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About the “predecessors” of the 2023 February earthquakes, Turkey

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Abstract In the frame of a comprehensive investigation of historical earthquakes of Anatolia, we propose a re-appraisal of four major earthquakes/sequences occurred after 1000 AD (1114/1115, 1269, 1513/1514 and 1544), which could be considered as predecessors of the earthquakes of February 6, 2023. The main purpose is to provide reliable parameter values for the investigated earthquakes. Our investigation consisted of: retrieving and analysing the main primary historical sources; identifying the localities mentioned and assessing macroseismic intensity; determining earthquake parameters (location, magnitude and – where possible – the source azimuth) with the repeatable and transparent “Boxer” method, after properly calibrating the relevant coefficient by considering recent earthquakes of the Anatolian region. Our investigations show that the 1114 earthquake can be considered as a predecessor of the main 2023 earthquake, although the latter ruptured a larger area; the earthquake of 1544 may be a predecessor of the second event of 2023, February; and that the background of the 1513/1514 earthquake is so poor that a lot of care is required while handling the currently available parameters. In conclusion, we also compare our results with the findings of paleoseismological investigation and discuss how they contribute to understanding the rupture history of the East Anatolian Fault.

Özet Anadolu’da meydana gelmiş olan tarihi depremlerle ilgili yürüttüğümüz kapsamlı çalışmanın bir parçası olarak 6 Şubat 2023 depremlerinin geçmiş benzerleri olarak değerlendirilmeye aday M.S. 1000 yılından itibaren meydana gelmiş olan dört deprem için (1114/1115, 1269, 1513/1514 ve 1544 depremleri) bir yeniden inceleme sunmaktayız. Bu makalenin ana amacı bahsi geçen depremler için güvenilir deprem parametreleri sunmaktır. Bu araştırmanın aşamaları (1) incelenen dört deprem için birincil bilgi kaynaklarını ortaya çıkarmak ve yeniden değerlendirmek; (2) bu kaynaklarda bahsi geçen yerleşimleri belirlemek ve bu noktalara şiddet değerleri atamak; (3) tekrar edilebilir ve şeffaf bir yöntem olan “Boxer” yöntemini kullanarak merkez üssü koordinatları, büyüklük ve -mümkün ise- kaynak yönü olarak özetleyebileceğimiz deprem parametrelerini belirlemektir. “Boxer” yönteminin bölgesel kalibrasyonu için Anadolu’da yakın geçmişte meydana gelmiş depremlerin şiddet dağılımları kullanılmıştır. Araştırmalarımızın sonucunda 1114 yılında meydan gelmiş olan deprem 2023 ana depreminin geçmiş bir benzeri olarak ortaya çıkmaktadır. Öte yandan 2023 depreminin çok daha uzun bir yırtılma meydana getirdiği unutulmamalıdır. 1544 depremi ikinci depremin bir benzeri olabilir. 1513/1514 depremi için ise mevcut verilerin yetersizliği vurgulanmakta ve literatürde önerilen parametrelerin çok dikkatli şekilde kullanılması gerektiğine dikkat çekilmektedir. Elde edilen deprem parametreleri paleosismik araştırmalar ile karşılaştırılmakta ve bu bulgular Doğu Anadolu Fayı’nın deprem geçmişini anlamaya yönelik olarak tartışılmaktadır.

Non-technical summary We try to answer to the usual question which is raised after a large earthquake: *“were there any predecessors of this earthquake?”*. The 1114 earthquake is acknowledged by media as possible predecessor, also being an earthquake sequence which, although very far away in time, survived in the memory of historians. Surprisingly, the 1513 or 1514 earthquake is also well known to the media. Its large magnitude (7.4) was initially given on the basis of poor data, and even though caution was later recommended by the original investigator, this optimistic value is now adopted by most scientists and, from them, by media. We reappraised the available information on three large earthquakes between 1000 and 1514, searched for new sources and determined location and magnitude of some of them with modern approaches. We show that the 1114 earthquake can be considered as a predecessor of the 2023 earthquake, similar in size and location. By contrast, we show that the background of the 1513 or 1514 and 1544 earthquakes is so poor that lot of care is required while handling the currently available parameters.

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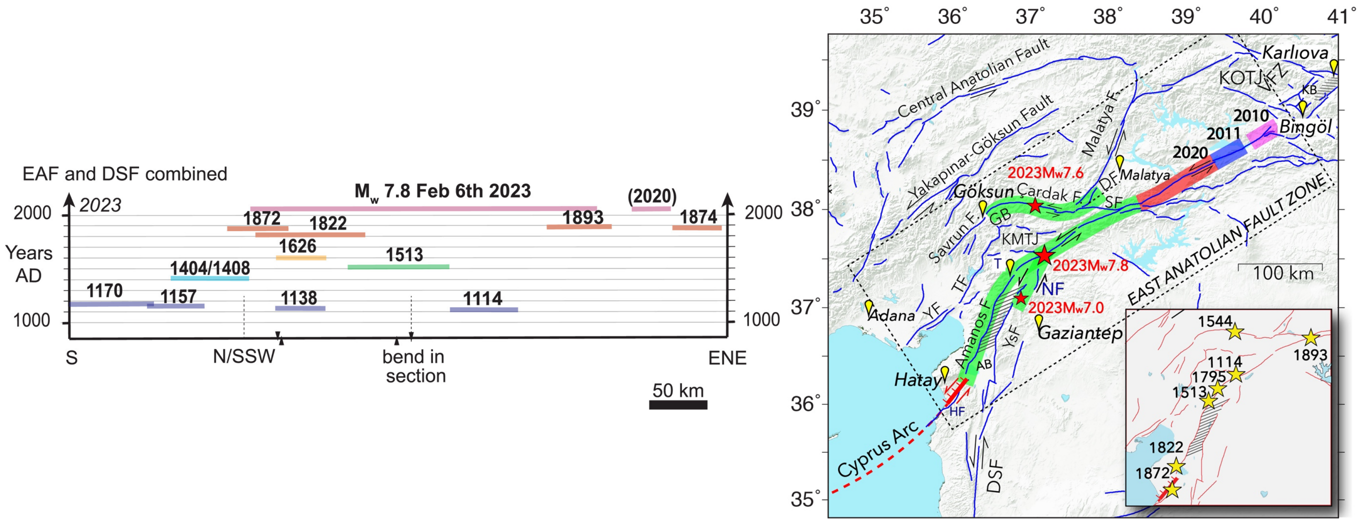

Figure 1 Left: Chrono-geographical interpretation of the large historical earthquake along the EAFZ as proposed by Carena et al. (2023) Right: Excerpt from Figure 1 by Karabulut et al. (2023) showing the epicentre of the main historical earthquakes and the main faults in the investigated area.

1 Introduction

In this paper, we aim at reviewing and interpreting the historical background of the earthquakes which are generally considered as the most recent, possible “predecessors” of the main, 2023 earthquakes, with the goal of determining reliable earthquake parameters.

By “predecessors” we mean here the large, past ruptures in the area which, from the historical evidence, appear to be equivalent or very similar to the recent events. We use this definition following some previous papers which make use of it in the title or text (Namegaya et al., 2011; Albini et al., 2012; Rajendran et al., 2016; Bourgeois and Pinegina, 2018; D., 1910); we do not suggest any implication concerning possible earthquake cycles.

In particular, our main goal is to present and discuss the reliability of the historical records and, as consequence, of the earthquake parameters which are derived from them – by other compilers as well as by us - so to make users aware of what they handle. As a matter of fact, parametric earthquake catalogues summarize in a standard, synthetic format the information contained in historical accounts which may be very different in terms of quality, amount of information, etc. Our aim is to show the uncertainty instead of hiding it.

Based on the historical data available before this paper and on the evidence of paleo-seismological investigation, some notable, recent papers (among them, Karabacak et al., 2023; Karabulut et al., 2023; Yönlü and Karabacak, 2023; Carena et al., 2023; Altunel et al., 2024; Güvercin et al., 2022) address the question whether the 2023 sequence is to be considered an exceptional event: in other words, whether the Eastern Anatolian Fault Zone (EAFZ) can rupture in this area according to different patterns. As an example, in Figure 1, Carena et al. (2023) and Karabulut et al. (2023) summarize the state-of-the-art from the data available before this investigation.

In the frame of a comprehensive investigation of Anatolian earthquakes, started well before the events of 2023 (Şeşetyan et al., 2020; Stucchi et al., 2022) and, after the 2020 Sivrice-Elazığ earthquake, mostly focussed on the EAFZ, we have reappraised four large earthquakes/sequences (1114a and b, or 1115a and b, two earthquakes; 1269, 1513 or 1514 and 1544; Figure 2), which could be considered as predecessors of the 2023 main events.

It is to be stressed that our discussion of the events is limited to provide the aspects essential to the comprehensive discussion. From the historical-seismological point of view a full paper would be needed for each of them

Our investigation consisted of: a) retrieving and analysing the main, possibly primary historical sources of the investigated earthquakes; b) assessing macroseismic data points (MDPs) by identifying the localities mentioned by the historical sources and assigning macroseismic intensity from their information; c) determining earthquake parameters (epicentral location, Mw and – where possible – the source azimuth) from those MDPs with a repeatable, transparent method, the so-called “Boxer” method (Gasperini et al., 1999) after properly calibrating the relevant coefficient using recent earthquakes of the Anatolian region.

In the following we will mainly use the place-names most commonly used at the time of the earthquakes, introducing the today denomination at the first call: e.g. Maraş (today Kahramanmaraş). Years are all intended here as AD or CE.

2 State-of-the-art

The long-term history and earthquake history of the region is well known. Many earthquakes are on record, documented by written sources, both before and since the times in which this region became a province of the Roman empire, about 2100 years ago. Many of the main towns of this area, such as Aleppo and Antioch (today Antakya, the capital district of Hatay province) have a

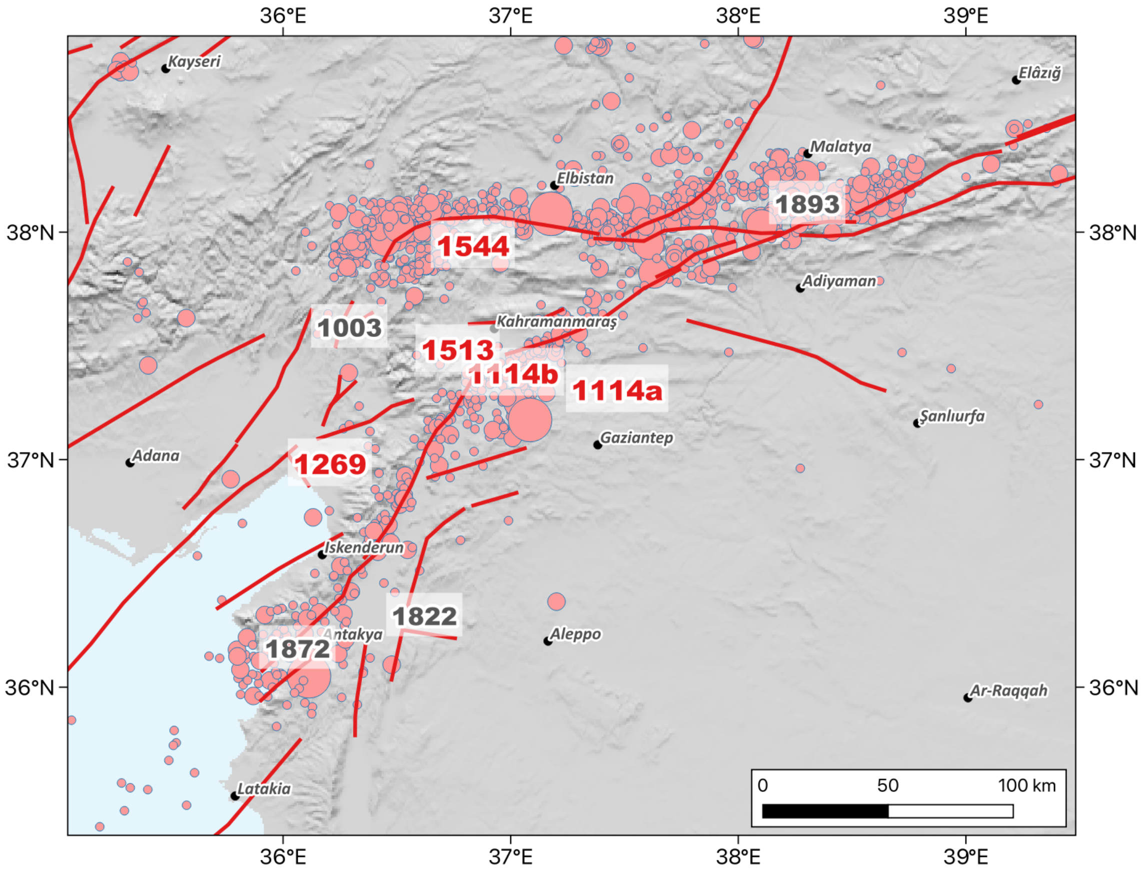

Figure 2 Approximate epicentral areas of the major EAFZ earthquakes of the period 1000-1900, superimposed on the 2023 seismic sequence. In red the earthquakes considered in this study. The 2023 seismicity (pink circles) comes from KOERI (Kandilli Observatory and Earthquake Research Institute); http://www.koeri.boun.edu.tr/scripts/lasteq.asp). Faults traces (red lines) from www.seismofaults.eu/; Digital Elevation Model from www.hawaii.edu/its/webservice/.

long history that includes eyewitness observations of many strong earthquakes.

Historical earthquakes of this area have been the object of several studies. We are not going into details of previous compilations and parametric catalogues, a comprehensive description of which can be found – for example – in Ambraseys et al. (2002), Ambraseys (2009). Starting from Hoff (1840), then Calvi (1941), Pınar and Lahn (1952), etc. at the turn of the century the varied studies have been summarized and parameterised by Soysal et al. (1981) and Shebalin and Tatevossian (1997) among others. The many modern papers dedicated to this area by N.N. Ambraseys, in particular Ambraseys (1989, 2004) culminated in the comprehensive compilation by Ambraseys (2009) which, unfortunately, does not supply earthquake parameters. Studies by the Guidoboni team, such as Guidoboni et al. (2004), Guidoboni and Comastri (2005), are summarized in the comprehensive website CFTI5med (Guidoboni et al., 2019) which, for this region, includes earthquakes up to 1500. These works do assess earthquake parameters from intensity data with the "Boxer" method, although the relevant calibration for the area is not known.

Sbeinati et al. (2009) investigated the earthquakes of the Syrian area including part of today Türkiye; they also provide intensity data and determine magnitudes by means of nomograms. The catalogue by Tan et al. (2008) picked up from the above mentioned material and more; the catalogues of the SHARE and EMME projects (Şeşetyan et al., 2013; Zare et al., 2014) mostly picked up from Soysal et al. (1981) converting epicentral intensity Io into moment magnitude (Mw). Recently, Satılmış (2016) investigated the 1893 earthquake while Ekin (2007) and Darawcheh et al. (2022) investigated the 1822 one in detail.

As a matter of fact, time, epicentral location and size of many earthquakes are still debatable; different parametric earthquake catalogues propose contrasting values for the same events, as shown in Figure 3.

Epicentral location and magnitude differences are mostly due to the assessment approach: epicentres are usually assessed in relation to the most damaged area and/or to the presumed fault segment source; the size of the earthquake is usually assessed from epicentral intensity and/or from the length of the fault segment - adopted as earthquake source - which is known with sufficient precision – although supplied without uncertainty - only from very recent studies.

Recently, Şeşetyan et al. (2023) and Meletti et al. (2023) assessed macroseismic intensity and determined earthquake parameters for some earthquakes after 1000 AD, using repeatable methods. Carena et al. (2023), attempting to identify the sources of large earthquakes in the Turkey-Syria border region after 1000 AD, revised available studies. For calculating magnitudes, they use the equation by Ambraseys and Finkel (1995)

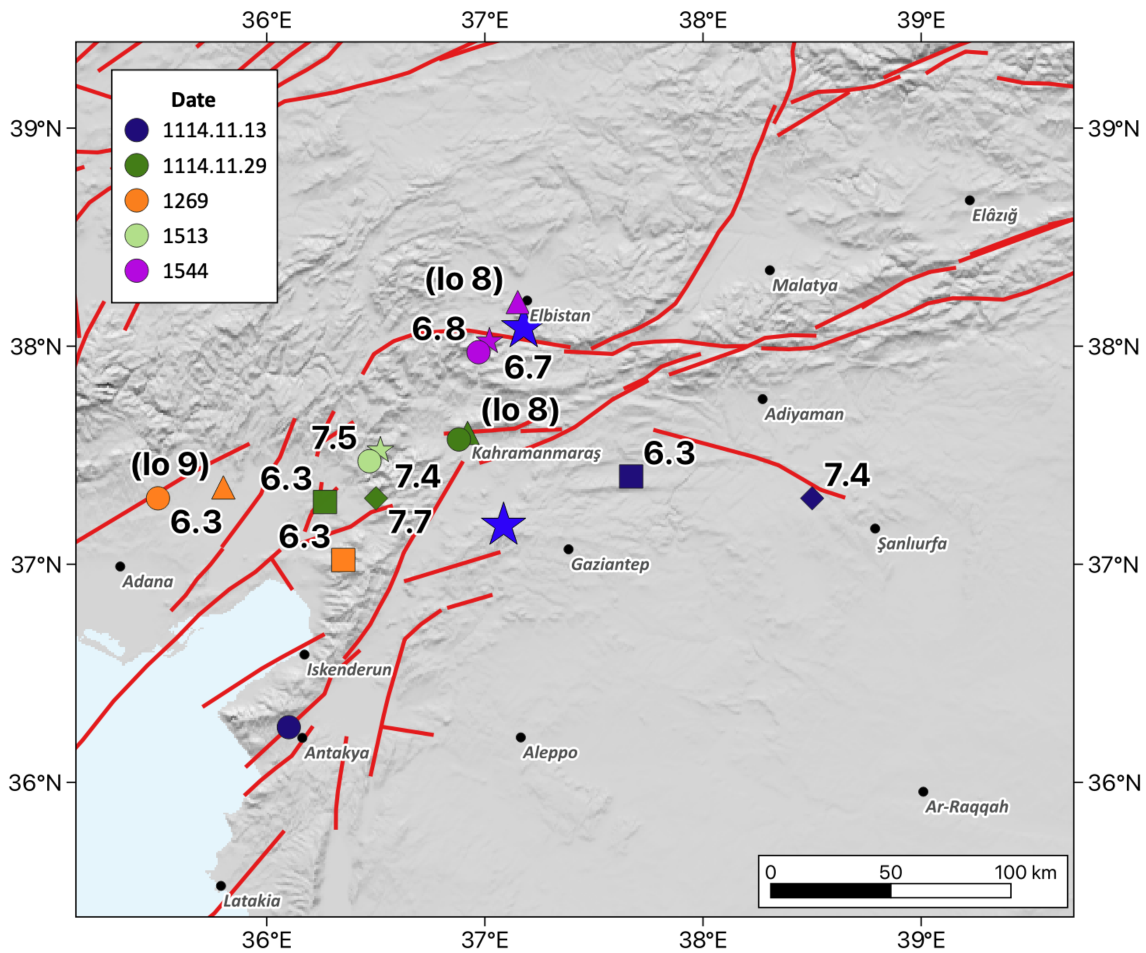

Figure 3 Epicentres and Mw of the earthquakes studied in this paper, according to: Ambraseys (1989) (stars); Soysal et al. (1981) (triangles); Sbeinati et al. (2009) (diamonds); Tan et al. (2008) (circles); Guidoboni et al. (2019) (squares). Io from Soysal et al. (1981). Blue stars represent the epicenters of the two, 2023 February 6, earthquakes.

$$M_F = -0.53 + 0.58(I_i) + 1.9610^{-3}(R_i) + 1.83\log(R_i) \quad (1)$$

where I_i is the macroseismic intensity at the site and R_i is the epicentral distance from the site.

This equation gives a "felt magnitude" based on a "felt area"; although such M_F is not calibrated against Mw, their results compare well enough to the values of other authors (although they quote Ambraseys, 2009, who does not give magnitudes in his volume), including those obtained for the recent, 2023 earthquakes. Meghraoui et al. (2024), discussing the stress propagation along the EAFZ, also present a new intensity distribution for the 1114 earthquake.

3 The investigation

3.1 A few words on history and historical sources

The complex history of the studied region cannot be summarised in a few lines here. It will be enough to say that in the last couple of millennia, the EAFZ was a frontier between cultural and political entities, that sometime interacted quietly enough, sometimes clashed harshly. For most of the period dealt with in this study (1000s-1500s), the political set-up of the region was very fragmented, especially in the 11th-14th centuries, when within this territory coexisted the Armenian Kingdom of Cilicia (1080-1375), the Frankish Crusader States (1095-1274) and the Mamluk Sultanate (1250-1517). In 1514-1520, the whole region, together with Syria, Palestine and Egypt, became part of the Ottoman Empire (Figure S2, in Supplementary Material S2).

The coexistence of different ethnic and cultural groups that had a stake in the region at different times, led to the production of a comparatively large assortment of written records that describe local occurrences in various languages and from different points of view. Curiously enough, these records are more plentiful in the earlier and more turbulent centuries, than after the whole region settled under a single rule. An extensive discussion of historical sources can be found in Guidoboni and Comastri (2005) and in Ambraseys (2009). In this paper we used 'original' sources only. This does not necessarily mean either 'firsthand' or 'eyewitnesses' sources, but simply those among the available records that, chronologically, are the oldest ones that pass on a given information, i.e. those that 'originate' that information. In some cases, the 'oldest' available source can be a century or more later than the event it describes: for instance, Kemal ad-Din (12^{th}-13^{th} c.) who lived about a century after 1114, is the oldest witness who describes the effects of the 1114 earthquake in Athareb, Azaz and Zardana. Readers unfamiliar with historical sources should keep in mind that the sources we will shortly discuss are "the best" possible ones, even if the information they provide is poor, conflicting, unclear, difficult to understand and – above all – not written purposely to meet the requirements of modern seismology. This is why, for instance, some conflicting interpretations in terms of the earthquake year persist (see the case of 1114 vs 1115 and 1513 vs 1514) without a final clue to solve it beyond any reasonable doubt; in such a case, one can decide for one of the options, may be showing the other one as well. Similarly, sometimes, uncertainty in the description of the localities and possible epicentral area is better represented with a question mark.

3.2 Macroseismic data points (MDPs): place-names and intensity assessment

The identification of place-names quoted by the sources is not straightforward, considering that the sources carry the name the locality had in the language and the time-period when they have been written; such names may have undergone several changes and, in addition, place-names may have been wrongly reported by translators from the original sources. In a few cases localities could not be found, even on the basis of previous dedicated studies or gazetteers. In other cases, the locality has changed not only name but also its location, because destroyed by wars or earthquakes: see for instance Melitene which became Malatya, today Battalgazi, and the new Malatya.

Macroseismic intensity assignment is discussed by a number of papers, including for instance Ambraseys (2009) with specific reference to this area. Also, the issue with the use of varied, modern intensity scales and their comparison is frequently discussed, mostly from a theoretical point of view, seldom considering that the uncertainty induced by the oldest historical records may be "larger" than the differences among the scales themselves.

In this paper, we are using the EMS-98 (Grünthal, 1998) which is currently the most used one in the European area. We are aware that historical accounts: a) are generally succinct and vague; b) do not consider buildings' vulnerability; c) may cumulate the effects of an earthquake sequence because of the above-mentioned reasons; d) may refer to an area rather than to a city when this is the most important, or the capital of the area itself; e) may refer to individual buildings (such as castles or monasteries) which, according to the EMS-98, are not suitable for assessing intensity.

As for problem a) and b), following EMS-98 in some cases we adopted range intensities such as 8-9 or even 8-10, which represent in some way the aleatory uncertainty connected with the data scarcity. We are aware that this choice may be unpalatable for some users, but we are convinced that it is better to show the uncertainty instead of compressing it arbitrarily. In other cases, we assigned HD (Heavy Damage) or D (damage). Problem c) may concern the 1114 sequence; problem d) has no evident solution, while for problem e) we assigned "HD" or similar notations.

In this paper, we use the place-names mostly used by the sources at the time of the earthquake, giving also other contemporary and todays' place-names.

3.3 Earthquake parameters determination

Earthquake parameters (time, location, epicentral intensity Io, magnitude) of historical earthquakes are usually determined from macroseismic data and/or from geological data; in this paper we deal with the first case. Time comes from the historical sources, sometimes from the comparison of several calendars; in a few cases a final agreement cannot be reached. When several MDPs are available, epicentral location and Mw can be determined by means of the "Boxer" method Gasperini et al. (1999, 2010) or by the one proposed by Bakun and Wentworth (1997). When just one or only a few MDPs are available, both methods do not succeed operating; therefore, the epicentre is located close to the locality where the maximum intensity (Ix) has been assigned; Io is then usually assessed as equal to Ix or slightly greater. Mw is then determined from Io by making use of Mw (Io) relationships. Both approaches require appropriate, regional calibration which is obtained by using good quality instrumental data. Details are given in Appendix 1.

4 Main earthquakes

4.1 The sequence of 1114 (or 1115)

4.1.1 History and sources

The 1114 or 1115 sequence was preceded by intense seismic activity in the Antioch area at the end of the 11^{th} century and was in some way the starting point of the so-called *"12^{th} century paroxysm in the Middle East"* which affected, according to Ambraseys (2004), EAFZ and DSFZ (Dead Sea Fault Zone). Due to the complex political situation of the affected area (Figure S2, Supplementary Material 2), the earliest available records of the 1114 or 1115 earthquakes are written in many languages (Latin, Armenian, Syriac and Arabic); only in a few cases they are written by people actually alive in 1114 or 1115, only one of which (Walter, 12^{th} c.) was almost certainly an eyewitness. Figure 4 summarizes – in a chronological view - the primary sources on which our interpretation of the sequence is mainly based (see Supplementary Material 2 for their texts).

4.1.2 Interpretation

According to the most common interpretation, there were at least three earthquakes: on August 10 and on November 13 and 29, 1114; the latter two were definitely damaging. A few sources date the last event to 29 November 1115 rather than 1114.

The effects of the August 10 earthquake are unknown because its only available record (Fulcher, 12th c., writ-

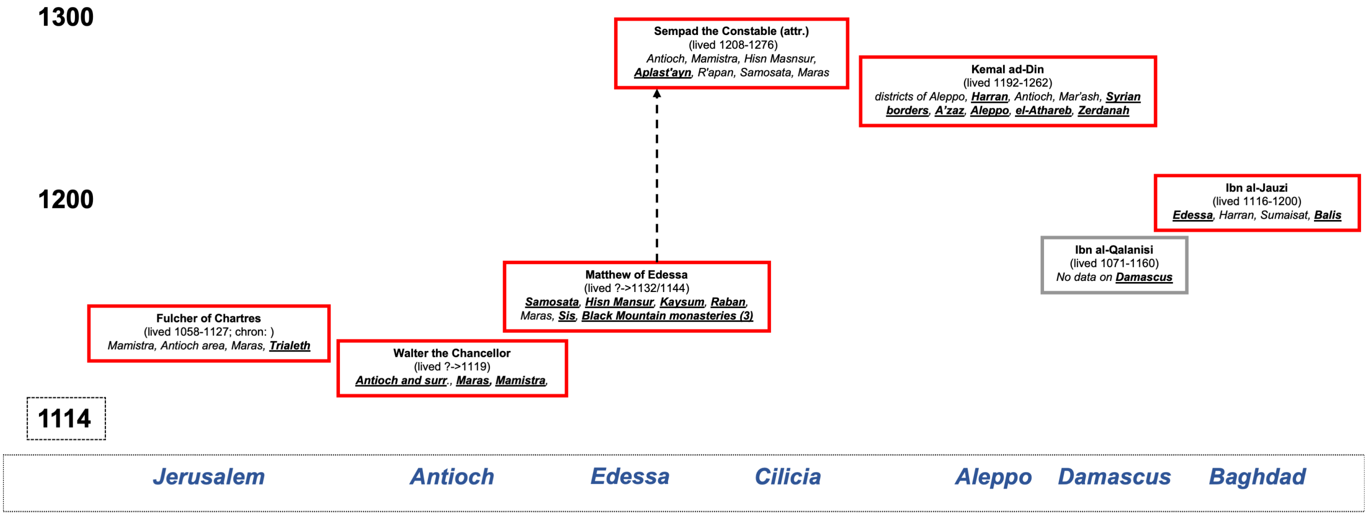

Figure 4 Main sources for the 1114 or 1115 sequence, posted according to a chronological scheme, with evidenced the life time of the authors and the localities they mention; underlined, bold, the earliest mentioned localities. In the bottom line the localities where the authors were mainly active.

ten in Jerusalem or nearby) does not describe effects. Ambraseys (2009) concludes that the August 10 was probably felt in Antioch, "caused damage to maritime cities and fortified towns with loss of life", and could have been located "offshore in the Iskenderun Bay". Unfortunately, he does not provide any evidence for this scenario, nor can this evidence be found in contemporary or sub-contemporary sources.

As for the other two events, most localities are quoted by one source only, with the exception of Antioch, Maraş, Mamistra and Samosata. Only one source clearly mentions two separate earthquakes in November, i.e. Walter (12^{th} c.), whose description of the shaking in Antioch on 29 November includes an aside in which he mentions damage previously undergone by Mamistra. It is therefore impossible to sort out with any certainty which localities were damaged by which earthquake. Lacking evidence to support the attribution of each locality to a specific earthquake, we stick to the interpretation by Alexandre (1990) and Ambraseys (2009), with the warning that damage described by the sources is likely to be the result of cumulative shaking and that this may influence – although slightly - the calculated magnitude of the November 29 earthquake.

Most sources indicate November 29, 1114 as the main earthquake, but a few indicate November 29, 1115 instead. Guidoboni and Comastri (2005), on the basis of a few sources, split the 1114 sequence in two large earthquakes which occurred more or less in the same area, a year apart, on November 13, 1114 and November 29, 1115, both causing heavy damage to Maraş and Mamistra (today Eski Misis). This interpretation is adopted by CFTI5med (Guidoboni et al., 2019), too.

We prefer the first date: the reasons for preferring it are discussed by Alexandre (1990) and by Ambraseys (2009), who also propose some "external clues" for assessing the year. We agree with this interpretation, also considering that none of the sources appears to be written between the two events. However, from the seismological point of view, assuming that the main earthquake – to which the highest damage of most localities is to be referred - happened on November 29, makes little difference whether this was in 1114 or 1115.

4.1.3 Macroseismic data points assessment

The identification of place-names quoted by the sources is not a major problem for this sequence. We did not assign intensity at Mamistra for the large, 29 November earthquake, as it was already heavily damaged by the previous earthquake. Also, we did not consider the locality of Elbistan, quoted by Ambraseys (2004, 2009) and by internet websites, because we were unable to find the relevant source. It is also interesting to observe that some of the Southern localities, such as Atharib (today Athareb) and Zaradna (today Zardana), were also damaged by the 1138 earthquake, as reported by the same, sub-contemporary sources which also report the effects of the 1114; moreover, such localities do not seem to have been damaged by any other earthquakes in the last thousand years.

Intensity assignment requires particular care for the well-known problems mentioned above, in particular because accounts are generally succinct and vague;

Some examples: *"Samosata. Hisn-Mansur. Kaysˇum and Raban were ravaged by this plague"* (Matthew); *"Sumaisat sank and its position was swallowed up. About 100 houses crashed down in Balis, where half the citadel was thrown down and half stayed secure."* (Ibn al-Jauzi, 11^{th} c.); *"The damage was not very serious in Aleppo but other places, like el-Athareb and Zerdanah, were almost completely destroyed"* (Kemal ad-Din, 12^{th}-13^{th} c.).

4.1.4 Earthquake parameters

For the earthquake of August 10, 1114, we are unable to propose earthquake parameters. For the one of November 13, there is no alternative than to locate the epicentre at Mamistra (Eski Misis), with epicentral intensity 8-

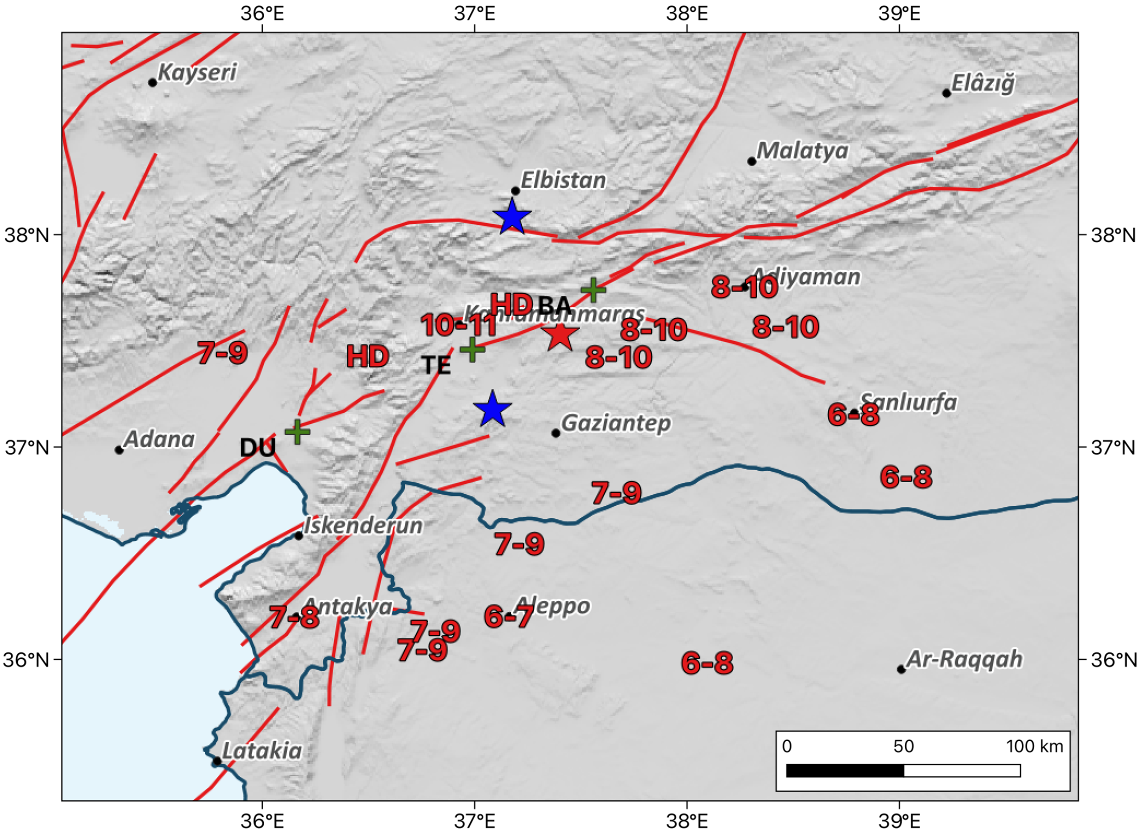

Figure 5 Macroseismic intensities (EM-98 intensity scale) assessed for the 29 November 1114 earthquake; HD means "Heavy Damage" in reference to individual buildings. Red star is the epicentre from this study, blue stars are those of the two, 2023 February 6 earthquakes; TE and BA indicate the sites of the paleoseismological investigation discussed by Yönlü and Karabacak (2023); DU the site of the paleoseismological investigation described by Duman et al. (2020). Macroseismic Data Points are given in Supplementary Material S1.

10 to which corresponds Mw = 6.4 +/- 0.32. For the main earthquake we get from Boxer Mw = 7.71 +/-0.23.

Figure 5 presents the MDPs distribution proposed for the main 1114 earthquake, the epicentral location obtained by this study, the position of the two sites, Tevekkelli and Balkar where paleo-seismological investigations described by Yönlü and Karabacak (2023) were performed and the position of the trench near Düziçi where Duman et al. (2020) claim they have identified the 1114 event.

4.2 1269 possibly April 17, Amanos?

Soysal et al. (1981) list two earthquakes in 1268 (I 9 in Sis and vicinity) and 1269 (I 8, Northern Syria, 1269) quoting for both Calvi (1941), though the latter gives only the 1268 date. Guidoboni and Comastri (2005) propose a single M 6.3 earthquake on 1269 April 17. The same magnitude is given by Tan et al. (2008) to an earthquake that occurred in 1268, September 10. SHEEC (Şeşetyan et al., 2013) and EMME (Zare et al., 2014) follow Soysal et al. (1981) by converting Io into Mw and assessing Mw 6.77.

Contemporary sources originate mostly from Cilicia (Sempad, 13th c.; Anonymous, 13th c.; Het'um, 13th c.) and Syria (Barebroyo, 13th c.). A 15th century Turkish scholar from Aintab (Al-Ayni, 15th c.) also add some original information (Figure 6).

This earthquake is traditionally associated with "Cilicia" (aka Lesser Armenia or the Armenian Principality and later Kingdom of Cilicia, as it was from 1080 to 1375), because some late accounts (Al-Maqrizi, 14th-15th c.; Al-Ayni, 14th-15th) locate it in the *"region of Sis"*. However, no source explicitly mentions damage to the town of Sis (the Kingdom capital, see of the Armenian Church and the target of extensive damage by Mamluk raids in 1266). Only five place-names are explicitly mentioned by the sources. With the possible exception of the settlement which Syriac chronicler Barebroyo (13th c.) calls *"the monastery of Balut the King"* (whose exact location is uncertain), all damage information refers to castles and monasteries located along the Western Flank of the Amanos Mountain (Black Mountain or Giaour Mountain in the past).

The identification of place-names (for this earthquake as well as for many others of this area) is not straightforward, because in most cases they refer to sites that have been in ruins since a long time and the many geographical studies and historical gazetteers available for this region (such as Manuelian and Boase, 1980; Vandekerckhove, 2014, etc) do not always agree on their identification.

Apart from Servandikar (today Savranda Kalesi) we propose the following identifications:

- Convent of Arka'kalin / Convent of Balut al-Malik: can be today Peri Kalesi;

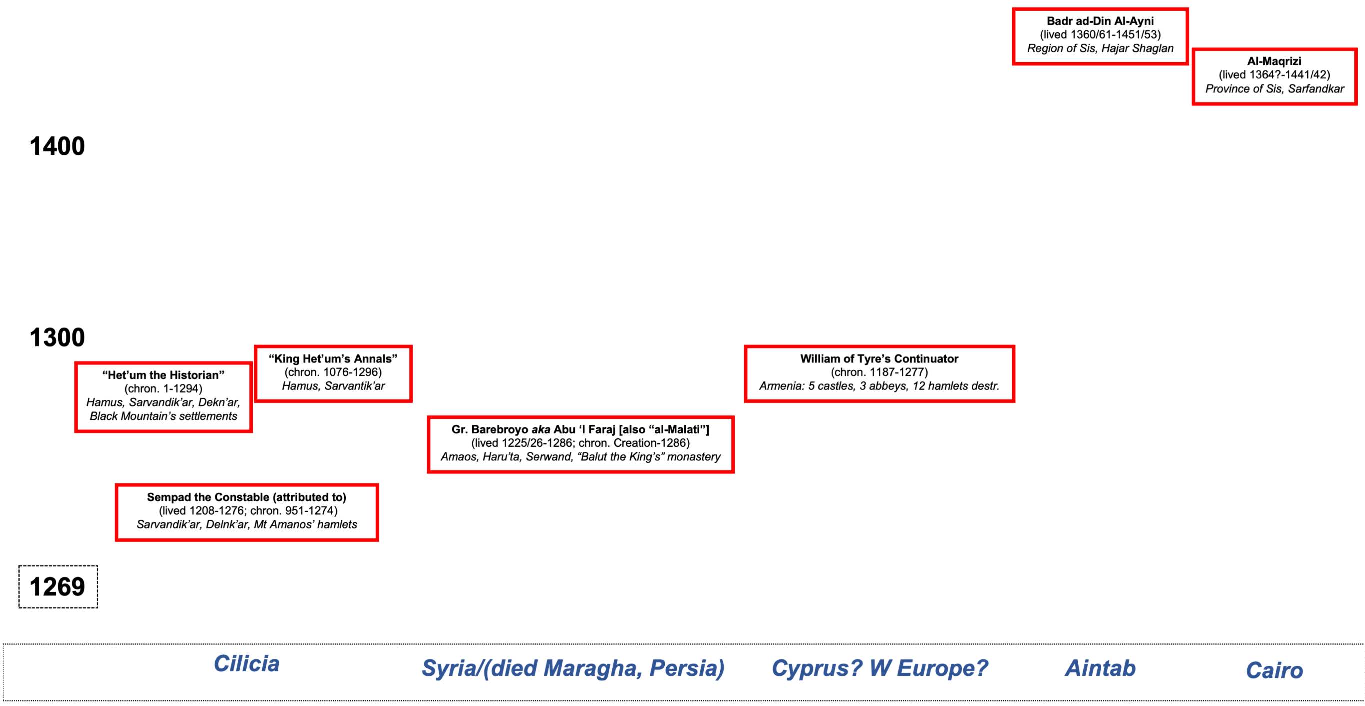

Figure 6 Chronology of the primary sources on the 1269 earthquake, including authors' lifespans, time coverage of their narratives and place-names mentioned in connection with the earthquake. At the bottom, the localities of likely compilation/interest of each source are indicated. Texts are given in S2.

- Amaos [Amus]: can be today Çardak;
- Haru'ta [Haruniye]: located close to today Duziçi;
- Hajar Shaglan [Hagar Suglan]: could be Çalan, near the so-called Amanos Gate.

Following the statement *"On that stretch of the mountain flank, many buildings and the fortress of Deznk'ar and many other places were completely demolished"* (Sempad, 13th c.) we decided to assess a single one MDP representative of the many monasteries located on the Amanos mountain.

Despite all attempts, Deghen'kar defies identification (Manuelian and Boase, 1980), as we cannot agree with its association to Lampron castle (Guidoboni and Comastri, 2005), which is very far away from the most damaged area. To all these place-names we assign HD (Heavy Damage).

Finally, we could not discover the location of Tell Hamdun, cited without any reference by Ambraseys (2009) but not mentioned by any of the historical sources. According to a late source Ambraseys (2009) says that the earthquake may have been felt on Nicosia, Cyprus, slightly damaging the church of St. Sophia.

In Figure 7 the MDPs and the calculated epicentre are shown; the resulting Mw is 6.86 +/- 0.28.

4.3 1513 or 1514, somewhere between Cilicia and Maraş?

An earthquake of 1513 or 1514 is known by modern catalogues starting from Soysal et al. (1981) who - seemingly uncertain whether to locate it in Malatya and/or Cilicia – mediated by assessing Io = 7 for an earthquake occurred in 1514, but without epicentral location.

Ambraseys (1989) dated the same earthquake in 1513, with M 7.4 and an epicentral location near Maras, on the Pazarcık segment of the EAFZ, on the basis of contemporary evidence (to be discussed later). Tan et al. (2008) adopt the same date/epicentre but increase magnitude to 7.5.

Later on, Ambraseys (2009) would recant his own earlier interpretation, observing that *"without further details this information is insufficient to indicate the precise date and area over which this earthquake was felt"*. For this reason the 1513 or 1514 earthquake was not considered by Stucchi et al. (2012) and EMME (Zare et al., 2014). Unfortunately, the interpretation by Ambraseys (1989) has been taken at face value by most investigators of the last quarter of century, while the later warning by Ambraseys (2009) has been mostly disregarded.

To date the only original information on this earthquake comes from a few lines of a letter sent from Damascus on March 10, 1514 by Andrea Alpago (1450?-1522), a Venetian subject and part-time informer of the Venetian government, transcribed by Marin Sanudo after 25 July 1514 (Sanudo, 16th c.):

"Se dice etiam per teramoti esser somerso et ruinato tre terre del Soltan ali confini del Turcho videlicet Malathia et Terso et Adena"

(It is also said that three places belonging to the Sultan [of Egypt], at the frontier with the Turk, have been ruined by earthquakes, i.e. Malathia, Terso [Tarsus] and Adena [Adana]).

The letter deals with political and military affairs of the Ottoman, Persian and Egyptian rulers of the time, adding at the end a few lines on three localities ruined by earthquakes at the border between the Ottoman and Mamluk domains. At the time both Cilicia and Malatya

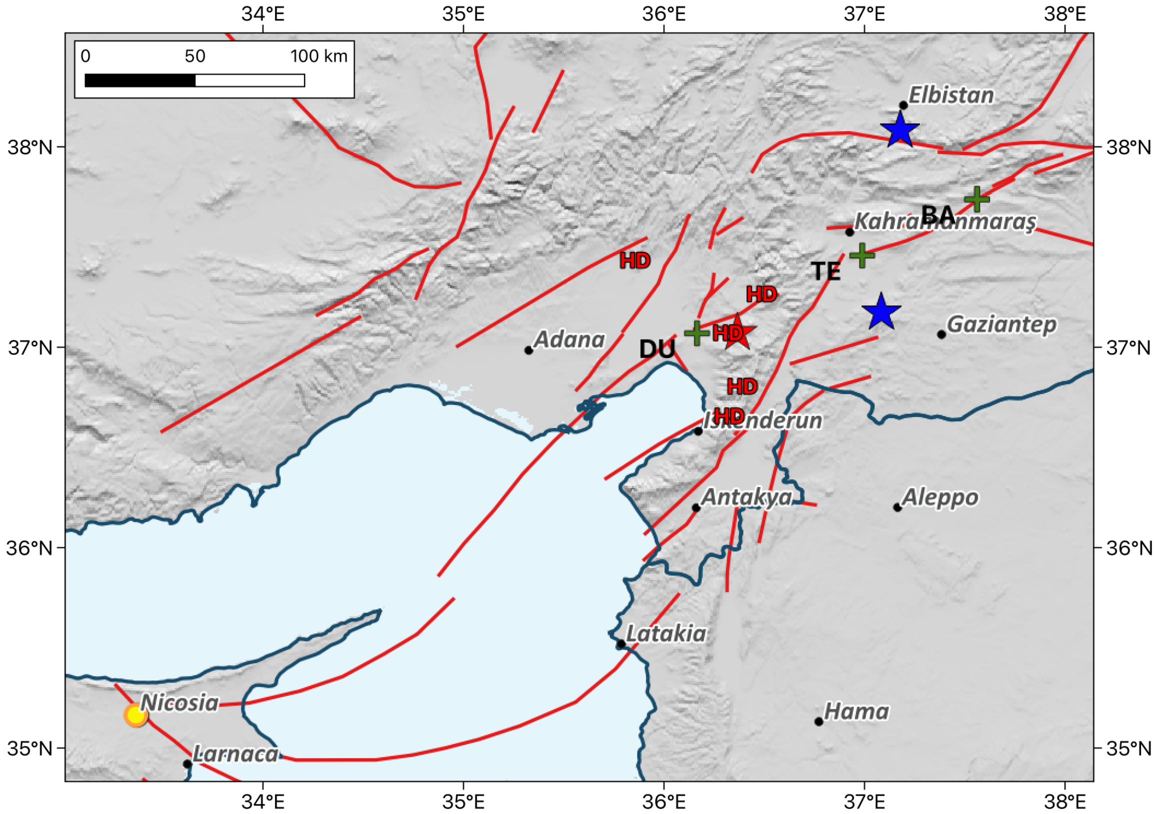

Figure 7 Macroseismic assignments and epicentre assessed for the earthquake of 1269. HD means "Heavy Damage" in reference to individual buildings. Red star is the epicentre from this study, blue stars are those of the two, 2023 February 6 earthquakes; TE and BA indicate the sites of the paleoseismological investigation discussed by Yönlü and Karabacak (2023); DU the site of the paleoseismological investigation described by Duman et al. (2020). Macroseismic Data Points are given in Supplementary Material S1.

were indeed part of the "client states" of the Egyptian Mamluk Sultan.

In spite of extensive research, we could not find any further information on this earthquake. We agree with Ambraseys (2009) about the insufficiency of the information and we believe it is unlikely that this was a large earthquake. As an example, using the equation given by Ambraseys (1989), to get M 7.4 - assuming the epicentre given by his work - the intensity value to be assigned to the three localities, Tarsus, Adana and Malatya should be no higher than 6, which hardly corresponds to the sources description: higher intensities, such as 7 or 8, would result in M = 7.5 or ≥ 8.

The large distance between Adana and Malatya raises doubts: for instance, the letter author may have transcribed as "Malatya" some other place-name, or he may have conflated information concerning two earthquakes, one in the area of Tarsus and Adana and another near Malatya. The absence of information on effects in other towns (Maraş, Antioch, Aleppo) could support this hypothesis. Whatever the solution, we stick to the Ambraseys' (2009) recommendation and, for the time being, we do not assign earthquake parameters. Figure 8 presents only the effects reported by the source, the epicentres of the 2023 main earthquakes and the sites of the already quoted paleo-seismological investigations.

4.4 1544 Between Elbistan and Zeytun?

This earthquake, the first large event in the EAFZ after the annexation of the region to the Ottoman Empire (1516) was first reported by Ambraseys (1975) from which Soysal et al. (1981) assessed Io = 8. Then Ambraseys (1989) mentioned Malatya, with M 6.7. Shebalin and Tatevossian (1997) give M 6.4; Ambraseys and Jackson (1998), M 6.5; Tan et al. (2008), Mw 6.8; SHEEC (Şeşetyan et al., 2013) and EMME (Zare et al., 2014) give Mw = 6.21 from Soysal et al. (1981), using Io.

The epicentral location is more or less the same for all these studies, that is along the Çardak fault not far from the epicentre of the second earthquake of 2023, February 6.

The only known historical source for this event is a 16th century Armenian chronicle:

*"in Hunvar 993 a. Arm. [*January 1544*] an earthquake took place; Zeytu'n collapsed and half of Aplstan sunk; Zeytu'n was buried under the mountain; it was trembling for six months" (Sivas Anon., 16th c.)*

According to the editor of the chronicle, this latter can be taken as contemporary for 1544; it does mention damage in Zeytun (today Süleymanlı) and Aplstan (today Elbistan), but not in Sivas.

We could not find evidence to support Ambraseys (2009) statement that the earthquake damaged Maraş. Moreover, no information is available for Aintab (today Gaziantep), Malatya, Urfa, Antioch and Aleppo. An in-

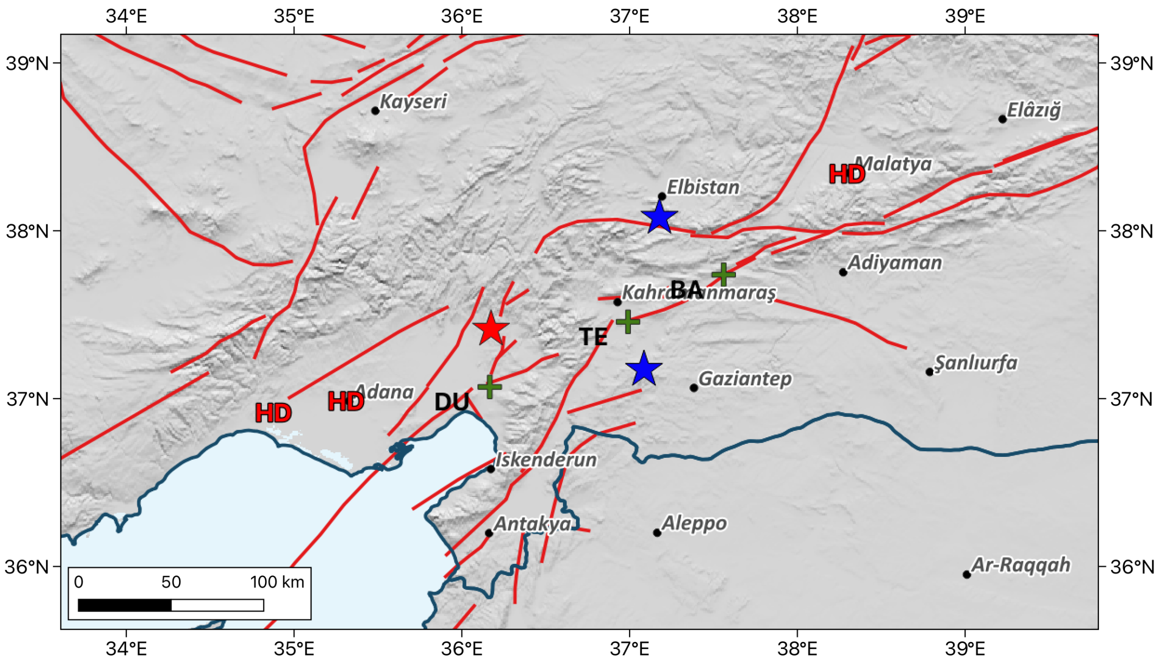

Figure 8 Macroseismic assignments for the earthquake of the year 1514: HD means "Heavy Damage". Red star is the epicentre from this study, blue stars are those of the two, 2023 February 6 earthquakes; TE and BA indicate the sites of the paleoseismological investigation discussed by Yönlü and Karabacak (2023); DU the site of the paleoseismological investigation described by Duman et al. (2020). Macroseismic Data Points are given in Supplementary Material S1.

teresting clue could come from the mention of damage possibly caused by an earthquake to the aqueduct of Djedjin, a few km south of Aintab, which supplied water to Aleppo. Mazloum (1938) dates this damage in 1544, without quoting any source. Sauvaget (1941) confirms it but he does not mention earthquake effects in the city. This information is earlier than the publication of the Hagopyan collection and should be considered as independent.

Considering the scanty information, we assign HD (heavy damage) to both localities and D (damage) to the aqueduct (Figure 9). We get Mw = 6.94 +/- 0.32; the epicentre falls more or less where the previous studies locate it, that is on the Çardak fault. In this case, too, we recommend to take these parameters with much caution.

5 Discussion

As mentioned above, our results come from the use of primary sources, only; this choice makes a difference with respect to results based on the conclusions of recent studies only.

We summarise in Table 1 and Figure 10 the main seismological results of our investigation: epicentral location, Io (when needed to assess Mw), Mw with uncertainty, and - when possible - the "box" obtained with the Boxer procedure, which represents the surface projection of the earthquake source.

Further than the four investigated earthquakes/sequences discussed above, we mention an earthquake that happened around 1003 (Ambraseys, 2009) which, according to Ibn Taghribirdi (15th c.) and al-Suyuti (15th c.), affected "*Sham, al-'Awasim and in ath-Thughur*". The names *Thughūr* and *al-ʿAwāṣim* seem to have been used interchangeably by 10th-11th century sources to indicate the Muslim side of the frontier between the Byzantine Empire and the Caliphates of Cilicia, northern Syria and Upper Mesopotamia (Bonner, 1994). Unfortunately, no details are available for assessing the earthquake parameters of this potentially large earthquake which consequently remains out of the parametric catalogues and, therefore, unknown to the users.

The currently defined sources for the 1872 and 1893 earthquakes were also partly involved in the area ruptured in 2023, while the source of the 1822 event is still debated. For a matter of length, we will not go into details; however, the historical sources available for these three earthquakes are good and abundant; we provide earthquake parameters for them, too.

The epicentral location and Mw that we calculated for the main earthquake of 1114 is close to the one of the first event of 6 February, 2023. Our "box" seems to match the Pazarcik segment of the EAFZ (we refer hereafter to the fault definitions used by Duman and Emre, 2013). At the two sites of Balkar and Tevekkelli (Figure 9), Yönlü and Karabacak (2023) report evidence of faulting dated between 990 and 1390 AD at the first site and an event with lower bound age of 1240 and 1470 AD at the second one, which could represent the effect of the 1114 earthquake. On the other hand, Duman et al. (2020), investigating the paleoseismology of the western Sürgü–Misis fault system, propose the results of several trenches and believe to have identified the 1115 event in some of them, in particular in the Düziçi fault segment, where their time-window is AD 1035–1215. This evidence is consistent with the hypothesis that damage to Sis (today Kozan) and to monasteries in the Black Moun-

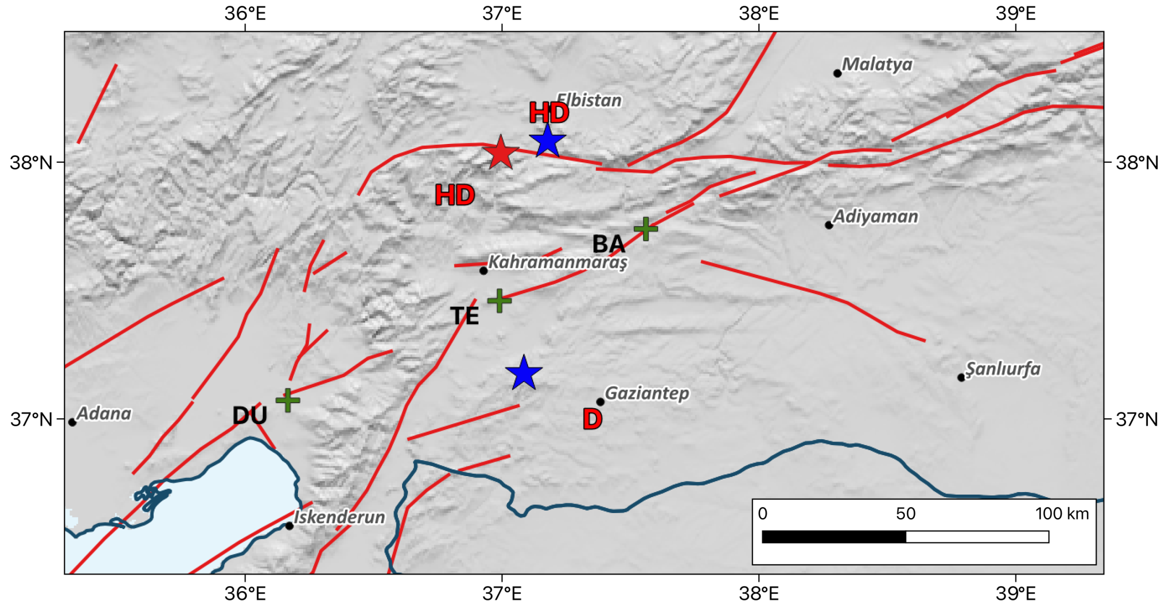

Figure 9 Macroseismic assignments for the earthquake of the year 1544. Red star is the epicentre from this study, blue stars are those of the two, 2023 February 6 earthquakes. Macroseismic Data Points are given in Supplementary Material S1.

Earthquake time	Epicentral latitude	Epicentral longitude	Epicentral area	Io	Mw	Mw unc.	Source azimuth	Source azim. unc.
1003	–	–	Around Amanos and EAF	–	–	–	–	–
1114.08.10	–	–	Gulf of Iskenderun ?	–	–	–	–	–
1114.11.13	37.400	37.670	Mamistra ?	8-9	6.30	0.32	–	–
1114.11.29	37.532	37.403	Maraş	–	7.71	0.23	89°	13°
1269	37.075	36.367	Amanos Mountain	–	6.86	0.28	3°	43°
1514 ≤ March 15	–	–	Tarsus/Adana + Malatya?		–	–	–	–
1544.01 ?	38.034	36.995	Btw Elbistan and Zeytun	9-10	6.94	0.32	–	–
1822.08.13	36.391	36.841	Antakya	–	7.44	0.32	–	–
1872.04.03	36.131	36.015	Amik Golu	–	6.90	0.44	–	–
1893.03.02	38.154	38.293	Malatya	–	6.86	0.51	–	–

Table 1 Summary of the earthquake parameters determined in this study.

tain could have been produced by the same earthquake which heavily damaged Mamistra (November 1114), although this remains a speculation, only, for the time being.

The 1269 earthquake was less energetic (M = 6.9) than the 1114 one and its parameters are less well constrained. Its "box" suggests that the Amanos segment could be the likeliest source, although the Toprakkale segment could be an alternative candidate.

As for the 1513/1514 earthquake, the first interpretation by Ambraseys (1989) (M 7.4) was taken by subsequent authors - and still is - as the absolute truth, suggesting a very large earthquake in connection with the Pazarcık segment. As described above this interpretation is based on very poor information; Ambraseys (2009) himself was aware of this, but his concern was largely ignored. This study cannot provide reliable epicentral location and magnitude estimates.

It is to be noted that, at the beginning of this millennium,Nalbant et al. (2002), while investigating the stress propagation along the EAFZ, considered the situation with and without this earthquake and, aware of the poorness of the historical data, suggested paleoseismological investigation to be performed to solve doubts. The results reported by Yönlü and Karabacak (2023) indicates that some evidence of an earthquake happened between 1430 and 1845 may have been found at the Tekevelli site but not at the Balkar site (Figure 8). In agreement with our conclusion, we believe that the Toprakkale or Karataş segments could represent a more appropriate option for the source, without discarding the possibility of a twin of the 1998 Adana earthquake.

In Figure 11 we provide a tentative scheme of chronogeographical interpretation of our results.

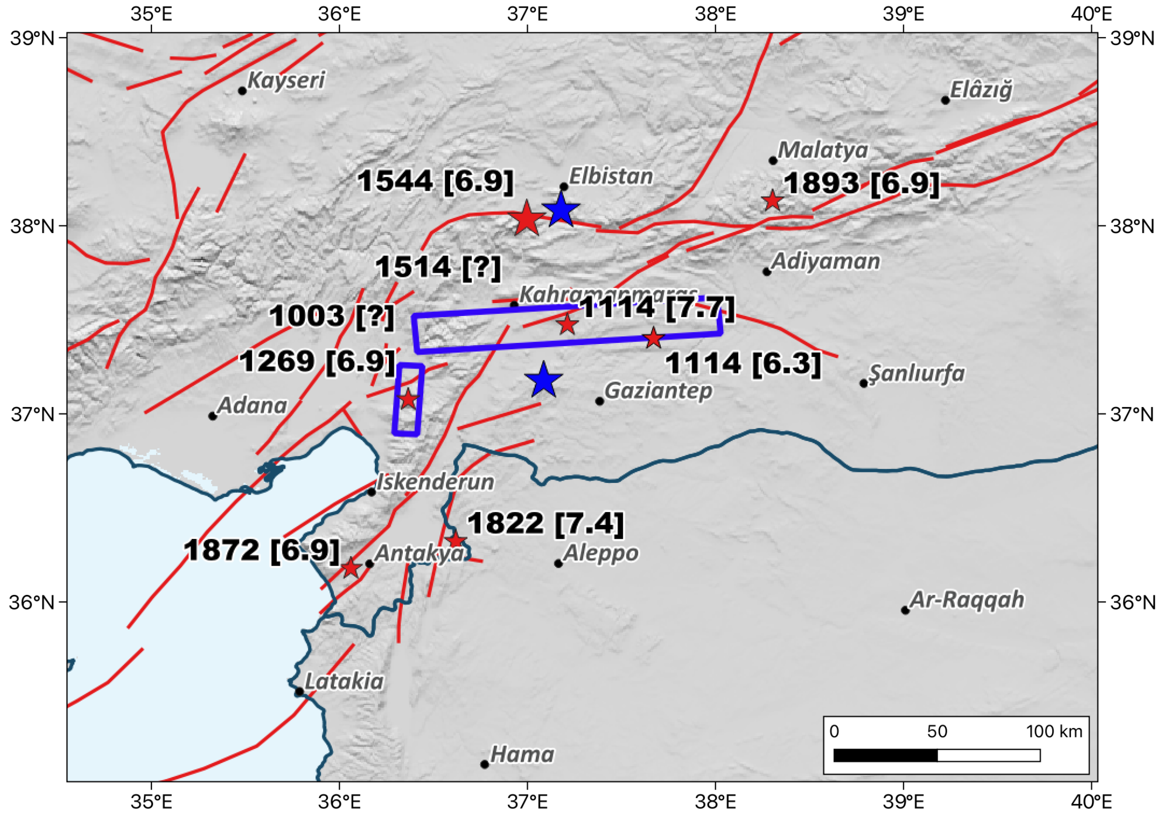

Figure 10 Seismogenic boxes, representing the projection of the earthquake source to the surface, epicentres (red stars) and Mw values determined by this study. Blue stars represent the epicentres of the two earthquakes of February 6, 2023.

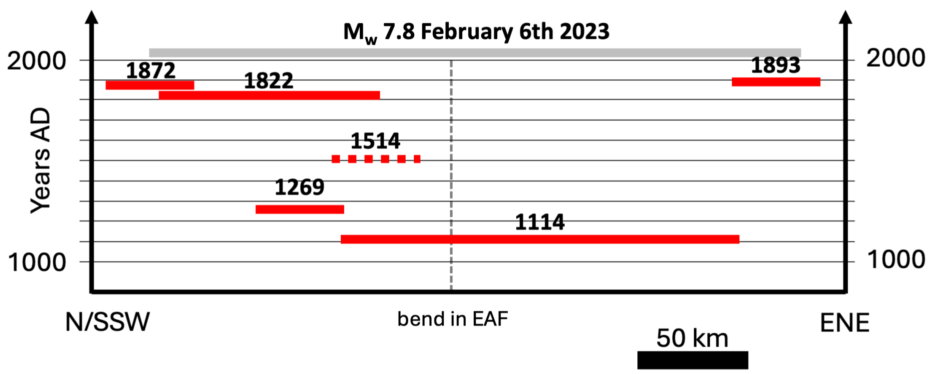

Figure 11 Chrono-geographical interpretation of the results of this investigation (in red), based on the scheme reported in Figure 1. Large earthquakes of 20th century are not represented.

6 Conclusion

We have reconsidered a few historical earthquakes which have interested the portion of EAF which ruptured in 2023. The Mw value we have obtained for the 29 November 1114 earthquake, is similar to the one of 2023, February 6. For the earthquakes of 13 November 1114 and 1544 we could assess epicentre location and intensity (Io), from which a Mw value has been derived. For the 1514 event, we believe that, for the time being, it is only possible to indicate an area where the earthquake(s) may have originated.

As for the "predecessors", we believe that:

- the sequence of 1114 presents similarities with the one of 2023 although the latter, undoubtedly, did rupture a larger area;
- we are convinced that the 1114 sequence may be composed by two large earthquakes, the one of November 29 being the largest, but that historical sources were not able to capture the different effects related to each of the two events; therefore, the intensity distribution we have analysed may represent cumulative effects for some/many localities, and this may influence also the epicentre location and the Mw value;
- the earthquakes of 1872 and 1893 did affect the extremities of the 2023 sequence, while the 1822 earthquake probably interested the Northern tip of DSFZ, instead;

- the earthquake of 1544 may be a predecessor of the second event of 2023, February 6, but its location and magnitude are not well constrained;
- for what concerns the 1514 earthquake, according to the data shown we do not believe it can be considered a predecessor of the first 2023 event.

As a conclusion, we recommend that our results, although the best possible in our opinion, are taken with "a pinch of salt". Investigators should be aware that, although we make use of repeatable, mathematical procedures, the original nature of the historical information is peculiar. Every investigator must be aware of the "fragility" of the historical information which is behind the knowledge of these earthquakes, although – at the same time – we must consider ourselves lucky to have it. On the other hand, paleoseismological data – usually - are not better constrained and, often, they too heavily rely on historical data of limited quality and radiometric dating. The association we propose for the investigated earthquakes with varied segments of the EAF must therefore be taken as a possibility.

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Data and code availability

Data from previous elaborations which have been used in Appendix 1 are available at https://doi.org/10.5281/zenodo.10854707 and https://doi.org/10.5281/zenodo.10854784

The code called "Boxer" (Gasperini et al., 1999) is available at https://emidius.mi.ingv.it/boxer

Competing interest

The authors have no competing interest.

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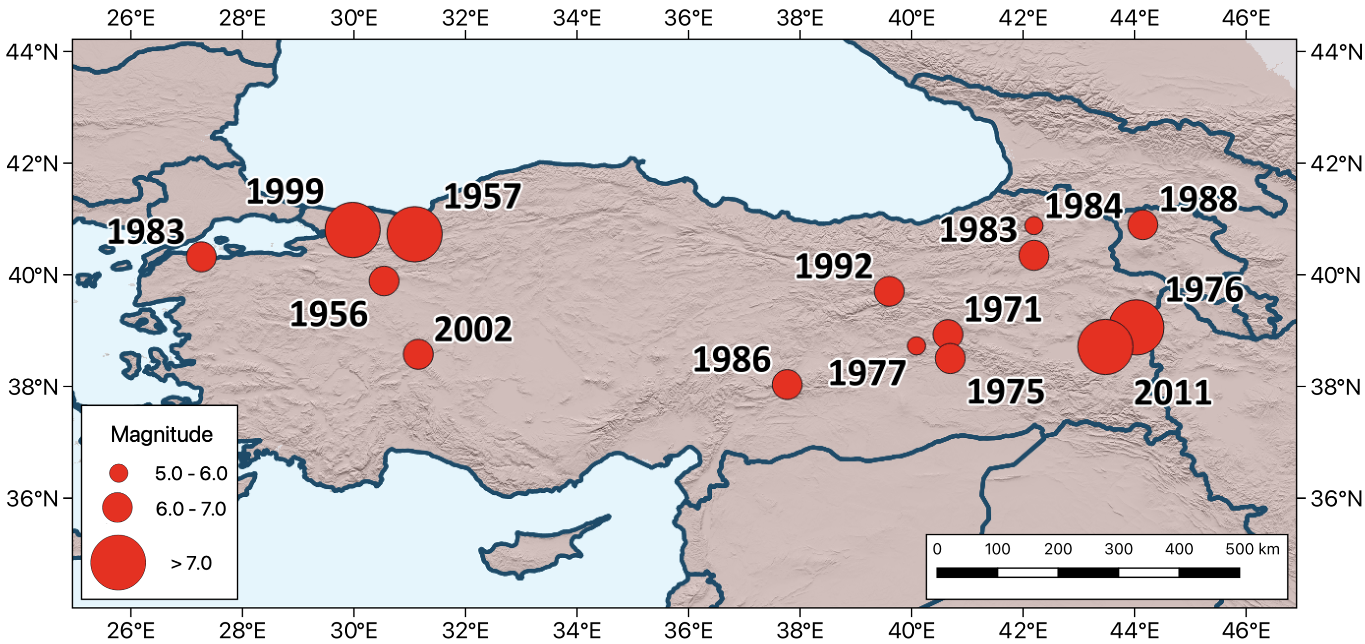

Figure A1 Location and size of the earthquakes reported in Table A1.

Ye	Mo	Da	Epicentral Area	N. of MDPs	Data source	Io	Mw	Mw unc.
1956	2	20	Eskişehir	52	Öcal (1959a)	8	6.23	0.50
1957	5	26	Abant	77	Öcal (1959b)	9	7.09	0.57
1971	5	22	Bingol	167	Şeşetyan et al. (2016)	10-11	6.58	0.20
1975	9	6	Diyarbakir-Lice	223	Şeşetyan et al. (2016)	11	6.60	0.20
1976	11	24	Çaldıran	79	Babayan (2006)	10	7.02	0.10
1977	3	25	Elazığ-Palu	69	Şeşetyan et al. (2016)	8-9	5.25	0.10
1983	7	5	Biga	28	Şeşetyan et al. (2016)	7-8	6.08	0.10
1983	10	30	Horasan-Narman	119	Şeşetyan et al. (2016)	9-10	6.57	0.10
1984	9	18	Erzurum-Balkaya	35	Şeşetyan et al. (2016)	8-9	5.50	0.10
1986	5	5	Malatya	121	Şeşetyan et al. (2016)	7-8	6.04	0.10
1988	12	7	Spitak	172	Gedakyan et al. (1991)	10	6.75	0.10
1992	3	13	Erzincan	149	Şeşetyan et al. (2016)	9-10	6.65	0.10
1999	8	17	Kocaeli	68	Şeşetyan et al. (2016)	9-10	7.58	0.10
2002	2	3	Sultandağı	126	Şeşetyan et al. (2016)	9-10	6.46	0.10
2011	10	23	Van	177	Şeşetyan et al. (2016)	9-10	7.14	0.10

Table A1 Earthquakes used for the Boxer calibration (data can be found at https://doi.org/10.5281/zenodo.10854707).

Appendix 1: Earthquake Parameters Determination

1) Boxer method.
In this method (Gasperini et al., 1999, 2010), the epicentre is calculated as a weighted mean of the position of the highest intensity observations; as for Mw, the code first categorises macroseismic observations into integer intensity classes, then it calculates a weighted mean magnitude (Mi) for each intensity class by means of the Sibol et al. (1987) formula:

$$Mi = c1 + c2log^2 Ai + c3Io^2 \qquad (2)$$

where Mi is the magnitude calculated for the i-th intensity class, Ai is the area for that intensity. and Io is a calculated epicentral intensity. Finally, the code allows to establish a rectangular box, centred on the epicentre, oriented along a calculated direction, the main dimension of which come from the Wells and Coppersmith (1994) relation.

The calibration of the constants c1, c2 and c3 is achieved using a calibration tool internal to the code, using a suitable number of recent earthquakes providing a good magnitude range, a good data set of instrumental parameters and a good number of MDPs.

There are few recent earthquakes in Türkiye and Syria for which reliable MDPs are available, as there is no institution in charge of permanently collecting macroseismic data in the aftermath of an earthquake. In some cases, intensity contour maps are published but the underlying data in terms of intensity values assigned to localities are not available. In most of the cases the available data are limited to the damage tolls at localities; felt information is missing in most cases. We could use data from Öcal (1959a,b), Babayan (2006) and Gedakyan et al.

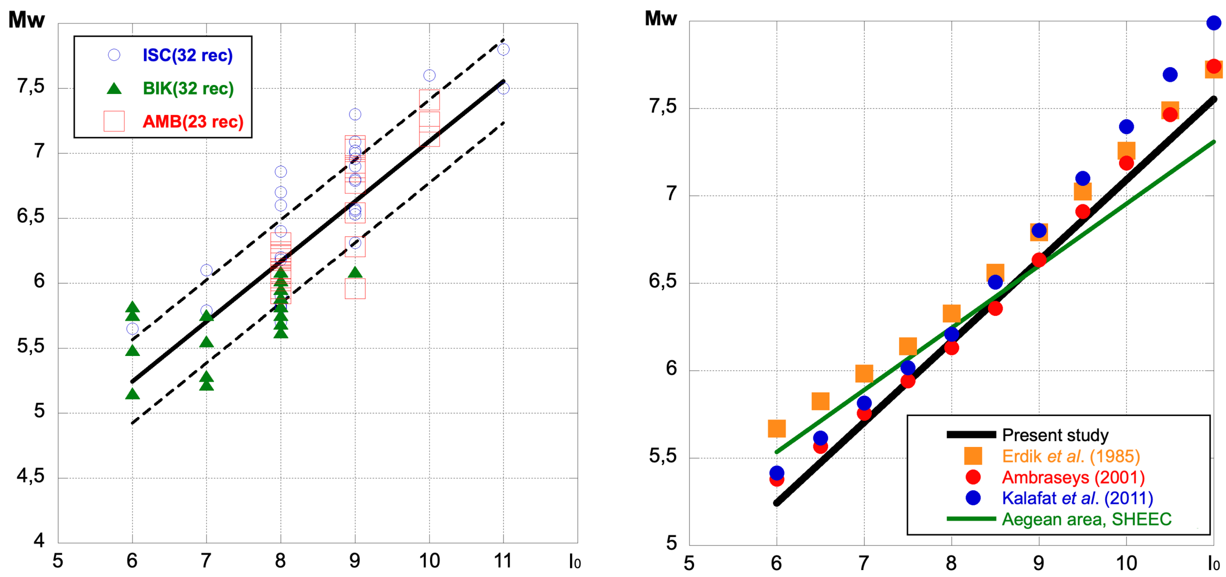

Figure A2 Left: Mw(Io) relation determined from 87 earthquakes; dashed lines show the standard deviation. ISC = data from International Seismological Summary; BIK = data from Bikce (2016); AMB = data from Ambraseys (2001). Data can be found at doi.org/10.5281/zenodo.10854784. Right: comparison of our result with the available relationships: for the ones using Ms, the Scordilis (2006) conversion to Mw has been applied. SHEEC stays for Stucchi et al. (2012).

(1991). To improve our dataset, we have used damage reports of the General Directorate of Disaster Affairs of Türkiye (AFAD) that contain detailed building damage data for many localities: macroseismic intensities have been assigned from damage information according to EMS-98 (Şeşetyan et al., 2016). Altogether we were able to retrieve 1655 MDPs for 15 earthquakes (Table A1) with intensities ranging from 2 to 11 and instrumental magnitude ranging from 5.25 to 7.60. In Figure A1 the epicentral locations of these earthquakes are plotted.

Using this dataset, we were able to determine the coefficients for the Boxer method (Table A2).

I	N	c1	c2	c3	σ	R^2(%)
4	6	5.59297±0.35	0.05511±0.04	-	0.35	9.7
5	11	5.82837±0.33	0.04762±0.02	-	0.33	28.3
6	12	4.90540±0.53	0.11714±0.04	-	0.45	41.3
7	11	5.20161±0.39	0.11838±0.03	-	0.39	64.8
8	8	5.12451±0.25	0.15158±0.02	-	0.11	89.5

Table A2 Resulting Boxer coefficients c1 and c2 for each intensity degree (I). N = number of earthquakes used; σ = standard deviation of the model; R^2 % = coefficient of variation, in percentage.

2) Moment magnitude from epicentral intensity.
A few Mw = f(Io) relationships are available for the Anatolian area:

- Erdik et al. (1985): Ms = 2.55 + 0.47 Io
- Ambraseys (2001): Ms = 1.58 + 0.56 Io
- Kalafat et al. (2011): Ms = 1.39 + 0.60 Io
- Stucchi et al. (2012): Mw = 0.16 + 0.68 Io

The methodology used for obtaining the last one is described by Gomez-Capera et al. (2015).

We have determined a new relationship by making use of 87 data (couples Mw and Io) selected as follows. As a reference dataset for this study we have adopted the Io values from Bikçe (2016), a study dedicated to earthquakes which caused fatalities and damage in the time-window 1900-2014. We have selected earthquakes avoiding aftershocks, offshore events and events after 1980, considering that our Mw(Io) relationship will be used for assessing Mw of historical earthquakes and that in the last 40 years the quality of the building stock has generally improved, so that – as a tendency – earthquakes with similar Mw will produce less damage than before 1980.

As for the magnitude, we have selected values according to the following priority scheme: from 1900 to 1930, Ambraseys (2001); after 1930, ISC (International Seismological Summary). For those entries for which no M values from the previous sources are available, Bikçe (2016) values have been used. Ambraseys (2001) and Bikçe (2016) use Ms; their values have been converted to Mw by means of the relation by Scordilis (2006). In total, we have 87 entries: 32 events from the ISC 2016 catalogue, 23 earthquakes from Ambraseys (2001) and 32 events from Bikçe (2016).

The resulting equation is the following:

$$Mw = 2.47 + 0.46 Io, (\sigma = 0.32, R^2 = 0.69) \quad (3)$$

In Figure A2 input data and the obtained relation are plotted with the corresponding uncertainty range. A comparison of our result to the above equations is also provided in the same figure.