

1 **Identification of Source Faults of Large Earthquakes in the Turkey-Syria Border**
2 **Region Between AD 1000 and Present, and their Relevance for the 2023 M_w 7.8**
3 **Pazarcık Earthquake**
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20 **Key Points:**

- 21 • We identified the source faults of fourteen large earthquakes along the East Anatolian
22 and northern Dead Sea fault systems
- 23 • Maximum magnitude for the East Anatolian fault zone is approximately 8.2 and large
24 earthquakes can rupture multiple segments
- 25 • Continental transforms may be described as having a collective memory
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28 Abstract

29 The February 6th, 2023, M_w 7.8 Pazarcık earthquake in the Turkey-Syria border region raises the
30 question of whether such a large earthquake could have been foreseen, as well as what is the
31 maximum possible magnitude (M_{max}) of earthquakes on the East Anatolian fault system and on
32 continental transform faults in general. To answer such questions, knowledge of past earthquakes
33 and of their causative faults is necessary. Here, we integrate data from historical seismology,
34 paleoseismology, archeoseismology, and remote sensing to identify the likely source faults of
35 fourteen $M_w \geq 7$ earthquakes between AD 1000 and the present in the region. We find that the
36 2023 Pazarcık earthquake could have been foreseen in terms of location (the East Anatolian
37 Fault) and timing (an earthquake along this fault was if anything overdue), but not magnitude.
38 We hypothesize that the maximum earthquake magnitude for the East Anatolian Fault is in fact
39 8.2, i.e. a single end-to-end rupture of the entire fault, and that the 2023 Pazarcık earthquake did
40 not reach M_{max} by chance only. In fact, we suggest that such unusually large events are hard to
41 model in terms of recurrence intervals, because they need a very specific set of circumstances to
42 line up before they can happen. We also conclude that seismic hazard assessment along
43 continental transforms cannot be done on individual fault systems, but must include neighboring
44 systems as well, because they are not kinematically independent at any time scale.

45

46 Plain Language Summary

47 On February 6th, 2023, there was a magnitude 7.8 earthquake in the Turkey-Syria border region.
48 It surprised many people, including many Earth scientists, because of where it happened (on the
49 East Anatolian fault) and because of how large it was. People wondered whether it could have
50 been foreseen, and how large an earthquake on this fault can really be. To figure this out, we
51 looked at the history of earthquakes in the region in the last 1000 years. We used information
52 from historical seismology, paleoseismology, archeoseismology, and remote sensing to identify
53 the faults that caused fourteen earthquakes with magnitude 7 or greater in this region. We found
54 that the location (East Anatolian Fault) and timing (it was due any time) of the 2023 earthquake
55 were foreseeable, but not the magnitude. In fact, we believe that the maximum magnitude for the
56 East Anatolian Fault is 8.2, and that the 2023 earthquake was below this maximum just by
57 chance. It is hard to say how often such large events can happen, because many different things

58 need to align. We also believe that it is necessary to look at neighboring fault systems when
59 estimating seismic hazards, because they are all connected.

60

61 **1 Introduction**

62 The occurrence of the Feb. 6th 2023 M_w 7.8 Pazarcık earthquake surprised not only the
63 public, but also a large part of the geoscience community, due to the event size and location. This
64 earthquake ruptured ~310 km of the left-lateral East Anatolian Fault (EAF) between Antakya and
65 Çelikhan (Figure 1), which is ~55% of its length. It also ruptured through multiple segment
66 boundaries (Figure 2). The EAF had been, until February 2023, a “forgotten” plate boundary
67 fault, with the great majority of the more recent works mainly dealing with the North Anatolian
68 Fault (NAF) because of its proximity to Istanbul and of its higher level of seismic activity in the
69 past century. Even the most recent earthquake on the EAF, the Jan. 24th 2020 Elâziğ M_w 6.8
70 event, received surprisingly little attention. There are only 13 geoscience papers about this
71 earthquake listed in Web of Science. For comparison, the 1999 Düzce earthquake along the NAF
72 had 15 publications listed over the first 3 years after the event, even though publishing rates have
73 increased rapidly over time.

74 The EAF, however, has been documented as very seismically active in historical records,
75 with magnitudes above 7.0 inferred for multiple earthquakes around the EAF in the past 1000
76 years (e.g. Ambraseys, 1989, 2009; Guidoboni & Comastri, 2005; Sbeinati et al., 2005). For
77 most of these earthquakes, though, the specific source faults were not identified. Lack of
78 knowledge of source faults precludes the calculation of fault slip rates and recurrence times, and
79 the estimation of seismic hazards and M_{max} . It also precludes having a rigorous base for stress
80 and strain modeling and for studying dynamic rupture propagation.

81 Our goal is therefore to systematically identify the most likely source of each large ($M_w \geq$
82 7.0) earthquake along the East Anatolian and Dead Sea fault systems between Lake Hazar in the
83 north and Qalaat El Hosn, Syria, in the south (Figure 1) in the past ~1000 years, because these
84 earthquakes may have had a direct and significant influence on the timing, location, and size of
85 the 2023 M_w 7.8 Pazarcık earthquake. The more recent an earthquake is, the more likely it is to
86 have been the “last event” on its source fault, determining the last coseismic and postseismic

87 stress changes associated with the fault itself. Before AD 1000 the historical records are anyway
88 very fragmentary, making it impossible to associate most earthquakes with a specific fault. By
89 integrating historical records with paleoseismological ones in a tectonic context, we aim to
90 identify a set of reasonable fault / earthquake pairs and any plausible alternatives that can be used
91 for both modeling purposes and the identification of key field sites for further studies.

92

93 **2 Method and Results**

94 The identification by previous authors of source faults of historical earthquakes along the
95 EAF and northern Dead Sea Fault zone (DSF) is patchy. The typical case is, for example, when a
96 historical seismology work assigns an earthquake to a fault simply on the basis that it is a known
97 active fault in the general epicentral area. Often the source faults identified in this way are then
98 reported by later authors without any critical re-evaluation, even in those cases when the original
99 author had clearly stated that they were just doing a “best guess” approach with no additional
100 data. In most cases each work identifies one or two earthquake / source pairs, or identifies
101 multiple earthquakes, but all on the same fault. Unfortunately, identifying source faults in
102 isolation or without looking at all data available in both time and space is more likely to result in
103 mis-identification, the more so the older the earthquake is. We have therefore started from
104 published historical seismology works, re-evaluating each piece of information from different
105 authors about the same earthquake, and combining this with data from paleoseismology and
106 remote sensing (often more recent), following the approach suggested by Daëron et al. (2007) for
107 future studies on the DSF. We have not developed new methods, software, or collected field
108 data. Rather, we have done a comprehensive review of the information that already exists, and
109 attempted to weed out inconsistencies and integrate information from different fields. Finally,
110 when reviewing information, we have done so for several earthquakes and faults simultaneously,
111 when these are (or could be) in the same sub-region.

112

113 2.1 Identification of source faults

114 In the case of the Turkey-Syria border region, several of the faults have been trenched, so
115 several events from the past 1000 years can be assigned to a specific fault with a reasonable

116 degree of confidence. In some cases, a couple of different options are equally plausible but,
117 overall, there is a limited combination of possible earthquake / source-fault pairs, because there
118 is only a limited number of faults in the area that are long enough to be credible source faults for
119 events of M_w 7 and above. We will start our analysis from those earthquakes for which there is
120 the most information available, and which may appear in one or more of the trenches, then move
121 to events which are less well-constrained. The order is not going to be strictly chronological,
122 because some of the older events are well-constrained, and some of the more recent ones are not.
123 We are going to start from the Amik basin area (Figure 1a), where the EAF and DSF come
124 together, and move first south and then north. The final list of earthquake / fault pairs that we
125 have determined to be the most likely can be found in Table 1, and the faults are shown in Figure
126 2b.

127 There are a few criteria that can be applied to the identification of the likely source fault
128 of a historical earthquake in the absence of dating of geological or archeological features: (1)
129 empirical relationships (e.g. Wells & Coppersmith, 1994) between earthquake size and fault
130 parameters (a large earthquake must have a long rupture, so determination of epicenter position
131 alone is not very meaningful), (2) the principle, based on Coulomb stress theory, that the same
132 fault segment or neighboring parallel faults with the same kinematics are highly unlikely to
133 produce two large earthquakes within a few years or even decades of each other, and (3) careful
134 reading of earthquake effect descriptions, paying particular attention to discussions by previous
135 authors concerning reliability of sources. The latter is especially important because it is not
136 uncommon for mistakes to be spread from one earthquake catalog to the next (or newly
137 introduced) when information is accidentally left out, or two smaller earthquakes are conflated
138 into a larger one.

139 A new source of information that we have today, which was not available when all the
140 work on historical earthquakes in this region was being carried out, is the occurrence of the 2023
141 M_w 7.8 and 7.5 Turkey / Syria earthquakes (M_w from U.S. Geological Survey, 2023), which
142 allowed us for example to verify that the empirical relationship used by previous authors to
143 estimate magnitudes for historical earthquakes in this region is indeed appropriate (see Appendix
144 A for details). This earthquake is also invaluable in that it shows how fault segmentation can be
145 overcome if the earthquake is large enough, i.e. we should not fall into the trap of automatically
146 assuming a rupture cannot propagate past a bend or step when examining historical earthquakes.

147 All the earthquakes that we consider are between AD 1000 and 2023, so “AD” is mostly
148 omitted throughout the paper. As no year has two earthquakes, throughout the text for simplicity
149 we only refer to the year of occurrence, omitting day and month. The precise date of each
150 earthquake (when known) is given in Table 1. Due to the fact that locality names and fault names
151 are very much relevant in this kind of work, in addition to the maps in Figure 1 we have supplied
152 details of naming (including rationale for specific choices) in Appendix B, and a full searchable
153 list of locality names with alternates as supplementary file ds04. Finally, as the number of place
154 names is quite large, we will not call a figure every time a place is mentioned: this paper should
155 be read with Figures 1 and 2 at hand at all times.

156

157 2.1.1 Amik basin and Dead Sea fault zone

158 We now apply the criteria described above to the earthquakes of 1872 and 1822. We start
159 with this pair because the 1822 earthquake was singled out by Ambraseys (1989) not only as one
160 of the largest earthquakes in the records, but also as one that took place in a region that - until
161 February 2023 - had very low seismicity.

162 Altunel et al. (2009) attributed the last event in their trenches at Demirköprü (Figure 3,
163 dated to between 1801 and 1940) to the 1872 earthquake based on their interpretation of
164 Ambraseys’s 1989 paper: “*Ambraseys (1989) reported that the 1822 earthquake took place in*
165 *the Karasu Valley located further north of the Amik Basin [...] it is therefore unlikely that the*
166 *event E1 can be related to the 1822 earthquake. Ambraseys (1989) also reports that the 1872*
167 *April 3 earthquake was responsible of heavy damage north and south of the former Amik Lake,*
168 *and in particular [...] around Qillig and Armenez. On the basis of both paleoseismic results and*
169 *historical accounts, we suggest that event E1 in trenches is related to the 1872 earthquake”.*

170 Ambraseys (1989), however, in the very next sentence to the one rephrased by Altunel et al.
171 (2009) also states (concerning the Qillig area and the 1872 earthquake): “*Here, it is said, the*
172 *earthquake split the ground in places and yellow sand filled the area, a description suggesting*
173 *widespread liquefaction”.*

174 Liquefaction can happen at large distances from a fault surface rupture
(Ambraseys, 1988; Papathanassiou et al., 2005), so evidence of liquefaction is not evidence for
175 surface rupture at or near liquefaction location. In 2023, the M_w 7.8 earthquake caused
176 liquefaction in Kumlu (Quillig) and many other localities in the southern and eastern Amik

177 basin, even though the fault rupture was along the Amanos mountains front, and liquefaction was
178 reported also from localities up to at least 40 km away (Taftsoğlu et al., 2023). Furthermore,
179 Ambraseys (1989) continues by writing, about the 1872 event: “*Also, between Batrakan and*
180 *Qaralu, the valley to the east of the hills is said to have dropped [...] and the ground was “rent”*
181 *all the way to Baghras, an allusion to faulting”*. The last three localities mentioned are at the foot
182 of the Amanos mountains, about 20 km apart along the mountain front, and 18 km west of the
183 trench site (Figures 1b and 3). Finally, the presumed location of the epicenter of the 1822 event
184 has no bearing on whether the source fault can or cannot pass through the trench, because the
185 epicenter of a historical earthquake simply indicates the center of the area of maximum damage
186 (i.e. the center of the “epicentral region”), but the source fault of the 1822 event must be at least
187 100 km long based on magnitude/length relationships, so it could easily go through the trench
188 site and have an epicenter elsewhere to the north. In fact, the isoseismals (lines of equal seismic
189 intensity) plot for the 1822 event of Ambraseys (1989) shows the maximum intensity as an
190 elongated region trending NNE, where the largest intensity isoseismal contains the trench
191 location.

192 If we consider all the evidence together, the most logical interpretation is that the likely
193 source of the 1872 event was the southernmost tip of the Amanos segment and, given the
194 widespread damage also reported all the way from Antakya to Samandağ, and in the mountain
195 villages on the Amanos mountains aligned parallel to this trend (Ambraseys, 1989), the faulting
196 likely extended in that direction towards the coast, possibly by linking with faults in the Antakya
197 fault zone (Figure 2b). Ambraseys (1989) plots isoseismals aligned with the southern termination
198 of the Amanos segment and centered on the Hatay graben. Ambraseys & Jackson (1998) stand
199 by the earlier interpretation of ground rupture for the 1872 event, as they report a 20 km rupture
200 length for this event in their catalog of “surface rupturing earthquakes”. This leaves the 1822
201 earthquake as the only possible rupture in the 1801–1940 age range to go through the trenches at
202 Demirköprü, because it is very unlikely that an unknown ground-rupturing earthquake (i.e. a
203 large one) would be missing from the records after 1800, especially one that would have strongly
204 affected such a historically important river crossing as the one at Demirköprü. If this is the case,
205 then also the event of compatible age (“after 1650 AD”) found by Akyüz et al. (2006) in the next
206 trench further south (Ziyaret, Figure 3) should be the 1822 earthquake.

207 The 1822 earthquake was a large event, as shown also by the fact that it was followed by
208 1.5 years of rather large aftershocks (Ambraseys, 1989, 2009), with the full aftershock sequence
209 terminating only after 30 months (Salamon, 2008). Ambraseys (1989) and Ambraseys & Jackson
210 (1998) estimated a magnitude of 7.5, which seems reasonable given the large area it affected and
211 the level of damage reported everywhere. Without explaining why, Sbeinati et al. (2005), though
212 also describing this as one of the most damaging earthquakes in the region, reduced the
213 magnitude to 7.0. A clue to the magnitude change could be the fact that several localities in
214 Turkey that had reported considerable damage (e.g. Gaziantep, and the towns west and northwest
215 of it) are not listed in their catalog, which would reduce the size of the affected area and thus the
216 magnitude. As there is no reason for the omission of these localities, we accept the determination
217 of M_w 7.5 of Ambraseys & Jackson (1998).

218 Different authors have placed the 1822 event either on the Amanos fault (e.g. Seyrek et
219 al., 2007), the Yesemek fault (e.g. Ambraseys & Melville, 1995; Duman & Emre, 2013), or the
220 St. Simeon fault (e.g. Karakhanian et al., 2008; Darawcheh et al., 2022). Even not considering
221 the likely presence of this earthquake in the trenches of Altunel et al. (2009) and Akyüz et al.
222 (2006) along the Orontes river valley, the Amanos fault is the least likely option: (1) the damage
223 pattern from the 1822 M_w 7.5 earthquake is shifted east and south compared to the damage
224 pattern of the 2023 M_w 7.8 earthquake (which definitely ruptured the Amanos segment, see
225 Figure 2b), (2) several foreshocks (the strongest preceding the mainshock by 30 minutes)
226 occurred in the region between Antakya, Latakia and Aleppo (Ambraseys, 1989, 2006),
227 suggesting that the main shock may have been triggered by the rupture of one of the many N-S
228 faults between the northern Ghab basin and the Amik basin, and (3) the epicenter estimated for
229 the 1822 event by both Ambraseys (1989) and Sbeinati et al. (2005) is located ~20 km east of the
230 Yesemek fault trace, albeit 60 km apart in latitude in either work (the location shift is also likely
231 due to the exclusion of the Turkish area around Gaziantep from the 2005 catalog). In addition,
232 Duman & Emre (2013) found no signs of a recent rupture along the Amanos fault in the Karasu
233 valley, whereas they claim that the Yesemek fault appears to show a fresher morphology, at least
234 in its northern segment (which is the one they checked in the field, on the Turkish side of the
235 border). Ambraseys (1989) identified the maximum intensity isoseismal as approximately
236 parallel to and slightly west of the Gaziantep-Kilis-Idlib trend. This is consistent with the
237 position and orientation of both the Yesemek fault and the northern segment of the St. Simeon

238 fault. Darawcheh et al. (2022) explicitly argue for the 1822 event to have originated on the St.
239 Simeon fault. These authors, however, identify as source fault what they call the “middle
240 segment” of the St. Simeon fault (actually, it is the southern segment, see Figure 4): this is a
241 mere 26 km long and a series of very short en-echelon segments (possibly a shear zone without a
242 throughgoing fault near the surface), i.e. too short to produce an earthquake of this magnitude.
243 Considering the parameters quoted by these authors (M_w 7.3 and a fault width of 15 km), an
244 average fault slip of about 10 m would be required, which is unrealistically large, as this is the
245 typical average slip value for M_w 8.0 (Wells & Coppersmith, 1994). A 26 km long fault would
246 normally produce roughly a M_w 6.7 earthquake, which does not match at all the historical
247 descriptions of destruction spread over a vast region. For the St. Simeon fault to be the source of
248 the 1822 earthquake, it would have had to rupture all the way from Afrin in the north to Sahen in
249 the south (i.e. rupturing part of the Apamea fault as well), breaking across the southern segment
250 too, which has a trend $\sim 30^\circ$ off from that of the two adjacent faults and, as pointed out above,
251 appears to be more a broad shear zone than a throughgoing fault. Also, if a surface rupture had
252 extended to the northeastern Ghab basin, the intensity at Maarret Missrin, Ram Hamdan, and
253 Binnish (all between 6 and 12 km from the southern St. Simeon fault segment) should have been
254 above the VII reported in Sbeinati et al. (2005). Finally, Karakhanian et al. (2008), while
255 speculating that the 1822 event may have occurred on the northern segment of the St. Simeon
256 fault (based on the epicenter location of Sbeinati et al., 2005), found no evidence of a recent
257 surface rupture on it, including at the site of the St. Simeon monastery, which they studied
258 extensively.

259 The most likely candidate for the 1822 earthquake thus appears to be the Yesemek fault
260 combined with part of the Qanaya-Babatorun fault, with a rupture extending from the Yesemek
261 fault northern segment for ~ 100 – 120 km south, past the Demirköprü bridge, to at least the Zyaret
262 trench of Akyüz et al. (2006) (Figure 2b, 3). The next trench south (Yazlık) does not have an
263 event of compatible age, though it is possible that the event is simply not visible in the trench
264 because it followed a slightly different strand. In any case, a rupture from the latitude of Islahiye
265 in the north to south past Demirköprü and into the Orontes valley would explain the especially
266 strong damage in the Quseir region (which was also struck by numerous aftershocks, reported by
267 Ambraseys, 2009) and at the main crossings on the Orontes river (Demirköprü and Jesr Al-

268 Shughour), and the high damage region extending all the way to Sages and Gaziantep in the
269 north.

270 The Yesemek fault has usually been mapped continuing south to the eastern edge of the
271 Amik basin (Duman & Emre, 2013) and possibly connecting to the Armanaz fault (Seyrek et al.,
272 2014). The Yesemek fault, however, splits into two branches south of 36.616643°N, both of
273 which are mapped as “active faults” in the active faults database of Zelenin et al. (2022). One
274 branch (the one called “Yesemek fault” or “East Hatay fault” by previous authors, see Appendix
275 B) continues with an almost N-S trend, whereas the other one turns southwest, following a series
276 of low hills, then disappears under the sediments of the Amik basin (Figure 2). We also know
277 that there is an active fault in the middle of the Amik basin. This fault is visible in the seismic
278 line of Perinçek & Çemen, 1990, and was re-interpreted by Seyrek et al. (2014), who reviewed
279 and synthesized existing subsurface data. Old geographic maps also show that the eastern
280 shoreline of the former Lake Amik and the eastern limit of the swamps north of the lake
281 followed this buried fault closely all the way to the eastern edge of the Karasu valley, meeting
282 the Yesemek fault there. It seems likely that this is the source fault of the 1822 earthquake
283 (Figure 2b), and that the fault interpreted by previous authors below the Amik basin is in fact the
284 Yesemek fault, which continues south and connects to the Qanaya-Babatorun fault near
285 Demirköprü.

286 The next pair of events that should be examined together is that of 1408 and 1404. The
287 1408 event has been identified most likely in all three trenches of Akyüz et al. (2006), who dated
288 event E1 “between 1310 and 1423” in the northernmost trench and “younger than 1019” in the
289 southernmost one. It could of course be either the 1404 or the 1408 earthquake, but as we will
290 see the 1404 earthquake is unlikely to have ruptured this far north. The maximum destruction
291 from the 1408 earthquake was along the trend from the Quseir region to Jesr Al-Shughour, with
292 significant damage also to Mahalibeh castle, and damage to Jableh and Latakia along the coast.
293 There is an open argument about the reported surface rupture, depending on the interpretation of
294 the Arabic word for the distance, given as either ~20 km (Ambraseys, 1989, 2009) or ~2 km
295 (Guidoboni & Comastri, 2005). The latter also claim there is no proof of damage in Antakya
296 (which in their case means magnitude reduction from the 6–7 of Ambraseys & Jackson, 1998, to
297 ~5.5), but Ambraseys (2009) reiterates that damage in Antakya is confirmed in reliable near-
298 contemporary Ottoman calendar sources, which Guidoboni & Comastri (2005) do not seem to be

299 aware of, as they do not mention them. Ambraseys (1989) puts forward two possibilities for the
300 source fault: either the Qanaya-Babatorun fault, or the Antakya fault zone, the latter based on the
301 fact that the damage extends towards the SW to the coast. A matter of contention here is again
302 the presumed surface rupture described in historical sources. Regardless of its length, the
303 location of the rupture is debated, because there is no agreement on where the village mentioned
304 in the ancient texts is located, near which the rupture may have terminated (the starting point was
305 in the Quseir region, i.e. between Antakya and the Orontes gorge, so not very specific either).
306 There are multiple spellings reported (Salthuam, Shalfuham, Salfhoum, Salthum), and this place
307 is identified by Ambraseys (1989, 2009) as Hisn Tell Kashfahan (in Jesr Al-Shughour), and by
308 Sbeinati et al. (2005) as Sfuhen (Sufuhon, on the eastern shoulder of the Ghab basin, Figure 1).
309 The latter seems to be too far east, and located on faults that are not connected to anything in the
310 Orontes gorge, but it could have been affected by a landslide triggered by the earthquake. So, if
311 Sufuhon is indeed the location mentioned, a landslide and a fault surface rupture must have
312 occurred at two different places. If Hisn Tell Kashfahan is the correct interpretation, then
313 landslide and fault surface rupture could have been at the same place. Either way, the earthquake
314 seems to have particularly affected one location that is clearly identifiable: the twin fortresses of
315 Shugr and Bekas (Shugur Qadim), located less than 2 km west of the Qanaya-Babatorun fault.
316 The key crossing on the Orontes of Jesr Al-Shughour, which sits on this fault trace, was also
317 destroyed. In Antakya, however, the damage does not appear to have been as extensive, so the
318 Qanaya-Babatorun fault seems a far more likely candidate than the Antakya fault zone, even
319 without considering the information from the trenches. The fault rupture most likely did not
320 extend north past the northernmost trench of Akyüz et al. (2006), because otherwise we would
321 expect reports of destruction at the Demirköprü historical “iron bridge”, as this crossing was a
322 vital one that had been in existence since well before 1000 AD. A ~40 km long rupture starting
323 at about the northern trench site and extending to Jesr Al-Shughour would produce a M_w 7.0
324 earthquake, in line with Ambraseys & Jackson (1998) estimate of a “6 to 7” magnitude. A 20 km
325 long rupture limited to the northern part of the fault appears too short to account for the
326 significant damage extending all the way to Mahalibeh castle, and a 2 km long rupture is
327 unrealistic, as the corresponding M_w 5.5. event would be too small to cause any damage along
328 the coast in Latakia and Jableh, which are 70 to 80 km away.

329 There is less information for the 1404 earthquake: Ambraseys (2009) and Guidoboni &
330 Comastri (2005) give essentially the same description from the same primary sources, and both
331 point out that one source wrongly adds some 1408 localities to the 1404 event description.
332 Sbeinati et al. (2005) used this source instead, apparently not realizing the problem, and
333 estimated M_w 7.4. Ambraseys & Barazangi (1989) estimated $M_w \geq 7.0$. This means the surface
334 rupture of the 1404 earthquake must have been at least 40 km long. From the damage
335 distribution, the source fault has to be somewhere around the Ghab basin. The Qanaya-
336 Babatorun fault is too far north to account for the significant damage to Marqab castle (on the
337 coast, 25 km south of Jableh), and for the intensity VII–VIII reported from Tripoli in Lebanon.
338 The Missyaf segment to the south is not a likely source, because the last event on this segment,
339 visible in the trench and in the displaced Roman aqueduct at Al-Harif, is the 1170 earthquake
340 (Meghraoui et al., 2003; Sbeinati et al., 2010). The two likely sources left are the Nusayriyah
341 fault at the western margin of the Ghab basin, and the Apamea fault at its eastern margin (Figure
342 2a). We believe the Nusayriyah fault to be the more likely source, based on two considerations.
343 The first is that the high damage reports are skewed towards the coast, pointing to a source on
344 the western rather than eastern Ghab basin, and the second is that an earthquake on this fault
345 segment in 1404 would be more effective in increasing the stress on the Qanaya-Babatorun fault,
346 which ruptured just 4 years later, than an earthquake on the Apamea fault. A final possibility,
347 which we cannot discount at this time, is that the earthquake resulted from the rupture of a fault
348 buried in the middle of the Ghab basin, as the presence of a fault here is known from geophysical
349 data (Rukieh et al., 2005).

350 The next significant event back in time in this area is the 1170 earthquake, which is well-
351 documented, with extensive descriptions by multiple authors (e.g. Ambraseys 1989, 2004, 2009;
352 Guidoboni et al. 2004b; Guidoboni & Comastri 2005). Guidoboni et al. (2004b) estimated M_w
353 7.7 +/- 0.22 and a fault length of 125 km. Ambraseys (2009) instead estimated M_w 7.3 +/- 0.3.
354 The source fault of this earthquakes has been identified by Meghraoui et al. (2003) as the
355 Missyaf segment of the DSF, with the 1170 event being the last rupture that occurred at the Al-
356 Harif aqueduct site. They suggested that the fault ruptured from Qalaat El Hosn to Apamea, a
357 distance of ~80 km. Meghraoui et al. (2003) and Sbeinati et al. (2010) established that the slip at
358 the aqueduct site in the 1170 event was 4 to 4.5 m. If this is maximum slip, it alone indicates M_w
359 7.3 to 7.4. This is compatible with the magnitude estimate of Ambraseys (2009), and reasonably

360 compatible with the damage distribution. The only outlier is the city of Aleppo as reported by
361 Guidoboni et al. (2004b), but Sbeinati et al. (2010) argue that these authors overestimated the
362 damage in Aleppo based on an erroneous interpretation of the chronicle by Ibn Al Athir. The
363 argument of Sbeinati et al. (2010) is reasonable, because the damage distribution is otherwise
364 very unusual, with a single intensity X locality (city of Aleppo) isolated and 200 km away from
365 the main intensity X region (Lebanon-Syria border southwest of Qalaat El Hosn). We therefore
366 agree with the source fault identification and rupture length of Meghraoui et al. (2003) and
367 Sbeinati et al. (2010).

368 In 1156–1157 there was a long earthquake sequence (an “earthquake storm”) in the
369 region between Homs and Aleppo, culminating with the largest event on Aug. 12, 1157
370 (Ambraseys, 2004, 2009). Guidoboni et al. (2004a) did not calculate magnitude or epicentral
371 area because of the difficulty in separating the numerous earthquakes in this period. Ambraseys
372 (2004, 2009) instead separated several of the larger events and calculated the magnitude of the
373 largest (7.2 +/- 0.3), and placed the location of the epicenter very close to the Missyaf fault near
374 Apamea. As mentioned above, the Missyaf fault last ruptured in 1170 through the Al-Harif site.
375 While it is possible that an older rupture followed a slightly different strand and did not pass
376 through the Al-Harif site, the Coulomb stress shadow due to an earthquake in 1157 would have
377 most likely precluded another large rupture of the same fault segment less than 30 years later.
378 Based on the damage pattern, the St. Simeon fault is too far north, and the Nusayriyah fault too
379 far west. That leaves the Apamea fault and another unnamed fault of similar length just 10 km
380 east of it (which here we name “Shaizar fault”, Figure 2a, 4). Because it appears that the most
381 damage was towards southeast (Hama, Salamiyah) and east (Ma’arat al-Nu’man, Kafar Tab,
382 Shaizar) of the Ghab basin, the Shaizar fault is a more likely source than the Apamea fault.
383 Sbeinati et al. (2005) put the epicenter on the Shaizar fault. Also, all of the 1156-1157 seismicity
384 was concentrated in the region between Aleppo and Hama east of this fault. The area is littered
385 with small faults (Figure 4), so it is conceivable that this is a case of small and moderate
386 earthquakes triggering one another, until one of them got close enough to trigger the largest of
387 these faults to rupture. The Apamea fault cannot, however, be excluded as a possible source
388 without further investigation.

389 We have previously argued that the St. Simeon fault is unlikely to be the source of the
390 1822 earthquake. There are two older earthquakes, however, which could have been produced by

391 this fault, in 1626 and 1138. The interpretation of this fault is controversial: some authors (e.g.
392 Westaway, 2004; Seyrek et al. 2014) claim that it belongs to an earlier tectonic phase and it is no
393 longer active. Others (Rukieh et al., 2005) instead consider it active, and some (Karakhanian et
394 al., 2008) have even found evidence of historical earthquake-related deformation along it, albeit
395 not an actual rupture of the main fault itself.

396 There is little information about the 1626 earthquake. Ambraseys only mentions it in his
397 2009 catalog and in Ambraseys & Finkel (1995), and Sbeinati et al. (2005) repeat the same
398 information, add one paragraph, and estimate a magnitude of 7.3. It appears to have been a fairly
399 damaging earthquake over a large area, but not much specific information has come to light.
400 Karakhanian et al. (2008) consider the St. Simeon fault a likely source, based on their
401 archeoseismological work on the St. Simeon monastery. A rupture of the northern segment of the
402 St. Simeon fault (~ 50 km long) could produce a M_w 7.2 earthquake, and in light of the reported
403 damage area (between Aleppo and Gaziantep) we believe that this fault is indeed a likely
404 candidate.

405 The authors who report extensively on the 1138 event are Ambraseys (2004, 2009),
406 Guidoboni et al. (2004a), and Guidoboni & Comastri (2005). Sbeinati et al. (2005) just give it a
407 brief mention, and this event does not even appear in the GEM historical catalog of Albini et al.
408 (2013). An estimated magnitude is only reported by Guidoboni & Comastri (2005) (M_e 6.0), and
409 apparently recalculated (without explanation, but from comparing the reported intensities it
410 seems it was done by just increasing the estimated intensity values) in the INGV catalog to M_e
411 7.5 (Guidoboni et al., 2018, 2019). Both Ambraseys (2004, 2009) and Guidoboni & Comastri
412 (2005) essentially give the same description concerning localities and damage, and date of the
413 earthquake. Guidoboni & Comastri (2005) also calculate the position of the epicenter on Mount
414 Quros, which is just 15 km north of the termination of the St. Simeon fault. On the basis of
415 where the highest damage was, and where the earthquake was felt, the St. Simeon northern
416 straight segment, which could produce a M_w 7.2 earthquake, is a likely source. The estimated M_e
417 7.5 (INGV) is excessive, because it corresponds to a 110-120 km long rupture, which would
418 mean a rupture involving also the Apamea fault into the northern Ghab basin, with a very
419 different damage distribution. In fact, Guidoboni et al. (2014a) suggested that the entire 1138-
420 1139 sequence involved faults north-northeast of the Ghab basin, and not any of the faults that
421 bound the basin itself. Besides the northern St. Simeon fault, there are no other long enough

422 faults in the vicinity and in the proper position that would give the observed damage pattern. A
423 magnitude of 6.0 (Guidoboni & Comastri, 2005) on the other hand is too small, because such an
424 earthquake would have a radius with strong (VI) shaking of only about 20 – 30 km, and several
425 localities that reported significant damage (e.g. Tell Khalid, Tell Amar, Bizaah) are 60 to 100 km
426 away.

427

428 2.1.2 Karasu valley and East Anatolian fault zone

429 The pairing of earthquakes and source faults along the EAF north of the Karasu valley,
430 between Türkoğlu and Elâziğ, is somewhat more straightforward - albeit not entirely free of
431 controversy - because there are fewer active faults that need to be considered, and fewer post-AD
432 1000 large earthquakes. We have included one earthquake from 2020 with M_w 6.8 (Elâziğ
433 earthquake, Table 1), which is below our M_w 7.0 limit, because this is the only instrumental, 21st
434 century and pre-2023 earthquake to have occurred along the EAF and it delimits the 2023 M_w 7.8
435 rupture northeastern extent (Figure 2b), so it is included here for completeness. This earthquake
436 ruptured part of the Pütürge segment and did not appear to have a surface rupture (Çetin et al.,
437 2020), though ~0.5 m of shallow slip was identified by Pousse-Beltran et al. (2020).

438 The 2020 Elâziğ earthquake rupture is sandwiched between two other relatively recent
439 events: 1874 M_w 7.1 and 1893 M_w 7.2 +/- 0.1 (Ambraseys, 1989; Ambraseys & Jackson, 1998;
440 Ambraseys, 2009). Ambraseys (2009) reported that he confirmed in the field in 1967 the surface
441 rupture of the 1874 event, which involved the Palu segment between Palu and Pütürge
442 (Ambraseys & Melville, 1995). His evaluation of the historical documents indicates a ground
443 rupture about 45 km long, with 1–2 m uplift of the eastern block and unspecified left-lateral
444 strike-slip displacement.

445 The 1893 calculated epicenter (Ambraseys, 2009) is near Çelikhan, and Ambraseys &
446 Melville (1995) attributed the earthquake to the Erkenek segment. In the historical reports a
447 surface rupture is not described anywhere, but for an earthquake of this magnitude it would be in
448 the range of 45 to 70 km long. The rupture did not propagate south into the Pazarcık segment, as
449 there is no trace of it in the Balkar and Tevekkelli trenches (Figure 3) of Yönlü (2012). On the
450 basis of the isoseismal plot and epicenter location of Ambraseys (2009), the earthquake likely
451 ruptured most of the Erkenek segment, stopping ~ 20 km SW of Pütürge in the north, and near

452 Erkenek in the south (Figure 2b). A smaller (M_w 6.8) event in 1905 with a similar epicentral area
453 may have completed the rupture of this fault segment to the south, likely without a surface
454 rupture (it does not appear in the “surface rupturing” event list of Ambraseys & Jackson, 1998,
455 whereas the 1893 event does).

456 The last rupture of the Pazarcık segment prior to 2023 is well-documented, because
457 multiple trenches have been excavated across it (Yönlü, 2012). There are two historical large
458 events in the vicinity of this segment that we need to consider: one in 1114, and the other in
459 1513/1514. The oldest of the two is the better documented one, even though it appears as two
460 separate events in different catalogs. This earthquake is discussed in detail by Ambraseys (2004),
461 who reported it as having happened on Nov. 29th 1114. Ambraseys (2004, 2009) went to some
462 length to explain why there are differences in reported dates, and concluded that Nov. 29th 1114
463 is the correct one. This earthquake was assigned a magnitude of “large” (i.e. 7.0 to 7.8) by
464 Ambraseys & Jackson (1998), and 6.9 +/- 0.3 by Ambraseys (2009). Guidoboni & Comastri
465 (2005) instead split the event in two, on different dates and locations (Nov. 13th 1114 Maraş, M_e
466 6.3, and Nov. 29^h 1115 Misis, M_e 6.4). Ambraseys (2009) states that it is unclear why they split
467 the event and that in 1114 there were several other strong shocks in the region before the one on
468 Nov. 29th, but the latter was by far the largest one in the series. One of the two shocks of
469 Guidoboni & Comastri (2005) (Nov. 13th 1114) is in fact listed as a separate foreshock by
470 Ambraseys (2009). Ambraseys (2009) also reported that some sources mention an earthquake in
471 this region in 1115, and this was likely a strong aftershock. Sbeinati et al. (2005) also split the
472 earthquake into two events that have same description and same general area, but different
473 magnitudes (7.4 and 7.7), both of them in Nov. 1114 (no day given, they just state within the
474 same entry that this event could be two earthquakes). Here the confusion is increased by the fact
475 that in the parametric list the authors supply two distinct epicenters and magnitudes, but an
476 identical list of affected localities and intensities, so it is unclear how they were able to compute
477 different epicenters and magnitudes. One of the two (M_w 7.4, with epicenter near Şanlıurfa, east
478 of the Euphrates valley) has been included in the GEM catalog of Albini et al. (2013), whereas
479 the second 1114 earthquake in the GEM catalog has been taken from Ambraseys (2009), again a
480 choice without apparent explanation. There is no trace in Ambraseys’s papers and in his 2009
481 catalog of any events in 1114 that affected mainly the region around Şanlıurfa: the two significant
482 “foreshocks” mentioned were in the Iskenderun bay region. In fact even the 1115 event of

483 Guidoboni & Comastri (2005) is located between the Iskenderun bay region and Maraş.
484 Ambraseys (2009) stressed how the descriptions of this earthquake are split between “western”
485 and “eastern” primary sources: this could explain the tendency of recent authors to produce two
486 main shocks for the same event. Finally, the parametric catalog of Kondorskaya & Ulomov
487 (1999) lists for this event M_w 8.1, and the event epicenter location (a single one for 1114, but on
488 August 10, the date for which Ambraseys 2004 reports a strong shock possibly offshore
489 Iskenderun) is placed between the locations of Ambraseys (2004) and Sbeinati et al. (2005).
490 Considering that M_w 8.1 is close to the magnitude expected for a complete rupture of the entire
491 EAF, this catalog clearly overestimates the size. In summary, for the earthquake of November
492 1114 the works of Ambraseys are more reliable, because there is a justification for each
493 determination made (date, location, magnitude) and clear exclusion of other possibilities. We
494 therefore chose to accept the information given in the latest work (Ambraseys, 2009) for the
495 parameters of this earthquake, which place it somewhere along the Pazarcık segment of the EAF.
496 Yönlü (2012) found a rupture compatible with a 1114 event in three trenches along the EAF
497 (Nacar, and Balkar 1 and 2, Figure 3): there E1 has been dated to before 1153 and after 677, and
498 this rupture is not present in their Tevekkelli trench, 35 km further southwest along the fault.
499 From the paleoseismological findings a surface rupture length of 60 km has been estimated
500 (Gürboğa, & Gökçe, 2019), placing the 1114 earthquake on the northern two-thirds of the
501 Pazarcık segment with M_w of at least 7.1. This is compatible with the size estimated by
502 Ambraseys (2009), but not with the estimates of Guidoboni & Comastri (2005), Sbeinati et al.
503 (2005), and Kondorskaya & Ulomov (1999), further confirming that the earthquake location of
504 Ambraseys (2009) is most likely the correct one. This event does not appear in any form in the
505 trenches and core from Lake Hazar (Hazar Gölü, Figure 3; Çetin et al., 2003; Hubert-Ferrari et
506 al., 2020), so probably its magnitude was not larger than the estimated 7.1, even though
507 Ambraseys & Jackson (1998) considered it a possible candidate for a truly large earthquake (i.e.
508 of magnitude closer to 7.8 than to 7.0).

509 The only authors to report on the 1513 earthquake in recent papers and catalogs are
510 Ambraseys (1989, 2009), and Ambraseys & Finkel (1995). The exact year (late 1513 or early
511 1514) is also debatable. There is very little specific information about the earthquake, but
512 Ambraseys (1989) claims that, given the size of the area over which it was felt (even in the
513 absence of specific damage descriptions), the magnitude was significant (≥ 7.4). Apparently, the

514 regions of Tarsus, Adana, Malatya, and around Haçin were strongly affected. His calculated
 515 epicenter location puts the earthquake within 30 km of the EAF (~ 30 km ENE of Türkoğlu),
 516 while the uncertainty radius is ~50 km, so a location of the event on the EAF is entirely
 517 plausible. The Tevekkelli trench of Yönlü (2012) contains a rupture for E1 dated to between
 518 1440 and 1630, which is compatible with an earthquake in 1513/1514. In the three trenches
 519 further northeast along the EAF (Nacar, and Balkar 1 and 2) instead E1 is dated to between 677
 520 and 1153, so the 1513 event is not visible. The closest trench to Tevekkelli (the Nacar trench) is
 521 35 km northeast of it, so the rupture should have stopped before reaching this point, which means
 522 it is unlikely for the 1513 earthquake to be the penultimate event (E2) tentatively identified by
 523 Çetin et. (2003) in one of their Lake Hazar trenches (they date E2 to AD 1393 – 1464, but claim
 524 that, because of dating uncertainties, it could be the 1513 earthquake). In the catalog of trenches
 525 in Turkey (Gürboğa & Gökçe, 2019), the 1513 rupture is estimated as 40 km long. This is barely
 526 the equivalent of a rupture of the Pazarcık segment between about 10 km southwest of the Nacar
 527 trench and Türkoğlu. A 40 km rupture however would not produce an earthquake above M_w 7.0.
 528 A M_w 7.4 earthquake requires a 80 km long rupture. That can be done by the rupture extending
 529 from south of the Nacar trench to Islahiye, i.e. rupturing the southern part of the Pazarcık
 530 segment and then the Nurdaği segment of the Amanos fault to the next bend south near Islahiye
 531 (Figure 2b). This would be more in line with an event that must have produced considerable
 532 damage to the region of Adana and Tarsus. A rupture stopping at Türkoğlu and a M_w of 7 would
 533 not have been sufficient, this region being 180 km away.

534

535 **3 Discussion: timing, location, and size of the 2023 M_w 7.8 Pazarcık earthquake**

536 3.1 Fault segmentation, rupture length, and earthquake size

537 In the Karasu valley, the central and southern Amanos fault (Hassa segment and most of
 538 the Kirikhan segment, Figure 2a) does not appear to have ruptured in a large earthquake at any
 539 time from at least AD 1000 to 2023 between Baghras and Islahiye, a fault length of ~70 km
 540 (Figure 2b, 5a). This could partly explain the unusually large size of the 2023 M_w 7.8 earthquake:
 541 the central and southern Amanos segments, which are separated from the Nurdaği segment by a
 542 releasing bend near Islahiye, and from each other by a restraining bend near Demrek (Duman &
 543 Emre, 2013), were stressed enough that the bends were not sufficient to stop a multi-segment

544 rupture. Thus the most likely reason we have not seen such large ruptures before on the EAF is
545 not because “fault segmentation” or “fault maturity” determine the maximum length of rupture in
546 plate boundary faults, but rather because they are infrequent and, therefore, not captured by the
547 comparatively short and incomplete earthquake history we have for the region. For a M_w 7.8
548 earthquake to happen, which, let’s not forget, ruptured over half of the EAF at once, we need a
549 rather specific set of circumstances that are hard to quantify in the absence of data.

550 Prior to 2023, there was considerable disagreement over the maximum size of
551 earthquakes on the EAF. For example, Hubert-Ferrari et al. (2020), on the basis of the historical
552 seismicity reports, assumed that magnitude 7.0 and above is likely, whereas some studies based
553 on the instrumental record alone considered M_{\max} for the EAF to be limited to M_w 6.8 (e.g.
554 Bayrak et al., 2015), while yet others proposed a range from M_w 6.7 to 7.4 depending on the
555 segment considered (e.g. Gülerce et al. 2017; Güvercin et al., 2022), with up to M_w 7.7 when
556 some segment combinations are explored in models (Gülerce et al., 2017). A good estimate of
557 M_{\max} , however, is crucial for seismic hazard assessments. In the case of faults like the EAF,
558 which have no large instrumentally-recorded events, knowledge about M_{\max} , recurrence
559 intervals, and rupture length can only come from a combination of historical records,
560 paleoseismological studies, geological analysis in tectonic context, and comparisons with similar
561 faults. Based on the information available at the time, the 2023 M_w 7.8 earthquake could have
562 been foreseen in terms of location and timing (an earthquake on the southern EAF was due any
563 time, this fault being a clearly active one currently in -what should have been an alarmingly-
564 quiescent period), but not in size, because the largest confirmed earthquake in historical catalogs
565 since AD 1000 for the region reached M_w 7.5 at most, with the majority of earthquakes being M_w
566 7 to 7.2 (Table 1). Besides, the source fault of the M_w 7.5 earthquake in 1822 is not technically
567 even part of the EAF system. Looking further back in time (before AD 1000) would not have
568 increased the number of truly large earthquakes, as such events are even harder to interpret the
569 older the records are: there are none listed for this area by Ambraseys & Jackson (1998), but that
570 does not mean none happened, just that they may not have been recognized or recorded. With no
571 earthquakes of comparable size in either instrumental or historic catalogs, we cannot calculate an
572 observed recurrence interval for $M_w \geq 7.8$ on the EAF, and are left with estimates based on
573 geodetic rates or longer-term average geological displacement rates (e.g. Friedrich et al., 2003).
574 This is only half the problem though: without a $M_w \geq 7.8$ in the records, the possibility that such

575 an earthquake would occur on the EAF was not seriously considered in seismic hazard
 576 calculations for the region by most authors. We propose that for the EAF M_{\max} is actually ~ 8.2 ,
 577 i.e. a complete rupture from the Karlova triple junction to the Amik triple junction (Figure 1d),
 578 and that all continental strike-slip plate boundary faults should be treated as having the same
 579 end-to-end rupture potential, unless proven otherwise. In this context, M_{\max} is reached in
 580 “superevents” that are infrequent and most likely highly non-periodic, especially for non-isolated
 581 plate boundary faults such as the EAF-DSF system (contrast with the Alpine Fault, NZ,
 582 Berryman et al., 2012) and thus not captured by even such a comparatively long historical record
 583 as we have for Anatolia. The 2023 M_w 7.8 earthquake did not reach M_{\max} only by chance. It
 584 appears that the combined effect of the larger stepover between the Erkenek and Pütürge
 585 segments and the coseismic Coulomb stress shadow from the 2020 Elâziğ event on the latter was
 586 enough to stop the 2023 rupture from dynamically propagating further to the northeast. If
 587 nothing else, the 2023 M_w 7.8 earthquake stands as a warning that continental transforms can
 588 fully rupture just as subduction zones can (see McCaffrey, 2008), in infrequent but devastating
 589 earthquakes.

590

591 3.2 Fault interactions, cascades, cycles, supercycles, and collective memory

592 The reason for the behavior of the EAF is multifaceted. First of all, there is the
 593 intertwined kinematics of the three plate boundary fault systems: EAF, DSF, and NAF (Figure
 594 1d). Hubert-Ferrari et al. (2003) pointed out that the EAF and NAF cannot move simultaneously,
 595 and that in the historical records since AD 100 the number of damaging earthquakes on each
 596 fault reflects this, with peak seismic activity switching from one fault zone to the other every few
 597 hundred years. For the DSF, Khair et al. (2000) also observe a switching between activity and
 598 quiescence, with quiescent periods of 450–700 years interrupted by active periods of 50–150
 599 years in the past two millennia. These are examples of supercycles (e.g. Philiposian and
 600 Meltzner, 2020; Salditch et al., 2020).

601 Whereas plate-boundary-scale kinematics and variations in long-term strain accumulation
 602 may control the acceleration and the turning-on-and-off of each fault zone on the million-year to
 603 the millennial scale (i.e. supercycles and clusters; see also Friedrich et al., 2003; Bennett et al.,
 604 2004, Lefevre et al., 2018), within each period of high activity the seismic behavior is likely

605 controlled by coseismic and postseismic Coulomb stress changes (King et al. 1994). The latter is
606 indicated by the clustering of earthquakes within relatively short time periods, and by the
607 propagation of ruptures in systematic fashion along some faults: for example, the classic NAF
608 behavior of east-to-west sequential ruptures (e.g. Barka, 1996; Stein et al., 1997; Hubert-Ferrari
609 et al., 2000, 2003), but also the behavior observed on the EAF, where a series of ruptures can
610 start at both ends of the fault system and move towards the center (Hubert-Ferrari et al., 2003).
611 Another potential example of this behavior is the rupture cascade (Philibosian and Meltzner
612 2021) of the 12th century (cf. Figure 7.2 in Marco and Klinger, 2014) along the EAF and DSF
613 systems in a southerly direction. The 1114 event occurred along the Parzarcik segment of the
614 EAF (Figure 2b). Then, the DSF ruptured several times as documented by the 1138, 1157, and
615 1170 events (Figure 2b and 5), and the 1202 event in Lebanon (South Yammouneh segment,
616 DSF, Daëron et al., 2007). After the 12th century cascade, both fault zones appear to have
617 ruptured irregularly. As a result, the time since the last major ($M_w > 7$) event varies along strike
618 of the fault zones. For the EAF, the times since the last rupture events are 130 years (Erkenek
619 segment), 500 years, 900 years, and over 1000 years for the Amanos segment (Figure 5a). These
620 seismic gaps are not due to a lack of data, but rather are an expression of the natural earthquake
621 behavior in active fault zones. Thus, for fault segments where a seismic gap exists, the maximum
622 possible earthquake magnitude (M_{max}) and recurrence times may be severely underestimated
623 unless historic seismic activity from the entire fault system has been considered. For example,
624 seismic hazard modeling conducted solely based on instrumental seismic records prior to
625 February 6th, 2023 treated such segments as inactive and underestimated M_{max} and the seismic
626 hazard (e.g. Bayrak et al., 2015). The February 6th, 2023 Pazarcik earthquake filled in the large
627 seismic gaps in the Amanos segment and several other seismic gaps along strike (Figure 5b). If
628 the same type of hazard modeling would be conducted after February 6th, the Amanos segment
629 will appear as active and be included, thereby likely overestimating its hazards in the near future.

630 Similar seismic gaps also exist along the DSF, some lasting for 200 years, while others
631 lasting for 620 years, and over 850 years (Figure 5c). These seismic gaps will grow, close, and
632 reopen repeatedly (Figure 5d) as long as strain accumulates across this active plate boundary,
633 and when a seismic gap exists without a stress shadow, the hazard is high. The identification of
634 seismically inactive but geodetically active regions along active fault zones is, therefore, an

635 important area of focus for future research and seismic hazard assessment, but additional
636 information is required to accurately forecast earthquake potential.

637 There is also an important role played by local fault configuration, in this case especially
638 the branching of EAF and DSF. The two systems are not independent, even on short time scales.
639 These two fault zones overlap, with faults from both zones running parallel to one another in a
640 strip just a few tens of km wide. Thus, in the Karasu valley and Amik basin, depending on
641 exactly which fault ruptures where, there can be either Coulomb stress loading or shadowing of
642 neighboring faults belonging to either fault zone. For example, the northwestern DSF strands
643 (Qanaya-Babatorun and Nusayriyah faults) have likely been loaded coseismically by the 2023
644 M_w 7.8 earthquake, simply on the basis of their relative position, geometry, and kinematics. On
645 the other hand, the Amanos segment and the Yesemek fault in the Karasu valley have the same
646 configuration as the southern San Andreas/San Jacinto fault pair in California: two closely-
647 spaced (15 to 30 km) subparallel faults with the same strike-slip kinematics. This is a situation
648 where the faults are effectively coupled: a large rupture on one fault would cause a significant
649 coseismic Coulomb stress drop on the other, delaying the next rupture (Carena et al., 2004). The
650 1822 earthquake on the Yesemek fault therefore must have delayed the occurrence of the next
651 earthquake on the central-southern Amanos fault, which at that point had not seen a rupture for at
652 least 800 years, and the end of this delay just happened to coincide with a fortuitous rupture
653 propagation from a minor fault in the Narlı fault zone (Figure 2a) to the main branch of the EAF
654 (Rosakis et al., 2023; U.S. Geological Survey, 2023), at a position on the Pazarcık segment of the
655 EAF that also had not seen a rupture in 900 years. This was a classic “domino effect” with all
656 tiles in the right place at the right time. We are thus left with a question that can be answered
657 only with further investigations: how often can the tiles line up in this specific order? It is not a
658 trivial problem: not only a specific set of circumstances can lead to an unusually large event, but
659 also activity on one fault system could control the timing of the next supercycle of its immediate
660 neighbor. It means that calculation of earthquake probability cannot be restricted to one fault, or
661 even one fault system: in the case of continental plate boundary faults it also needs to include the
662 neighboring fault systems. Plate boundary faults may not just have a “long term memory”
663 (Salditch et al., 2020), but also a “collective memory”, which would call for earthquake
664 probability calculation at much larger scales than are generally considered.

665

666 4 Conclusions

667 By considering the previous rupture history and geometric configuration of the faults
668 involved, we were able to explain why the 2023 M_w 7.8 earthquake occurred on the southern half
669 of the EAF, why the conditions were right for it to occur now, and why it was unusually large
670 compared to previous events in the region. Based on the historical seismic records of the region,
671 the 2023 M_w 7.8 Pazarcık earthquake was foreseeable in space and time, but not in size. M_{\max} for
672 the EAF is likely ~ 8.2 , with the limit rupture length being the distance between the two triple
673 junctions that delimit it. The 2023 earthquake may not have reached M_{\max} simply by chance: if
674 the 2020 Elâziğ earthquake had not happened where and when it did, would the 2023 rupture
675 have continued propagating towards the northeast? This is a question that could be answered by
676 combining Coulomb stress models and dynamic rupture models. If nothing else, what we have
677 learned from the 2023 M_w 7.8 Pazarcık earthquake is that segmentation of continental transform
678 faults is not relevant for calculating M_{\max} , because truly large earthquakes can jump across
679 segment boundaries. Such earthquakes are so infrequent, however, that they are difficult to
680 study, and therefore hard to foresee.

681

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683

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690 <https://dx.doi.org/10.5285/df93e92a3adc46b9a5c4bd3a547cd242>), active fault database
691 (<https://doi.org/10.5194/essd-14-4489-2022>), preliminary surface rupture mapping (Reitman et al.,
692 2023, <https://doi.org/10.5066/P985I7U2>), and texture-shading program (Brown, 2014;
693 <https://app.box.com/v/textureshading>). The file with the electronic version of the ruptures listed in
694 Table 1 and shown in Figure 2b is part of the supplementary material. We have also included in the
695 supplement the uninterpreted base images of Figures 2b and 4.

696

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- 926

927 **Table 1.** List of earthquakes and corresponding source faults.

Date ^a	M _w ^b	Name ^a	Rupture length (km) ^b	Aftershocks (months)	Source fault or fault segment
Feb. 06, 2023	7.8	Pazarcık	~ 310	ongoing	Amanos, Pazarcık, & Erkenek s.
Jan. 24, 2020	6.8	Elâziğ	(~ 35)	19 ^c	Pütürge s.
Mar. 02, 1893	7.2 +/- 0.1	Malatya	~ 60	> 12 ^d	Erkenek s.
Jan. 14, 1874	7.1	Sarikamiş	~ 45	≥ 12 ^f	Palu s.
Apr. 03, 1872	7.2	Amik Gölü	~ 50	10 ^c	Kirikhan s. & Antakya f. z.
Aug. 13, 1822	7.5	Southeastern Anatolia	~ 110	30 ^c	Yesemek f. & Qanaya-Babatorun f.
Jan. 21, 1626	7.2	Hama	~ 50	unknown	northern St. Simeon f.
1513/1514	≥ 7.4	Malatya	≥ 80	unknown	Pazarcık & Nurdağı s.
Dec. 29, 1408	7.0	Shugr-Bekas	~ 40	unknown	Qanaya-Babatorun f.
Feb. 20, 1404	≥ 7.0	Aleppo	≥ 40	≥ 9 ^{f,g}	Nusayriyah f.
Jun. 29, 1170	7.3 – 7.4	Shaizar	~ 80	4 ^c	Missyaf f.
Aug. 12, 1157	7.2	Apamea	~ 50	21 ^c	Shaizar f.
Oct. 11, 1138	7.2	Atharib	~ 50	8 ^c	northern St. Simeon f.
Nov. 29, 1114	≥ 7.2	Antioch, Maraş	≥ 50	5 ^f	Pazarcık s.

928

929 ^aAmbraseys (2009), except for events from 2020 (Çetin et al. 2020) and 2023 (U.S. Geological
930 Survey, 2023).

931 ^b For most of the earthquakes we have estimated surface rupture lengths based on Wells &
932 Coppersmith (1994), unless lengths were reported in original sources (discussion in text). The
933 magnitude reported here is our preferred one among the sources discussed in the text. For the
934 Elâziğ earthquake the rupture length value is in brackets because it did not rupture at the surface,
935 though it had shallow slip (Pousse-Beltran et al., 2020).

936 ^c Salamon, 2008; ^dSatılmış, 2016; ^eÖztürk, 2021; ^fAmbraseys, 2009

937 ^g not possible to really distinguish all aftershocks of 1404 from foreshocks of 1408.

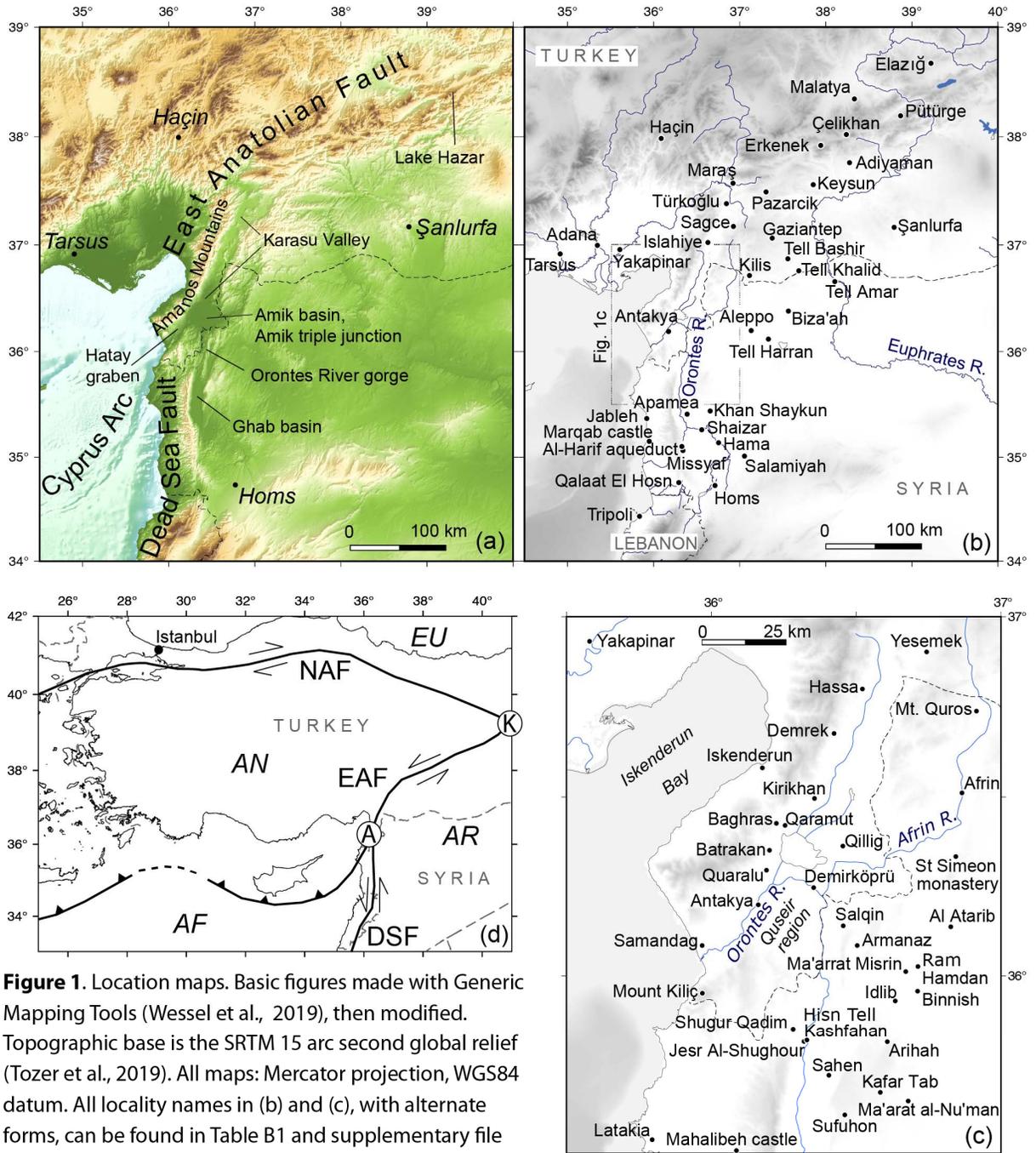


Figure 1. Location maps. Basic figures made with Generic Mapping Tools (Wessel et al., 2019), then modified. Topographic base is the SRTM 15 arc second global relief (Tozer et al., 2019). All maps: Mercator projection, WGS84 datum. All locality names in (b) and (c), with alternate forms, can be found in Table B1 and supplementary file ds04. NAF = North Anatolian Fault, EAF = East Anatolian Fault, DSF = Dead Sea Fault, K = Karlovia triple junction, A = Amik triple junction; AF = African plate, AN = Anatolian plate, AR = Arabian plate, EU = Eurasian plate.

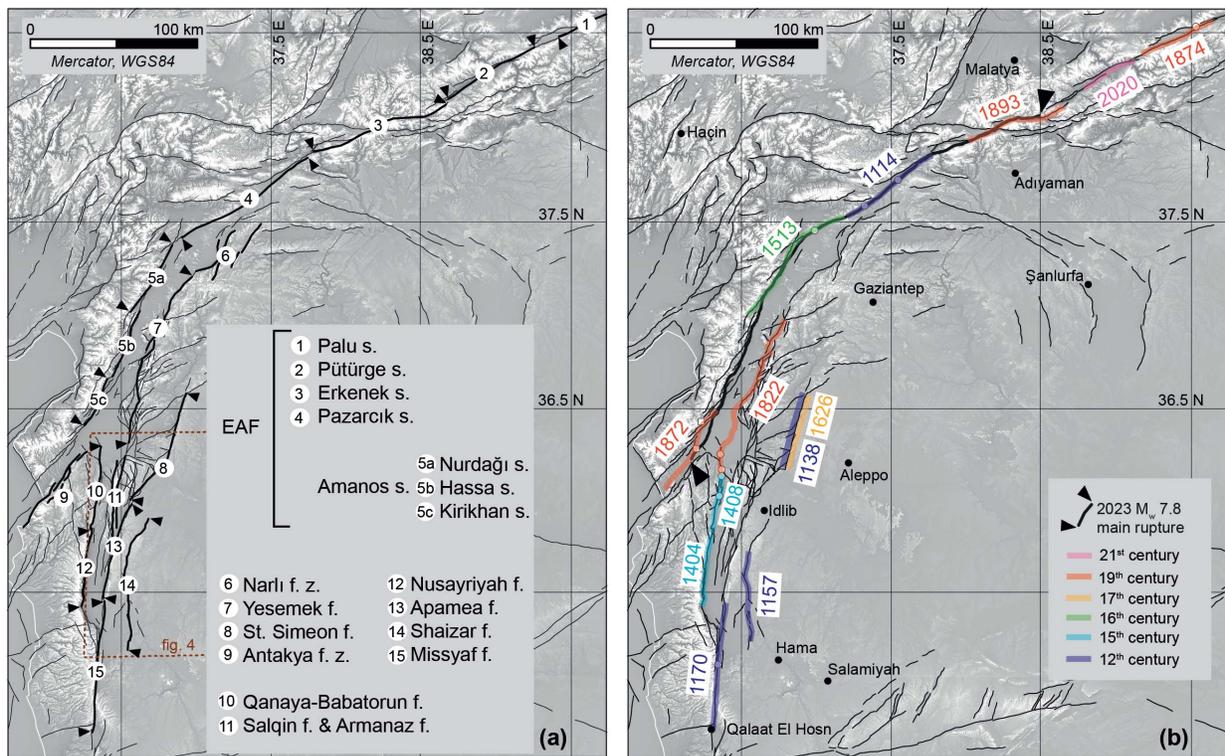


Figure 2. (a) Fault names (see Appendix B for details). The Amanos segment of the EAF is split into three further segments. Bends and stepovers are not labeled here because we do not refer to them; their names can be found in Duman & Emre (2013). s. = segment, f. = fault, f. z. = fault zone. (b) Fault rupture/earthquake pairs from Table 1. Base map and other elements are described and referenced in figure 3. Original uninterpreted base map included as supplementary file ds01, and ruptures as supplementary file ds03.

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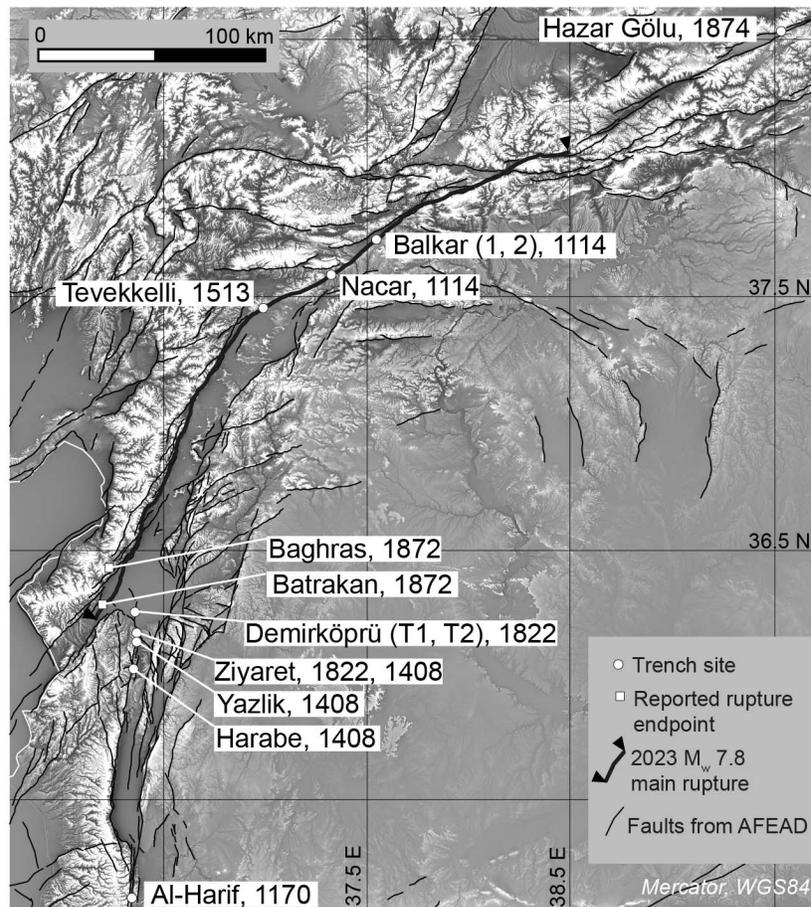


Figure 3. Location and names of trenches, and approximate historical fault rupture endpoints mentioned in the text, with the relevant pre-2023 earthquake/s indicated for each one. See references in text for each trench name. AFEAD faults are from Zelenin et al. (2022), whereas the 2023 main rupture we remapped ourselves from the pixel tracking data of Ou et al. (2023) and ForMTMTer - EOST (2023), and from the preliminary maps of Reitman et al. (2023). Basemap derived from the 30 m GLO-30 Copernicus DEM (European Space Agency, 2021), processed by applying the texture shading technique of Brown (2014).

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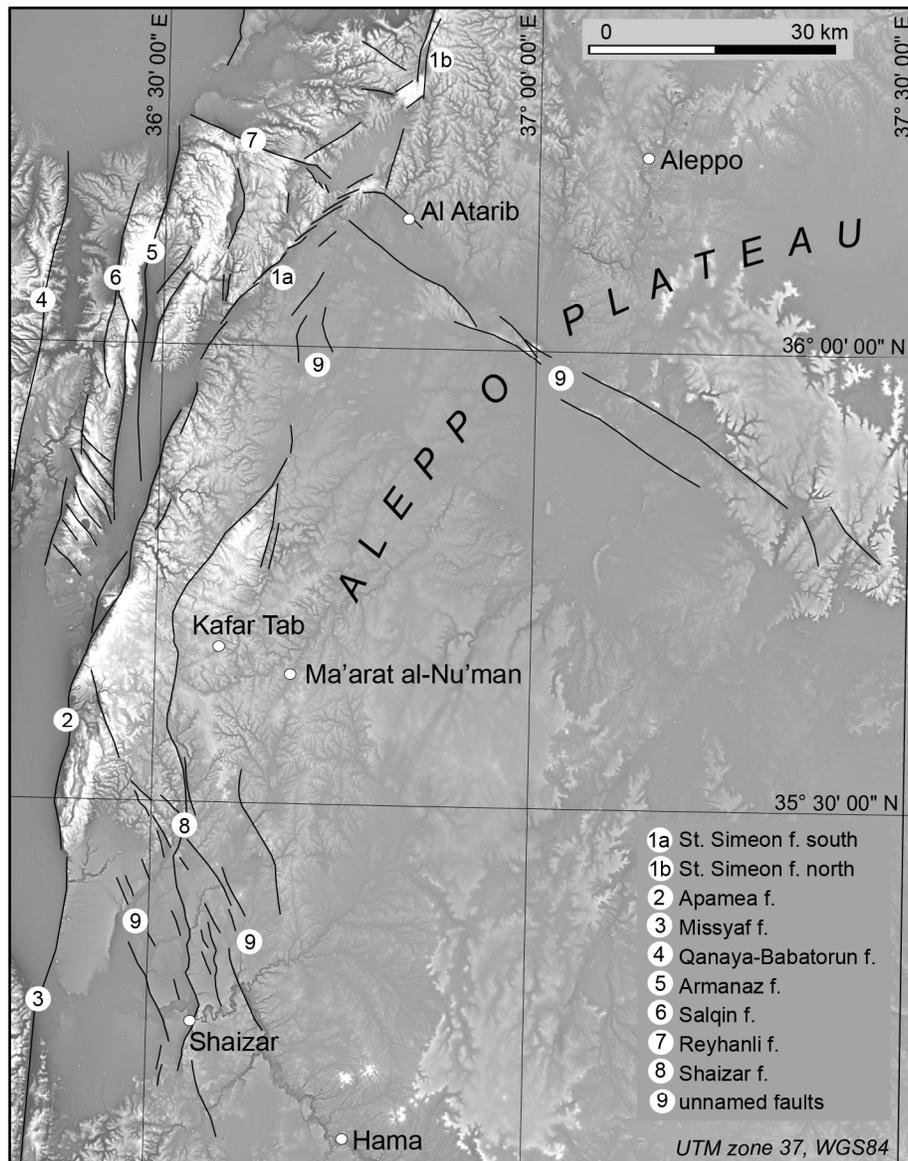


Figure 4. Faults that we mapped using the 30 m GLO-30 Copernicus DEM (European Space Agency, 2021) processed by applying the texture shading technique of Brown (2014), which can be used to enhance fine details (e.g. scarps). We mapped only the very sharpest features, which are likely to be active faults, but there are also numerous other more subtle lineaments. The background image has been muted for clarity; a full-strength and full-resolution uninterpreted image is included as a supplement (file ds02).

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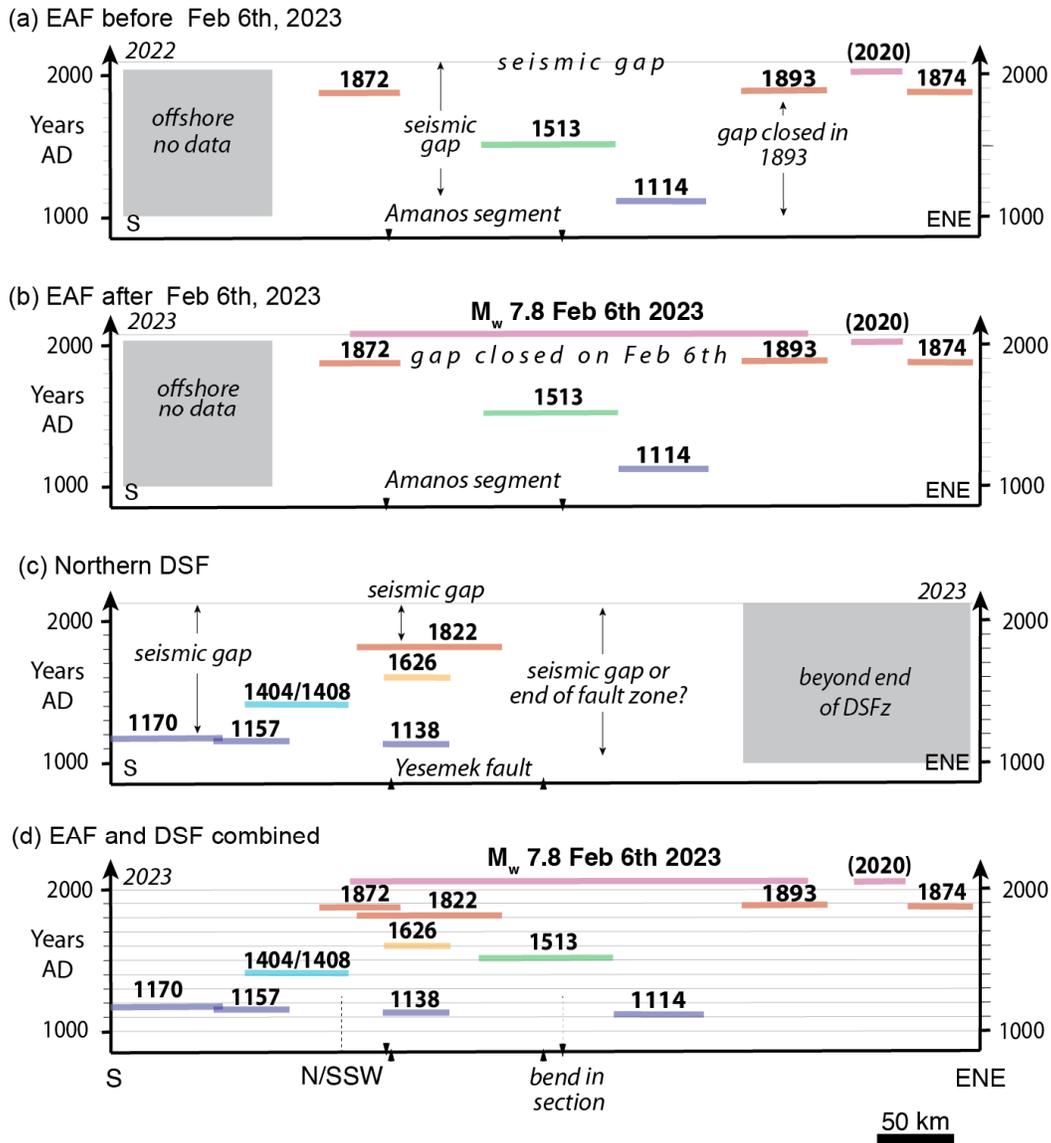


Figure 5. Space-time pattern of historic earthquakes along the EAF and northern DSF (see Figure 2 for location). The position and extent of $M > 7$ ruptures (horizontal bars) are justified in the text. (a and b) Pattern of $M > 7$ ruptures for the western portion of the EAF prior to and after February 6th, 2023. (c) Pattern of $M > 7$ ruptures for the northern DSF. (d) Pattern of all recorded $M > 7$ ruptures for the region in which both active strike-slip fault systems (EAF and DSF) overlap spatially and interact kinematically.

947 **Appendix A: earthquake magnitudes**

948 For earthquake magnitudes between 6.2 and 8.2 and depth of focus < 70 km, $M_w = M_s$
 949 (Scordilis, 2006). As we only consider events in this magnitude range and discuss a few
 950 instrumental events for which M_w is reported, we always use M_w in our text unless it is necessary
 951 to specifically mention another type of magnitude, with the understanding that, when citing
 952 historical sources, these mostly reported either M_s determined using local empirical relationships
 953 based on rupture length, or M_F (“felt magnitude” equivalent to M_s , see below) (e.g. Ambraseys,
 954 1988; Ambraseys & Barazangi, 1989). Another magnitude used by the INGV CIFT5Med catalog
 955 (Guidoboni et al., 2018, 2019) is M_e , which here stands for “magnitude equivalent” (i.e.
 956 equivalent to M_w) as calculated from intensities (whereas usually M_e stands for “energy
 957 magnitude” calculated from energy release) which, as far as uncertainties are concerned, we treat
 958 as M_F , because it is also fundamentally based on reported intensity areas. The difference between
 959 M_e and M_F appears to be simply the specific relationship between intensity and magnitude used,
 960 which for M_e is the one of Gasperini and Ferrari (2000). Considering that the largest source of
 961 uncertainty in estimating magnitude is the interpretation of the historical descriptions themselves,
 962 which determine what intensity is assigned to each place (for example, where one author assigns
 963 intensity X, another may assign intensity VIII), the specific relationship used does not seem to be
 964 overly important, as long as it is properly calibrated for local conditions.

965 To better understand this source of uncertainty, we have recalculated magnitudes
 966 ourselves for all the historical earthquakes that we considered whenever sufficient information
 967 was available, using the M_F relationship developed for Turkey by Ambraseys & Finkel (1987)
 968 and re-interpreting assigned intensities from descriptions if necessary (especially in cases of
 969 conflicting opinions), before deciding which reported magnitude to adopt in our work:

$$970 \quad M_F = -0.53 + 0.58(I_i) + 1.96 \times 10^{-3}(R_i) + 1.83 \log(R_i),$$

971 where R_i is the average radius (in km) of the isoseismal of intensity I_i

972 The reason we used M_F in our own tests instead of M_s is because not all events have a
 973 reported rupture length (which, even when reported, may be underestimated, as discussed by
 974 Ambraseys & Jackson, 1998), but nearly all have at least a “felt area”. From comparing previous
 975 authors’ works in this region with our own test results, the uncertainty in magnitude estimated
 976 for historical earthquakes of +/- 0.3 (Ambraseys, 1989) seems to be about right (Table A1).

977 The addition of the 2023 events allowed us also to verify that this empirical relationship
978 is indeed appropriate for the region, as the M_F we calculated for the two events using intensity
979 maps from U.S. Geological Survey (2023) are $7.7 +0.2/-0.1$ and $7.3 +/-0.2$ respectively (Table
980 A1). Considering that different seismological laboratories in the US and Turkey (USGS, GCMT,
981 GEOSCOPE, KOERI) have variably reported M_w of 7.7, 7.8, and 8.0 for the first event, and 7.5,
982 7.6, and 7.7 for the second, our estimate of M_F is well within range and validates the use of this
983 formula for older earthquakes in the region, with $+/- 0.3$ also a reasonable, conservative
984 uncertainty.

985

986 **Table A1.** List of earthquakes with M_F recalculated by us, and all magnitudes reported by
 987 previous authors.

Date^b	M_F	Reported magnitude	Name^b
Feb. 06, 2023	7.3 +/- 0.2	M_w 7.5, 7.6, 7.7	Elbistan
Feb. 06, 2023	7.7 +0.2/-0.1	M_w 7.7, 7.8, 8.0	Pazarcık
Jan. 24, 2020	6.6	M_w 6.7, 6.8	Elâziğ
Mar. 02, 1893	7.0	≥ 7.1 ; 7.2 +/- 0.1	Malatya
Jan. 14, 1874	7.0 +/- 0.1	≥ 7.1	Sarikamiş
Apr. 03, 1872	7.1 +0.2/-0.1	5.9 ^c ; ≤ 7.2 ; 7.2	Amik Gölü
Aug. 13, 1822	7.5 +0.3/-0.2	7.0; ≥ 7.4 ; 7.5	Southeastern Anatolia
Jan. 21, 1626	-	7.2	Hama
1513/1514	$\geq 7.4^d$	≥ 7.4	Malatya
Dec. 29, 1408	7.1 +/- 0.1	7.0; 6 to 7; 7.4	Shugr-Bekas
Feb. 20, 1404	7.4	≥ 7.0 ; 7.4	Aleppo
Jun. 29, 1170	7.3 +0.2/-0.4	7.3 – 7.4; 7.3 +/- 0.3; 7 to 7.8; 7.7	Shaizar
Aug. 12, 1157	7.4 +/- 0.1	7.2 +/- 0.3; 7.4	Apamea
Oct. 11, 1138	7.1 +/- 0.5	6.0; 7.5	Atharib
Nov. 29, 1114	7.3 +/- 0.4	6.9 +/- 0.3; ≥ 7.2 ; 7.4; ≥ 7.8	Antioch, Maraş

988
 989 ^a Unless M_w is explicitly indicated, the reported magnitude is either M_s , M_F , or M_e as explained
 990 in the text.

991 ^b Ambraseys (2009) except for 2020 (Çetin et al., 2020) and 2023 events (U.S. Geological
 992 Survey, 2023).

993 ^c Sbeinati et al. (2005). It is unclear where they get this low value from, because it is very
 994 different from those of the authors they cite, and it seems to conflict with the size of the high
 995 damage area and the highest reported intensity when compared to the other events they have in
 996 the same catalog.

997 ^d Due to the limited information, only one intensity area can be defined, so the magnitude
 998 depends on whether this intensity is assigned as VI or VII (because significant “destruction” was
 999 reported in all localities mentioned, it should be at least VI, i.e. strong shaking).

1000

1001

1002 Appendix B: fault names and place names

1003 There seems to be no generally accepted standard about names of faults and fault
1004 segments in the region. One problem is the political border between Turkey and Syria: as it
1005 happens too often, faults (and their names) have a tendency to end or change at the border. The
1006 Active Faults of Eurasia Database (AFEAD) of Zelenin et al. (2022) often does not label the
1007 individual fault segments beyond naming the general fault zone to which they belong. For the
1008 East Anatolian fault system, we have decided to use the segment names and segment boundaries
1009 as defined in Duman & Emre (2013), because these authors go through the effort of
1010 systematically providing detailed maps, coordinates, and names in a way that is easy to follow.
1011 In the case of faults that are traditionally considered part of the Dead Sea fault system, the choice
1012 is less straightforward, because even when a fault has been labeled, its endpoints are usually ill-
1013 defined, or a vague description (e.g. “fault on the eastern side of the Ghab basin”) is given, and
1014 maps in publications are small and hard to read. We chose to use the labeling of Westaway
1015 (2004) and Seyrek et al. (2012) for the following faults: Qanaya-Babatorun (called instead
1016 “Hacıpaşa segment” to the Syrian border by Akyüz et al., 2006), Nusayriyah, Apamea, Salqin,
1017 and Armanaz, which are named after nearby towns and villages. These authors also define a
1018 “East Hatay fault” on the eastern edge of the Karasu graben, whereas the same fault is called
1019 “Yesemek fault” by Duman & Emre (2013). We chose to keep the latter name because it has
1020 been assigned based on the fault going through the village of Yesemek, whereas “East Hatay”
1021 refers to a region. Finally, different authors assign the name “Afrin” (or Aafrin) fault to two
1022 entirely different faults that pass near the town of Afrin. One of these two does not appear in our
1023 analysis, but to avoid any confusion, we have decided to call the fault that we discuss “St.
1024 Simeon fault” as named by Rukieh et al. (2005) and Karakhanian et al. (2008) due to the fault
1025 passing through the St. Simeon monastery site (whereas Westaway, 2004, and Seyrek et al.,
1026 2012, call this “Afrin fault”). We were not able to find any existing names for the faults east of
1027 Apamea in Syria (on the Aleppo plateau, between the Ghab basin and Aleppo, see Figure 4), so
1028 to avoid using the “unnamed” label more than necessary, we named the largest of these “Shaizar
1029 fault”, because it goes through the town bearing this name, which was destroyed in the 1157
1030 earthquake.

1031 Place names in this region have changed throughout the centuries depending on who
1032 controlled which territory, and even today the same name is spelled differently depending on

1033 transliteration and on native language of the writer. In reading the various publications and
1034 earthquake catalogs we had to go to some lengths to match place names from one publication to
1035 the next, and to modern-day names that anyone can find on Google Earth. Thus, besides the
1036 standard map with locations (Figure 1), we are also including a simplified table of place names
1037 in this appendix (Table B1), plus an electronic version of it that reports all the variants we have
1038 encountered (up to six), coordinates, and any comments where needed (Supplementary file
1039 ds04). The list is by no means exhaustive, but it should help readers find their way from one
1040 publication to the next. In our paper we have decided which name to use mostly based on the
1041 primary source of our information, except for those cases where a modern name was easier to
1042 find in online searches and the name appears many times in our text (e.g. Demirköprü instead of
1043 Jisr al-Hadid). In those cases where the modern locality name has nothing to do with the one in
1044 historical records (we just matched positions between the published map and Google Earth map
1045 to identify its coordinates), we have kept the historical name in our text and maps, but supplied
1046 the name of today's nearest locality in the table (e.g. Batrakan/Atatürk).

1047

1048 **Table B1.** Place names from Figure 1, listed alphabetically in first column: in bold is the version
 1049 used in text and figures. Full version in Supplementary file ds04.

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<i>Google Earth name</i>	<i>Alternate name 1</i>	<i>Alternate name 2</i>
Afamiyah	Apamea	Afamea
Afrin	Aafrine	Aafrin
Al Atarib	Al-Atareb	Cerepum
Alazi	Qaralu	
Aleppo	Halab	Halep
Antakya	Antioch	Hatay
Armanaz	Armenhaz	
Asmacık	Tell Khalid	Trihalet
Atatürk	Batrankan	
Bakras Kalesi	Baghras	Bagras
Biza'ah	Bizza	
Demirköprü	Jisr al-Hadid	Jisr El Hadid
Gaziantep	Aintab	Gaziaintab
Hama	Hamat	Hamath
Haram	Harim	Uringa
Homs	Hims	Emesa
Iskenderun	Alexandretta	Scanderoon
Jableh	Jeble	Jabala
Jesr Al-Shughour	Jisr al-Shughur	Jisr as-Shugr
karamurt Hani	Qaramut	
Khan Shaykhun	Han Sheikhun	
Kharamanmaraş	Maraş	Germanicea
Kozkalesi	Quseyr	Quseir
Kumlu	Qillig	Quilliq
Latakia	Al-Ladhiqiya	Laodicea
Ma'arat al-Nu'man	Marre	Arra
Ma'arrat Misrin	Ma'aret Masrin	Megaret Basrin
Mahalibeh castle	Qalaat Blatnes	Balatonus
Marqab castle	Markab	Margat
Missyaf	Masyaf	Misyaf
Mount Kiliç	Mount Cassius	Al-Akraa
Orontes / Asi	Arantu	
Qalaat El Hosn	Krak (Crak, or Crac) des Chevaliers	Hisn al-Akrad
Saimbeyli	Haçin	Kaza Haçin
Sakcagoz	Sagce	Sakçagözü
Salamiyah	Salamyya	Salamiyyah
Salqin	Salqein	
Samandag	Suaidiya	Seleucia
Şanlurfa	Urfa	Edessa
Serjilla	Kafar Tab	Capharda
Shaizar	Shayzar	
Shugur Qadim	Castles of Shughur and Bekas	Shugr-Bekas
Tell Arn	Tell Harran	Tal 'Aran
Tilbasar Kalesi	Tell Bashir	Turbessel
Tripoli	Tarabulus	
Yakapınar	Misis	Mopsuestia