 that surface displacements derived from the InSAR data contain from 3 to 7 days of post-
99 seismic deformation, which might affect our modeling of the coseismic phase (Ragon, Sladen,
100 Bletery, et al., 2019; Twardzik et al., 2019). InSAR and dense pixel offsets from the ALOS-
101 2 descending track cover 1 year of preseismic and 1 month of postseismic deformation,
102 and thus also include long-term deformation. To improve computational efficiency, we
103 resample InSAR observations based on model resolution (Lohman & Simons, 2005) with
104 quadtree regions ranging from 12 km to 1.2-2 km wide. We remove data points that are
105 within 500 m of the fault trace to prevent spatial aliasing. We estimate measurement
106 uncertainties following Jolivet et al. (2012, Fig. S2). We also use 3 components coseis-
107 mic GNSS offsets at 6 stations located within 120 km of the rupture (Fig. 2). These off-
108 sets have been processed by Melgar et al. (2020) and extracted from high-rate GNSS dis-
109 placements.

110 **2.2 Fault geometry and elastic structure**

111 Duman and Emre (2013) mapped the main surface trace of the Pütürge segment
112 as a relatively continuous sinusoidal trend interrupted by small bends and step-overs whose
113 width do not exceed the kilometer. Over the Lake Hazar releasing bend (Fig. 1c), the
114 fault trace divides into multiple parallel lineaments that outline a 10 km wide fault zone
115 (e.g., Garcia Moreno et al., 2011). Around Doğyanol, the fault strike abruptly changes
116 by 10° . West of the rupture area, two major bends affect the Pütürge segment before
117 it links to the Erkenek segment. The strike change around Doğyanol has been well out-
118 lined by InSAR data as well (Figs 2, S1), although the rupture did not reach the sur-
119 face. We build on these observations, as well as on the location of the aftershocks and

120 previous seismicity (Bulut et al., 2012; Melgar et al., 2020) to define the surface geom-
 121 etry of the causative fault. Hereafter, we will refer to the two bends of the causative fault
 122 as the main bend (bend of $\sim 10^\circ$ around the city of Doganyol, refer to Fig. 1c) and the
 123 second bend (east of the main bend).

124 InSAR data show largest amplitudes north of the fault (Fig. 2), suggesting that
 125 the fault is slightly dipping northward, as confirmed by the aftershocks (Melgar et al.,
 126 2020; Pousse-Beltran et al., 2020). We thus assume a fault dipping of 79° northward (Fig. 1d),
 127 from its south-western end to 30 km eastward, the dip angle linearly decreases to 75°
 128 further east. We discretize the fault into 203 triangular subfaults whose side range from
 129 1.5 km at the surface to 4-5 km at depth. We also assume a layered crustal model (Tab. S1)
 130 derived from the seismic velocity models for NE Turkey proposed by Maden (2012) and
 131 by the V_p/V_s ratio proposed by Ozer et al. (2019), and compute coseismic Green's func-
 132 tions following Zhu and Rivera (2002).

133 2.3 Bayesian Sampling of the inverse problem

134 In this study, we explore the full solution space of co-seismic slip distributions com-
 135 patible with geodetic observations in order to sample the range of plausible models. The
 136 sampling is performed with a Bayesian approach implemented in the AlTar2 package,
 137 originally formulated by Minson et al. (2013). AlTar combines the Metropolis algorithm
 138 with a tempering process to iteratively sample the solution space. A large number of sam-
 139 ples are tested in parallel at each transitional step, which is followed by a resampling step,
 140 allowing us to select only the most probable models. The probability of each sample to
 141 be selected depends on its ability to fit the observations \mathbf{d}_{obs} within the uncertainties
 142 $\mathbf{C}_\chi = \mathbf{C}_d + \mathbf{C}_p$, where \mathbf{C}_d represents the observational errors and \mathbf{C}_p the epistemic
 143 uncertainties introduced by approximations of the forward model (e.g., Minson et al.,
 144 2013; Duputel et al., 2014; Ragon et al., 2018; Ragon, Sladen, & Simons, 2019).

145 The solution space is evaluated through repeated updates of the probability den-
 146 sity function (PDF) of each sampled parameter

$$p(\mathbf{m}, \beta_i) \propto p(\mathbf{m}) \cdot \exp[-\beta_i \cdot \chi(\mathbf{m})], \quad (1)$$

147 where \mathbf{m} is the sampled model, $p(\mathbf{m})$ the prior information on this sample, i corresponds
 148 to each iteration and β evolves dynamically from 0 to 1 to optimize the parameter space
 149 exploration (Minson et al., 2013). $\chi(\mathbf{m})$ is the misfit function which quantifies the dis-

150 crepancies between observations and predictions within uncertainties described by the
 151 covariance matrix \mathbf{C}_χ (Tarantola, 2005; Minson et al., 2013, 2014; Duputel et al., 2014)

$$\chi(\mathbf{m}) = \frac{1}{2}[\mathbf{d}_{\text{obs}} - \mathbf{G}(\mathbf{m})]^T \cdot \mathbf{C}_\chi^{-1} \cdot [\mathbf{d}_{\text{obs}} - \mathbf{G}(\mathbf{m})]. \quad (2)$$

152 We solve for both slip amplitude and rake, within the assumed unrestrictive posi-
 153 tive uniform prior distribution $p(\mathbf{m}) = \mathcal{U}(0 \text{ m}, 20 \text{ m})$ for the strike-slip parameters,
 154 and within the restrictive Gaussian prior distribution centered on zero for the dip-slip
 155 parameters $p(\mathbf{m}) = \mathcal{N}(0 \text{ m}, 1 \text{ m})$.

156 Ad-hoc choices of regularization, such as smoothing or moment minimization, arti-
 157 ficially restrict the range of possible models and strongly bias the inferred slip distri-
 158 butions towards simplistic overly-smoothed solutions (e.g., Du et al., 1992; Causse et al.,
 159 2010). In our approach, we do not impose any type of prior regularization and explore
 160 the entire solution space, i.e. the entire range of possible slip models. The final output
 161 thus consists in a series of models sampled from among the most plausible models of the
 162 full solution space. To explore the results, we consider probabilistic variables, such as
 163 a combination of the mean of the sampled models and the associated posterior uncer-
 164 tainty (standard deviation).

165 2.4 Accounting for epistemic uncertainties

166 Our estimates of fault slip are driven by the quality and quantity of observations,
 167 but also by the way we build the forward model and any other prior information we in-
 168 clude in the problem. Any prior choice made to evaluate the Green's function (includ-
 169 ing problem parameterization and description of the Earth interior) will have a signif-
 170 icant impact on inferred model parameters (e.g., Beresnev, 2003; Hartzell et al., 2007;
 171 Yagi & Fukahata, 2008; Razafindrakoto & Mai, 2014; Duputel et al., 2014; Gallovič et
 172 al., 2015; Diao et al., 2016; Mai et al., 2016). So-called epistemic uncertainties stem from
 173 our imperfect description, or simplification, of the parameters describing the Earth in-
 174 terior, such as crustal properties (e.g., rheology), fault geometry or regional character-
 175 istics (e.g., topography, Langer et al., 2020). In contrast, aleatoric uncertainties will de-
 176 rive from random, or unknown, processes. In this study, we account for the epistemic
 177 uncertainties caused by our poor knowledge of the fault dip, the fault position, and the
 178 elastic layered crustal structure, following the methodologies presented by Duputel et

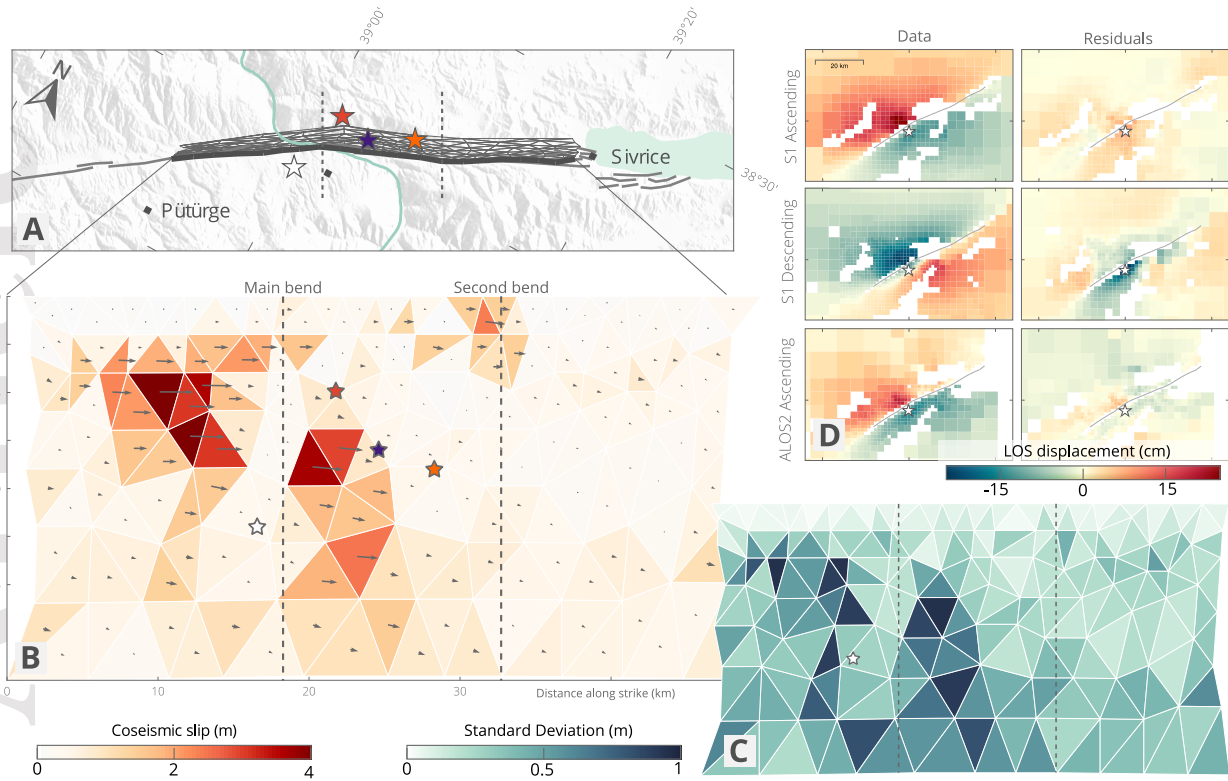


Figure 3. Inferred average slip model and associated posterior uncertainty for the Elaziğ earthquake. (a) Map view of the fault trace, subfaults contours at depth and local setting. Possible epicenters are shown with white, red, purple and orange stars (from left to right on the map), respectively from GCMT, Jamalreyhani et al. (2020), KOERI and AFAD (2020). (b) Depth view of the average total slip amplitudes and directions. (c) Standard deviation of the inferred strike-slip parameters. (d) Observed and predicted surface displacement in the LOS direction from Sentinel-1 ascending and descending, and ALOS-2 ascending, InSAR.

179

al. (2014); Ragon et al. (2018); Ragon, Sladen, and Simons (2019). A part of the aleatoric uncertainties is also quantified with our stochastic approach.

180

181

We assume 1 km uncertainty (1σ) in the location of the surface projection of the fault, and 5° uncertainty (1σ) in the fault dip, the fault rotating as a whole around its assumed dip (Fig. 1). We assume uncertainties on the shear modulus for every layer (Poisson's ratio is held constant within each layer), the uncertainty decreasing with depth (Fig. 1, Tab. S1).

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3 Results

We infer primarily strike-slip fault slip (Fig. 3). Most of the slip is imaged around the main bend (localized around the city of Doganyol, Fig. 3a). Slip exceeds 3 m within two slip patches, from 2 to 10 km depth west of the main bend and from 7 to 10 km depth east of the main bend. Associated posterior uncertainty for these patches can reach up to ~ 1 m for highest amplitudes (Fig. 3c). West of the main bend, the rupture extends down to greater depths (7 - 15 km) with moderate slip amplitudes of ~ 2 m. At depth, the posterior model uncertainty reaches up to 1 m. The posterior marginal distributions all show well-delineated Gaussian shapes (Fig. S3), even for the smallest slip amplitudes. The posterior PDFs on subfaults in between these two main slip patches indicate well resolved very low slip amplitudes (Fig. S3), suggesting that the two patches are disconnected (Fig. 3c).

One other narrow slip patch can be observed west of the main bend, at the location of the second bend. Slip is imaged from the surface to 4-km-depth, with maximum amplitudes reaching 2.5 m at the surface, and with relatively small posterior uncertainty. This patch is not connected with the main slip patches, and does not seem to correspond to any $M_w > 4$ aftershock (relocated by Melgar et al., 2020; Pousse-Beltran et al., 2020). This slip may be coseismic or afterslip (given that the InSAR data span a period up to one month after the mainshock).

Observations are well fit by the predictions of our model (Table S3, Figs. 3(d), S5, S6, S7 and S8 for the InSAR and GNSS data respectively), within the assumed uncertainties and possible remaining noise (in particular for the pixel-offset data). Accounting for epistemic uncertainties mitigates overfitting (Ragon et al., 2018). Residuals are expected to be larger than if epistemic biases are neglected. The descending interferograms present larger residuals (Figs. S5, S6, S7) because the assumed fault geometry is primarily constrained by ascending data, and the descending imaging geometry is less favorably oriented (the LOS has a 45° angle with the fault strike).

We also infer the slip distribution of the Elazığ earthquake assuming a planar fault structure dipping of 85° towards the north and embedded within a homogeneous half space, without introducing any epistemic uncertainty (Fig S9). Unlike our preferred model, the slip is concentrated in a single shallow and extended slip patch with low posterior uncertainty. Highest amplitudes (up to 3.5 m) are reached above the main bend, from

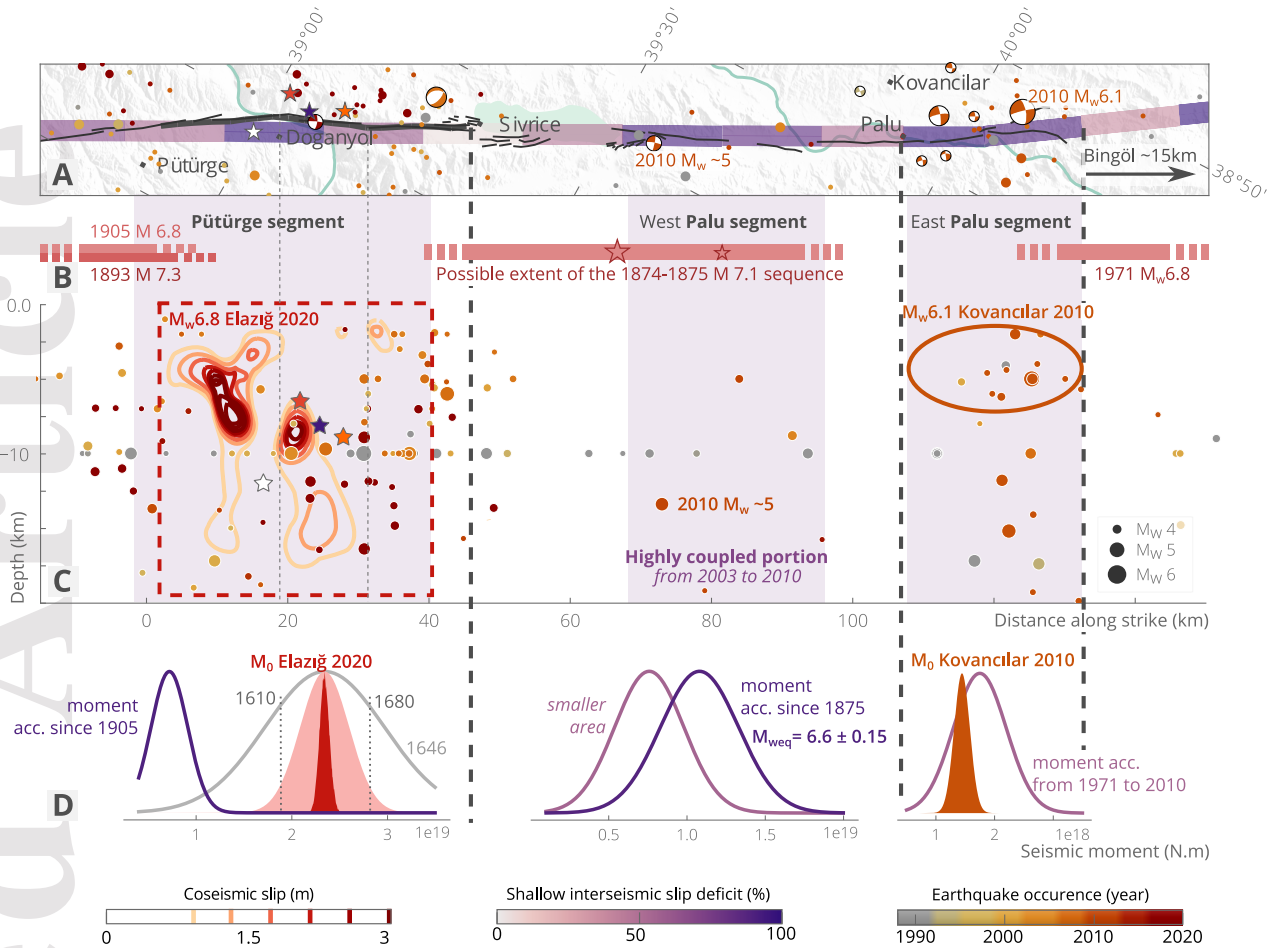


Figure 4. Comparison between the spatial distributions of the 2020 Elazığ earthquake rupture, historical earthquakes, highly coupled sections of the EAF, and seismic moment accumulated since last historical rupture in relation with seismic moment released by the most recent event. (continued)

218 1.5 to 9 km depth. Low slip values are inferred at depths greater than 10 km and lower
 219 than 1.5 km. Some slip is also inferred around the second bend. As expected, the fit of
 220 the predicted displacement to the observations is good (Table S3, Figs. S10, S11, S12 and
 221 S13), descending interferograms still presenting larger residuals, and slightly better than
 222 with our preferred inference.

223 **4 Discussion and Conclusion**

Figure 4. Comparison between the spatial distributions of the 2020 Elazığ earthquake rupture, historical earthquakes, highly coupled sections of the EAF, and seismic moment accumulated since last historical rupture in relation with seismic moment released by the most recent event. (A) Map view of two segments the East Anatolian Fault (black lines), overlaid with historical and recent seismicity from 1900 to January 2020 (Retrieved from AFAD, 2020; NEIC, 2020; Melgar et al., 2020), shallow interseismic slip deficit (Bletery et al., 2020) and our assumed fault trace for the 2020 Elazığ event (thick black line). (B) Possible rupture extents for the 4 most recent $M_w > 6.5$ earthquakes that struck the mapped segments of the EAF before the Elazığ event, inferred from Ambraseys (1989); Hubert-Ferrari et al. (2020). Red stars denote the locations of the mainshock and aftershock of the 1874 sequence (Ambraseys, 1989). Fault segments of the central EAF are indicated, from Duman and Emre (2013). (C) Depth extent of the slip amplitude inferred for the 2020 Elazığ event (Fig. 3), along with the highly coupled sections of the EAF between 2003 and 2010 (Bletery et al., 2020), and the possible extent of the 2010 M_w 6.1 Kovancilar earthquake estimated from the spatial coverage of aftershocks and basic scaling laws (Wells & Copper-smith, 1994; Tan et al., 2011), as well as historical and recent seismicity from 1900 to January 2020. (D) For highly coupled portion of each segment, comparison of PDFs of accumulated seismic moment since last historical rupture (in purple), with the seismic moment (M_0) of last recent earthquakes, i.e. the 2020 Elazığ (red) or 2010 Kovancilar (orange) events. For the Pütürge segment, the PDF and mean of accumulated seismic moment since the time needed to accumulate the Elazığ event M_0 are shown in gray, and the PDFs of the Elazığ M_0 are derived from our preferred slip model (red), with a version accounting for uncertainties in the shear modulus ($\mu = 2.8 \pm 0.3 \cdot 10^1$ GPa, light red).

224 4.1 A stochastic view of the 2020 Elazığ coseismic rupture

225 Assuming a realistic fault geometry and crystal structure, and accounting for re-
 226 lated epistemic uncertainties, we estimate the slip distribution of the 2020 Elazığ earth-
 227 quake with a Bayesian inference approach. We show that the coseismic rupture affects
 228 almost the full width of the Pütürge segment, down to 15-km-depth, with a geodetic mo-
 229 ment $M_0 = 2.34 \pm 0.25 \cdot 10^{19}$ N · m and an equivalent moment magnitude of 6.84 ($\mu =$
 230 $2.8 \pm 0.3 \cdot 10^1$ GPa). Two disconnected slip patches host most of the slip: one patch shows
 231 slip exceeding 3 m from ~ 3 to ~ 10 km depth east of the main bend, while the second
 232 slip patch extends from 7-km-depth down to 15-km-depth with slip amplitudes larger
 233 than 2 m just west of the main bend (Fig. 3).

234 A large shallow slip (0-5 km, 2.5 m in amplitude) is also imaged around the sec-
235 ond bend. While the standard deviation associated with this shallow slip patch is rel-
236 atively small, its amplitude is poorly constrained by scarce, and possibly noisy, data points
237 largely affected by snowy conditions (Figs. S5, S6, S7). Some of our InSAR data cov-
238 ering up to one month after the mainshock, some imaged deformation, such as this shal-
239 low patch, might actually be postseismic. Yet, the surface displacement from 1 week to
240 5 months after the mainshock does not reach more than a few centimeters (Fig. S14),
241 suggesting that, if afterslip occurred, it was in the hours following the mainshock and
242 with a limited amplitude (as the amplitude of early afterslip often scales with the longer
243 term postseismic deformation, e.g., Twardzik et al., 2019), thus probably not excessively
244 affecting our slip estimates.

245 The inferred slip distribution changes significantly if we assume a planar fault em-
246 bedded in a homogeneous crust and we neglect uncertainties stemming from the assump-
247 tion of a simplified Earth interior. In particular, a single and shallower slip patch is in-
248 ferred around the epicenter, no slip larger than 50 cm being imaged above 2 km, or larger
249 than 80 cm below 10 km depth. The pronounced slip deficit imaged when assuming a
250 simplified forward model (Fig. S15) might suggest that the shallow slip deficit observed
251 by Pousse-Beltran et al. (2020) may be an artifact deriving from modeling choices, as
252 proposed by Xu et al. (2016) and Ragon et al. (2018).

253 The location of the epicenter, as estimated from different institutions and authors,
254 comes with more than 16 and 20 kilometers uncertainty in depth and position, respec-
255 tively (e.g., Jamalreyhani et al., 2020; Tatar et al., 2020). While some models proposed
256 a location around the main bend, many others proposed epicenters rather located in be-
257 tween the two bends (Fig. 3). Robust interpretation on rupture directivity is largely af-
258 fected by uncertainty in epicenters location, although our results suggest the rupture of
259 the Elazığ earthquake might be mostly unilateral to the SW.

260 Our estimates of the pattern of fault slip differ from other estimates based on sim-
261 ilar data (e.g., Melgar et al., 2020; Pousse-Beltran et al., 2020; Cheloni & Akinci, 2020;
262 Dođru et al., 2020). Our preferred model is very different from Pousse-Beltran et al. (2020);
263 Cheloni and Akinci (2020); Dođru et al. (2020), where peak slip reaches only 2 m over
264 the main bend. In contrast, our preferred model shares many characteristics with the
265 preferred one of Melgar et al. (2020), especially for the peak slip location and the over-

266 all shape of the ruptured areas, although they image large slip values east of the KO-
267 ERI epicenter. Melgar et al. (2020) preferred model being primarily driven by high-rate
268 GNSS data and assuming a 1D crustal structure, these shared characteristics suggest that
269 assuming a layered crustal model is necessary to infer robust slip estimates in this re-
270 gion.

271 4.2 Structurally driven slip on the Pütürge segment

272 Fault segmentation and bends are thought to act as geometric barriers that can
273 influence, or even drive, rupture initiation, termination and propagation (e.g., G. King
274 & Nabelek, 1985; A. A. Barka & Kadinsky-Cade, 1988; Wesnousky, 2006; Duan & Oglesby,
275 2005; Aochi et al., 2002; Perrin et al., 2016; Klinger, 2010). Similarly, creeping sections
276 might act as barriers to earthquake propagation (e.g., G. C. P. King, 1986; Chlieh et al.,
277 2008; Perfettini et al., 2010; Kaneko et al., 2010).

278 The coseismic rupture of the Elazığ earthquake likely started in a relatively pla-
279 nar portion of the fault, in between its two main bends (refer to Fig. 3, Jamalreyhani
280 et al., 2020). Similarly, peak slip amplitudes and most of the slip are located in relatively
281 smooth areas, and surround the main bend where well-resolved low slip values have been
282 imaged. The absence of slip in the main bend is a robust characteristic of our preferred
283 slip model, which has not been imaged in previous studies (e.g., Melgar et al., 2020). The
284 event thus likely ruptured a first portion of the Pütürge segment, stopped at the main
285 bend acting as a barrier, and then broke a second portion, a process that has been ob-
286 served in numerical simulations (e.g., Kato et al., 1999; Duan & Oglesby, 2005). A per-
287 turbation of the rupture propagation by the main bend well correlates with the appar-
288 ent rupture velocity decrease around the geometrical complexity (imaged by back-projection
289 of waveforms, Pousse-Beltran et al., 2020), and the two distinct peaks of the source time
290 function (automatically determined, Vallée & Douet, 2016).

291 Slip slowly decreases towards Lake Hazar (Fig. 4). Aftershocks activity also declines
292 abruptly at the basin boundary (Melgar et al., 2020; Jamalreyhani et al., 2020). The pull-
293 apart basin hosting Lake Hazar might thus have acted as a geometrical barrier to the
294 ruptured asperity (as also observed for the Haiyuan fault, China, Liu-Zeng et al., 2007;
295 Jolivet et al., 2013). To the west, no specific geometrical complexity is imaged at the sur-

296 face, and the rupture may have stopped at the maximum length of the fault segment (Klinger,
297 2010).

298 Finally, the location of the main bend also corresponds to the portion of the EAF
299 that shows maximum shallow interseismic slip deficit ($>90\%$, Fig. 4). Inferred slip partly
300 overlays this portion of maximum slip deficit, but the coseismic rupture also extends over
301 moderately coupled regions (30-40%) at greater depths (from 8 to 15-km-depth). The
302 second bend, to the northeast of the main bend (Fig. 3), is also surrounded by large (>2
303 m) slip amplitudes at shallow depths.

304 Altogether, these observations suggest that the distribution of subsurface fault slip
305 during the Elazığ earthquake may largely reflect complexities in the fault geometry. Rup-
306 tured portions appear to be relatively smooth. In contrast, the main fault bend likely
307 acted as a barrier to rupture propagation, over which no slip has been imaged, similarly
308 to the structure responsible for the pull-apart basin of Lake Hazar. The bend is not prone
309 either to aseismic slip (at least at shallow depths). The deepest imaged slip patch, down
310 to 15-km-depth, confirms that the seismogenic depth is deeper than 10 km for the cen-
311 tral EAF (Bulut et al., 2012). Our results do not seem to corroborate the shallow lock-
312 ing depth (full creep below 5 km) inferred by Cavalíe and Jónsson (2014). This behav-
313 ior appears similar to the NAF, where large earthquakes occur on faults also prone to
314 aseismic slip (Cakir et al., 2005, 2014b; Schmittbuhl et al., 2016).

315 4.3 Seismic potential of the Palu segment

316 From Pütürge to Bingöl, interseismic slip deficit above 5-km-depth varies along strike,
317 as inferred from geodetic data from 2003 to 2010 (Bletery et al., 2020, Figs 4, S16). Three
318 main sections of large shallow interseismic slip deficit ($>70\%$) are clearly distinct: one
319 on the Pütürge segment, another on the West Palu segment, and a last one east of the
320 city of Palu, on the East Palu segment. Before the Elazığ event, this portion of the EAF
321 was struck by 4 large earthquakes in the last 200 years. Two $M \sim 6.8$ and $M \sim 7.3$ oc-
322 curred west of Lake Hazar in 1893 and 1905 (Ambraseys, 1989). In 1874-1875, a sequence
323 of two $M \sim 7.1$ and $M \sim 6.7$ likely struck the region between Sivrice and Palu (Ambraseys,
324 1989; Cetin et al., 2003; Hubert-Ferrari et al., 2017). East of the locality of Palu, the re-
325 gion around the city of Bingöl was affected by a M_w 6.8 in 1971 (Ambraseys, 1989; Am-
326 braseys & Jackson, 1998).

327 Slip deficit has accumulated on the EAF since these recent historical ruptures, and
328 the newly coupled portions (from 2003 to 2010) are preferably located in between the
329 historically ruptured segments (Bletery et al., 2020). The 2010 M_w 6.1 earthquake that
330 occurred near Kovancilar (Akkar et al., 2011) appears to have filled the possible seismic
331 gap between the 1874 sequence and the 1971 Bingöl event (Fig. 4B). Similarly, the ex-
332 tent of the Elazığ rupture well overlays with a highly coupled portion of the EAF, and
333 it may have filled a possible gap between the 1893/1905 earthquakes and the 1874 se-
334 quence (Melgar et al., 2020; Duman & Emre, 2013).

335 We compare the seismic moment accumulated since the possible last historic rup-
336 ture of the Pütürge segment (1905) with the seismic moment released during the 2020
337 Elazığ earthquake (Fig. 4D). To do so, we calculate the seismic moment for the area rup-
338 tured by the event according to our slip model, and account for uncertainties in ruptured
339 area ($\sigma = 3 \text{ km}^2$), shear modulus ($\mu = 2.8 \pm 0.3 \cdot 10^1 \text{ GPa}$), coupling and slip rates
340 (according to Bletery et al., 2020). The moment released by the 2020 event is largely greater
341 than the one accumulated since 1905 ($2.34 \pm 0.25 \gg 0.72 \pm 0.19 \cdot 10^{19} \text{ N} \cdot \text{m}$). Around
342 475 years (since 1646) would be necessary to accumulate the moment released by the Elazığ
343 earthquake, assuming constant coupling and slip rates, confirming that the Pütürge seg-
344 ment did probably not rupture during the last historical events, and effectively was a seis-
345 mic gap. We make the same comparison for the East Palu segment, and show that the
346 moment released by the 2010 M_w 6.1 Kovancilar earthquake well matches the moment
347 accumulated from the 1971 Bingöl event to 2010 ($1.58 \pm 0.2 \approx 2.19 \pm 0.56 \cdot 10^{18} \text{ N} \cdot \text{m}$,
348 Fig. 4D), suggesting this portion of the EAF actually ruptured during the 1971 event,
349 and that all of the accumulated moment has been released at the time of the Kovancilar
350 earthquake. Since 2010, the seismic moment of the East Palu segment likely accumu-
351 lated again to reach $4.48 \pm 0.5 \cdot 10^{17} \text{ N} \cdot \text{m}$, which corresponds to a $M_w \approx 5.73$

352 Although the portions of the EAF that have been affected by the Elazığ and Ko-
353 vancilar events show seismic activity in the 20 years preceding these events, the West
354 Palu segment is characterized by relatively low seismic activity (Fig. 4). Together with
355 the low slip deficit at depth (or shallow 5 km locking depth, Cavalié & Jónsson, 2014;
356 Bletery et al., 2020), the lack of seismicity might suggest that the West Palu segment
357 is creeping. However, this segment also shows large interseismic slip deficit in its shal-
358 low portion ($< 5\text{-km-depth}$), and at greater depths even larger than for the Pütürge seg-
359 ment (before the 2020 event, Bletery et al., 2020, Fig. S16). Ground shaking maps de-

360 rived from press reports and testimonies suggest the 1874 sequence likely initiated at depth
361 just west of Lake Hazar (Ambraseys, 1989), near the epicenter of a $M_w \sim 5$ earthquake
362 that occurred in 2010. The West Palu segment is thus capable of producing large earth-
363 quakes. Cheloni and Akinci (2020) also suggest that the Elaziğ event led to an increase
364 in the Coulomb stress of the Palu segment. Altogether, these observations suggest that
365 the West Palu segment of the central EAF is likely seismogenic. If it were to rupture,
366 the moment accumulated since 1875 on the highly coupled portion is of $7.58 \pm 2.2 \cdot 10^{18} \text{ N} \cdot \text{m}$
367 (light purple in Fig. 4D), and may reach $1.08 \pm 0.25 \cdot 10^{19} \text{ N} \cdot \text{m}$ if the rupture extends
368 from Lake Hazar to the city of Palu (dark purple in Fig. 4D), which would correspond
369 to a $M_w \sim 6.6 \pm 0.15$ earthquake.

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389 [.com/jolivet/csi](https://github.com/jolivet/csi), only accessible via github at publication date) Python library (Jolivet
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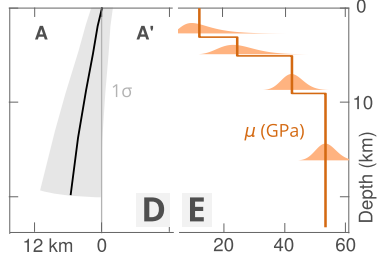
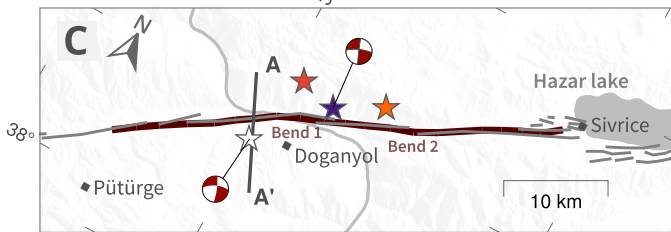
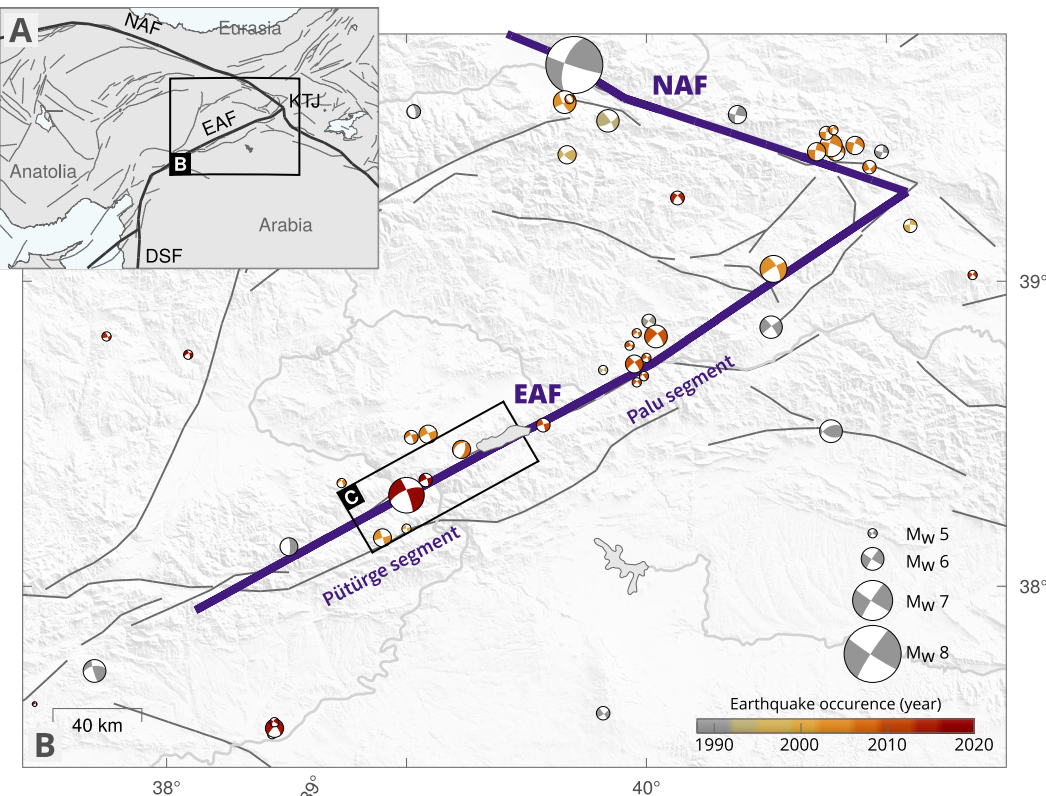
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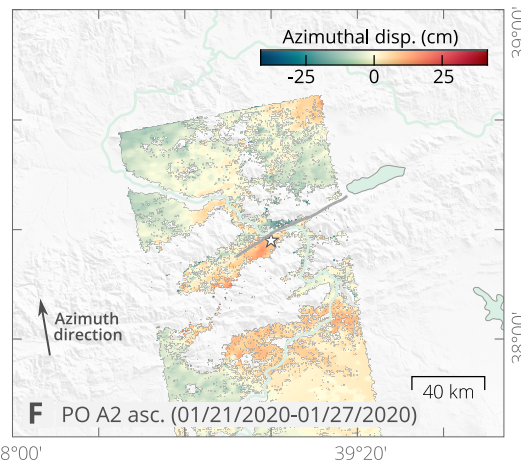
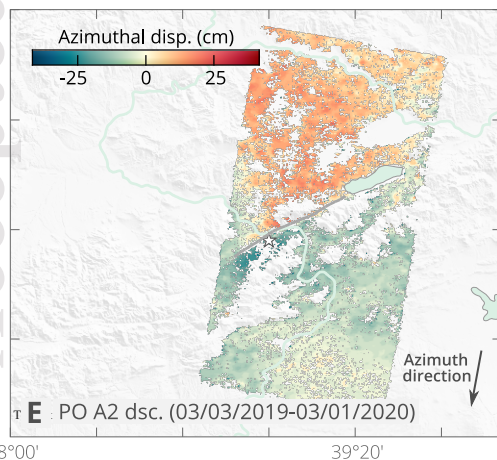
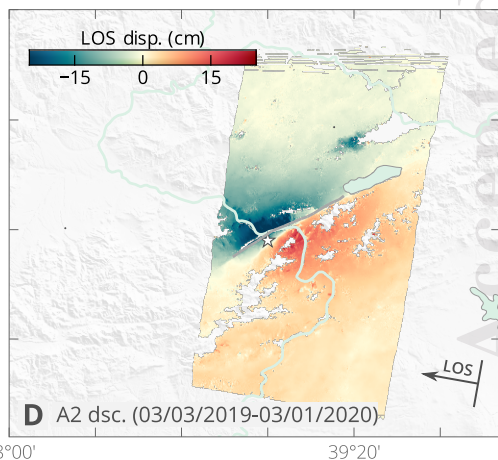
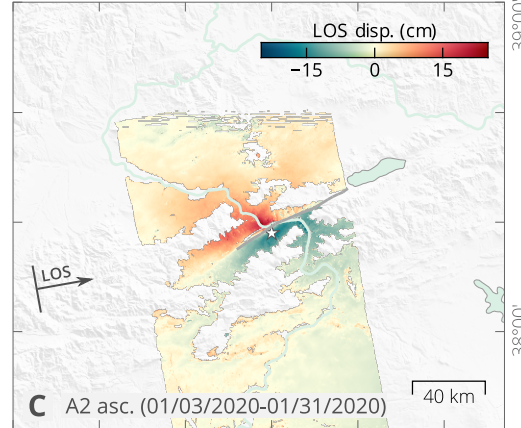
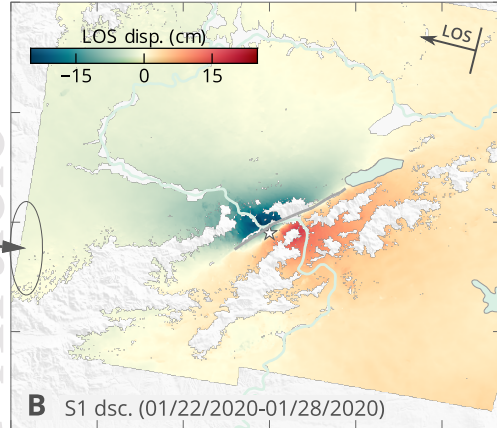
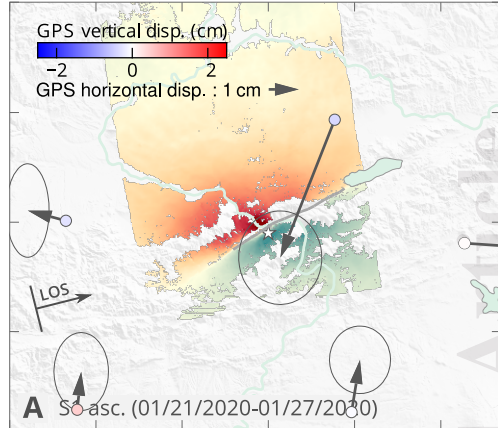
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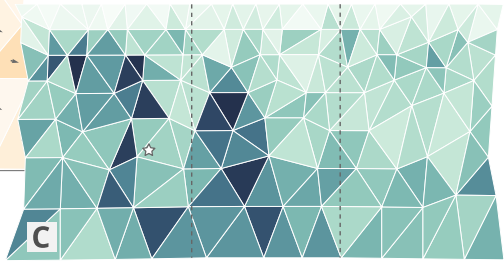
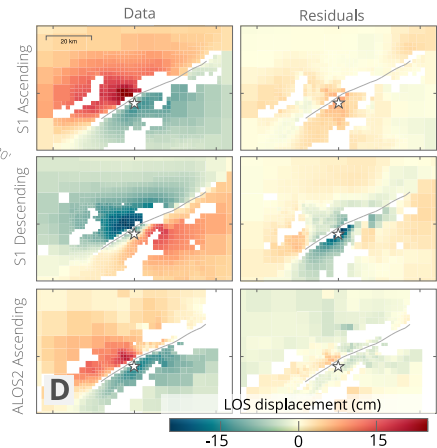
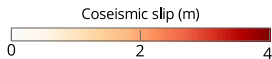
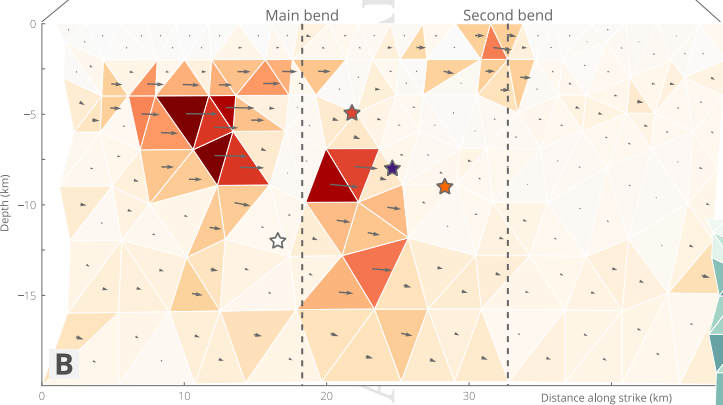
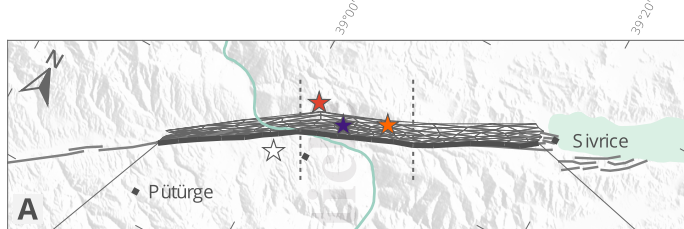
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