Identification of Source Faults of Large Earthquakes in the Turkey-Syria Border Region Between AD 1000 and the Present, and their Relevance for the 2023 M_w 7.8 Pazarcık Earthquake

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Motivation

On February 6th, 2023, there was a magnitude 7.8 earthquake in the Turkey-Syria border region. It surprised many people, including many Earth scientists, because of where it happened (on the East Anatolian fault) and because of how large it was.

People wondered whether it could have been foreseen, and how large an earthquake on this fault can really be (M_{max}, i.e. maximum magnitude).

Location Maps

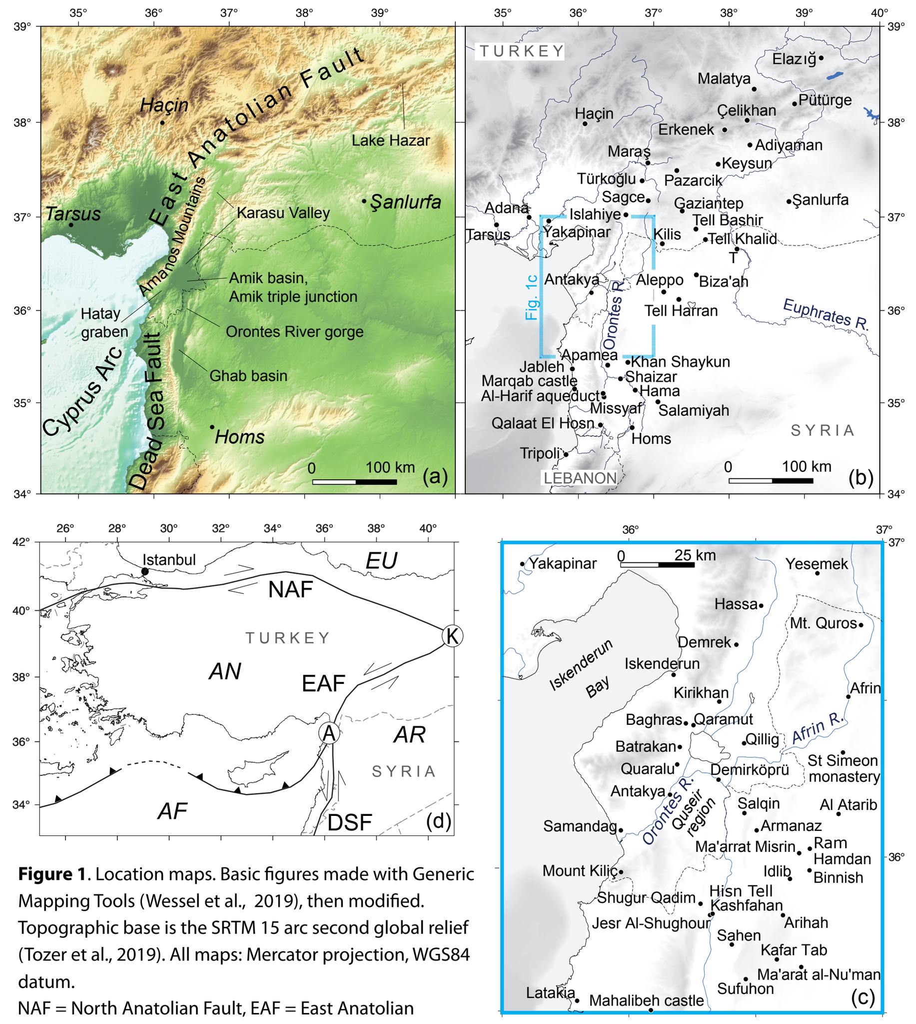

Figure 1. Location maps. Basic figures made with Generic Mapping Tools (Wessel et al., 2019), then modified. Topographic base is the SRTM 15 arc second global relief (Tozer et al., 2019). All maps: Mercator projection, WGS84 datum.
NAF = North Anatolian Fault, EAF = East Anatolian Fault, DSF = Dead Sea Fault, K = Karliova triple junction, A = Amik triple junction; AF = African plate, AN = Anatolian plate, AR = Arabian plate, EU = Eurasian plate.

Method

To figure out maximum earthquake size and whether the earthquake should have been expected, we looked at the history of earthquakes in the region in the last 1000 years and looked for their causative faults. We used information from historical seismology, paleoseismology, archeoseismology, and remote sensing to identify the faults that caused fourteen earthquakes with magnitude $M_w \geq 7$ or greater between AD 1000 and the present in this region.

Results

We found that the location (East Anatolian Fault) and timing (it was due any time) of the 2023 earthquake were foreseeable, but not the magnitude.

We determined that the maximum magnitude for the East Anatolian Fault is likely 8.2, and that the 2023 earthquake was below this maximum by chance. It is hard to say how often such large events can happen, because many different things need to align. We also believe that it is necessary to look at neighboring fault systems when estimating seismic hazards, because they interact.

Conclusions and Future Work

Such unusually large events are hard to model in terms of recurrence intervals, and seismic hazard assessment along continental transforms cannot be done on individual fault systems but must include neighboring fault systems as well, because they are not kinematically independent at any time scale.

Fault and Segment Names

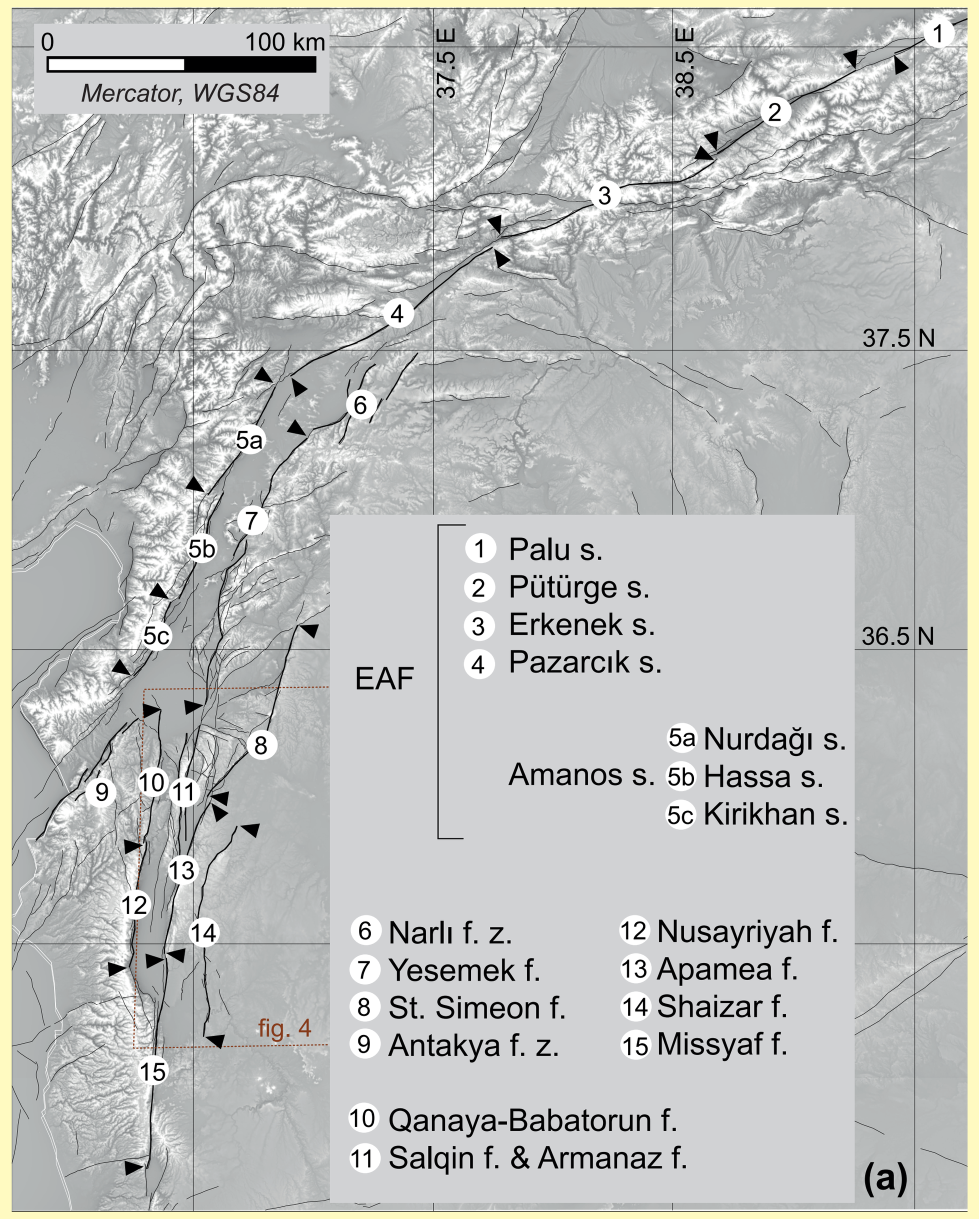

Figure 2a. The Amanos segment of the EAF is split into three further segments; their names can be found in Duman & Emre (2103). Detailed map of northern DSF zone in **figure 4**. s. = segment, f. = fault, f. z. = fault zone.

Fault Rupture / Earthquake Pairs

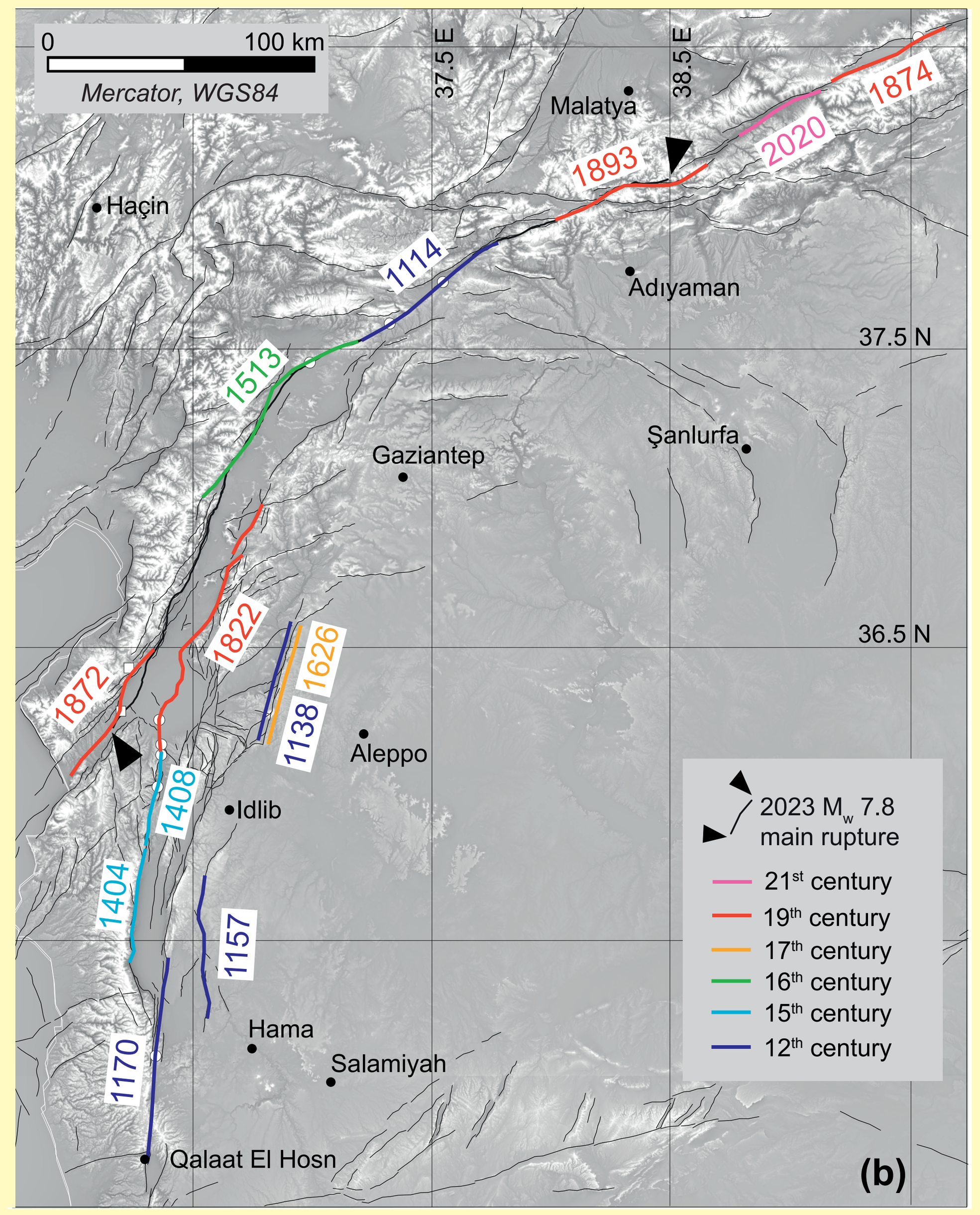

Figure 2b. Fault rupture/earthquake pairs from **Table 1**. Base map and other elements are described and referenced in **figure 3**.

Key Points

- **Maximum magnitude for the East Anatolian fault zone is about 8.2.** The maximum earthquake magnitude (M_{max}) for the East Anatolian Fault is a single end-to-end rupture of the entire fault; the 2023 Pazarcık earthquake did not reach M_{max} by a fortuitous combination of circumstances.

- **In the last 1000 years there were at least 14 large earthquakes ($M_w \geq 7$) along the East Anatolian and northern Dead Sea fault systems.**

- **Continental plate-boundary transform faults may have a „collective memory“** due to their coupling by geometric characteristics and stress transfer patterns among them. This necessitates earthquake probability calculations on a much larger scale than is generally considered.

Scan QR-code to **access references & manuscript**, including magnitude calculations and lists of place names (*Tectonics, Dec. 2023*).

We are grateful to our Turkish colleagues, Cengiz Zabci, Sinan Akciz, Sinan Özeren, and Celâl Şengör, who shared their insights about the unfolding disastrous earthquakes via social media and personal discussions. We dedicate our work to the numerous Turkish citizens (e.g., Elif Altinçekiç, Fatih Altaylı, Baltaci Bilal, Koray Güngör, Arinci Volkan Tahir), who were affected by these earthquakes and shared their traumatic experiences with us, and who invited one of us (AMF) to talk about these earthquakes publically while our Turkish colleagues were examining the rupture traces.

Space-Time Pattern of Historic Earthquakes Along the EAF and Northern DSF

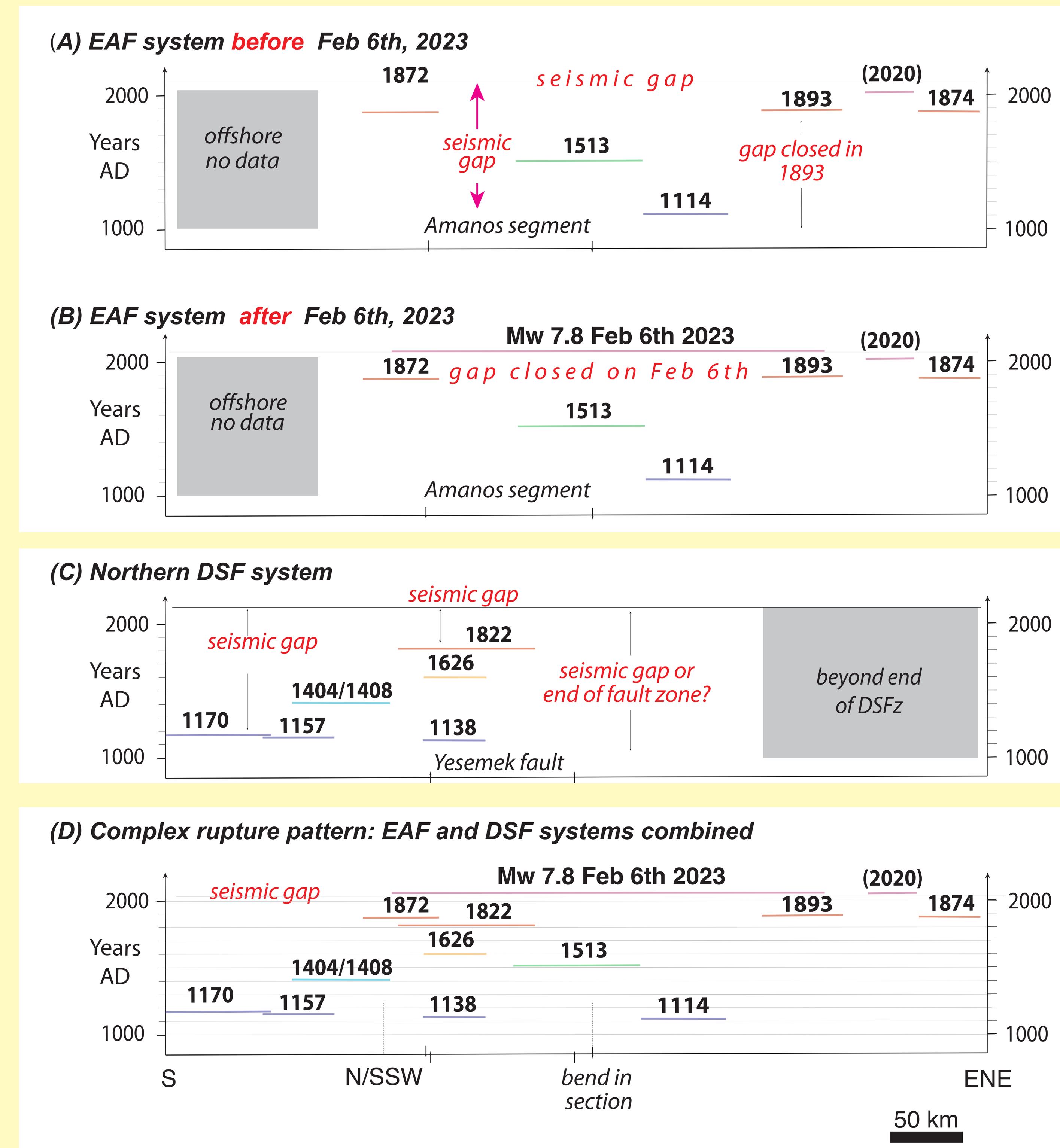

Figure 5: See **figure 2** for location of segments and earthquakes. **The position and extent of M_w> 7 ruptures (horizontal bars), which were inferred from historic records and paleoseismological studies, are justified in the manuscript (Scan QR code to access it).** (A and B) Pattern of M_w>7 ruptures for the western portion of the EAF prior to and after February 6th, 2023. (C) Pattern of M_w>7 ruptures for the northern DSF. (D) Pattern of all recorded M_w>7 ruptures for the region in which both active strike-slip faults (EAF and DSF) overlap spatially and interact kinematically.

Earthquakes & 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[e]	Pütürge s.
Mar. 02, 1893	7.2 +/- 0.1	Malatya	~60	>12[d]	Erkenek s.
Jan. 14, 1874	7.1	Sarikamis	~45	≥12[f]	Palu s.
Apr. 03, 1872	7.2	Amik Gölu	~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 & Nurdaği s.
Dec. 29, 1408	7.0	Shugr-Bekas	~40	unknown	Qanaya-Babatorun
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, Maras	≥ 50	5[f]	Pazarcık s.

Table 1.

a) Ambraseys (2009), except for events from 2020 (Çetin et al. 2020) and 2023 (U.S. Geological Survey, 2023).

b) For most of the earthquakes we have estimated surface rupture lengths based on Wells & Coppersmith (1994), unless lengths were reported in original sources. The magnitude reported here is our preferred one among the sources discussed in the manuscript **(Scan the QR code to access it)***. For the Elâziğ earthquake the rupture length value is in brackets because it did not rupture at the surface, though it had shallow slip (Pousse-Beltran et al., 2020).*

c) Salamon, 2008;
d) Satılmış, 2016;
e) Öztürk, 2021;
f) Ambraseys, 2009

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

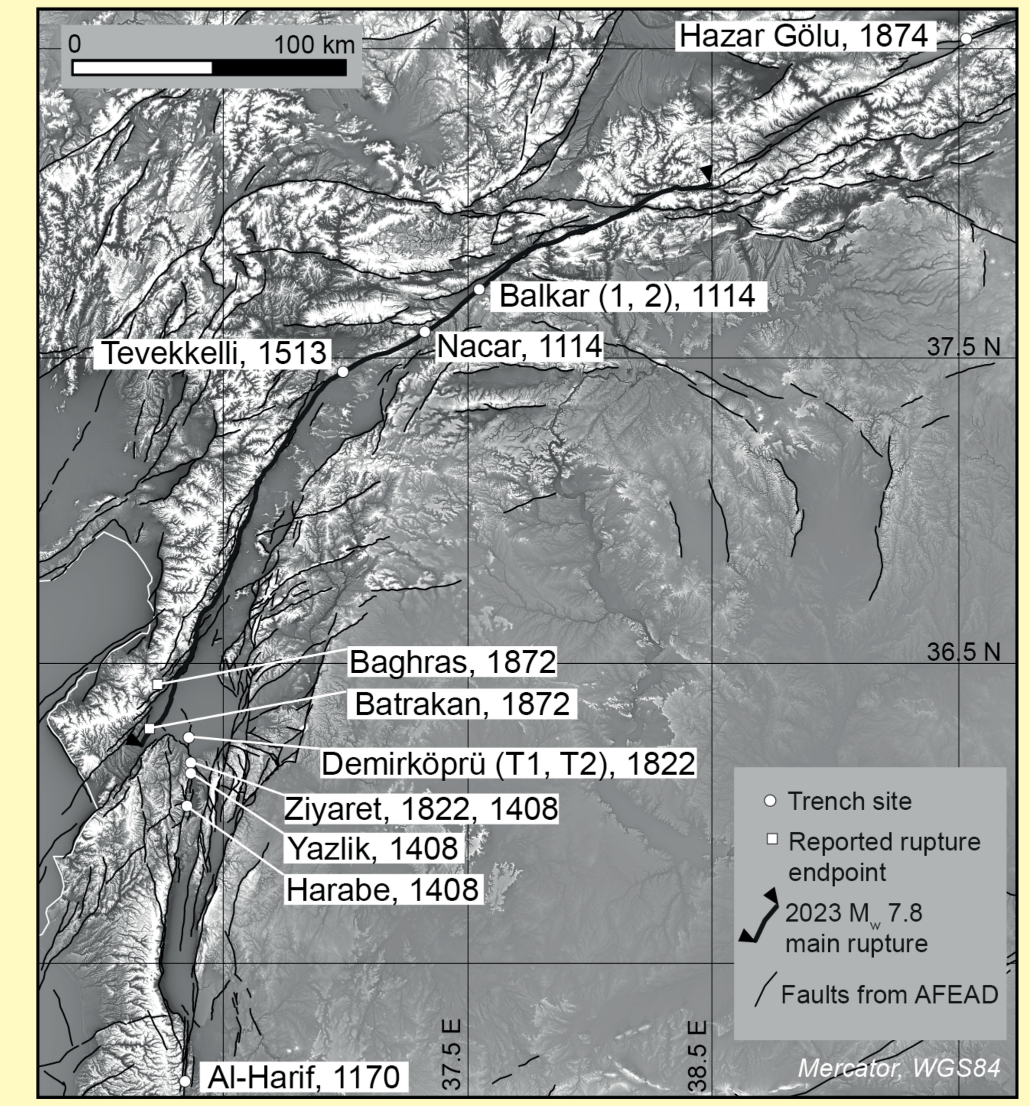

Figure 3. Location and names of trenches, and approximate rupture endpoints, with the relevant pre-2023 earthquake/s indicated for each one. AFEAD faults are from Zelenin et al. (2022), whereas the 2023 main rupture we remapped ourselves from the pixel tracking data of Ou et al. (2023) and ForM™Ter - EOST (2023), and from the preliminary maps of Reitman et al. (2023). Basemap is the 30 m GLO-30 Copernicus DEM processed by applying the texture shading technique of Brown (2014).

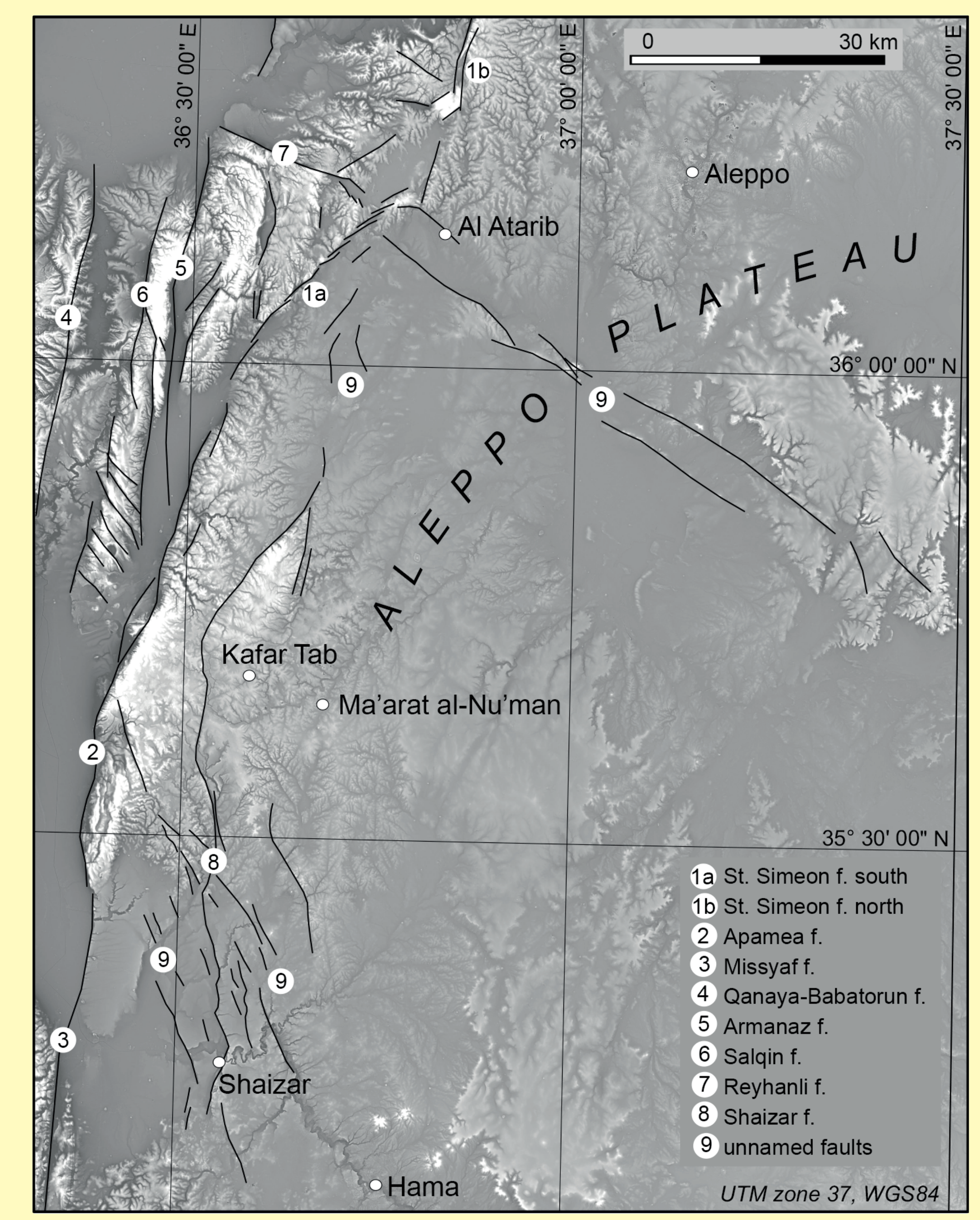

Figure 4. Faults that we mapped using the 30 m GLO-30 Copernicus DEM processed by applying the texture shading technique of Brown (2014), which can be used to enhance fine details (e.g. scarps). We only mapped very sharp features, which are likely to be active faults, but there are also numerous other more subtle lineaments.