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Earthquake doublet in Turkey and Syria

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The human tragedy caused by the earthquake doublet on 6 February 2023 in Turkey and Syria is difficult to comprehend. While earthquake scientists are trying to understand this seismic event, its catastrophic impact highlights heightened risk in the entire region.

On 6 February 2023, a moment magnitude (Mw) 7.8 earthquake struck southern and central Turkey and northern and western Syria. The earthquake was the strongest in Turkey in more than 80 years. Approximately 9 h later, a Mw 7.6 earthquake occurred to the north-northeast from the first, in Kahramanmaraş Province. As of 6 March 2023, the earthquake doublet and the whole 2023 Kahramanmaraş Earthquake Sequence resulted in an official death toll of over 45,000 in Turkey, according to the Disaster and Emergency Management Authority (AFAD), bringing the total toll including Syria to more than 52,000. This is the fifth-deadliest earthquake of the 21st century (Fig. 1)[1]. The two events were not a complete surprise—seismologists have warned of possible damaging earthquakes in Turkey for many decades. However, both quakes were larger than any previously recorded in this region. Earthquakes in 1893, 1872, 1822, and 1513, for instance, reached estimated magnitudes of 7.0–7.5[2].

The Anatolian Plate—where Turkey sits—is bounded by two major faults: the North Anatolian Fault Zone and the East Anatolian Fault Zone (Fig. 2a). The 2023 Kahramanmaraş Earthquake Sequence occurred on the East Anatolian Fault Zone, a left-lateral strike-slip fault that divides the Anatolian Plate from the northern part of the Arabian Plate, where Syria is located (Fig. 2a). Tectonic slip deficit across the East Anatolian Fault Zone accumulates at a rate of roughly 10 mm per year. Strain accumulates as the plates converge, and is intermittently released by occasional earthquakes of magnitude 7 or more.

Hundreds of thousands of people live within just a few kilometres of the East Anatolian Fault. This is not a coincidence. Biodiversity and natural resources such as water and fertile lands often concentrate near active fault zones[3]. As a result, human populations, modern infrastructure and economic centres are commonly concentrated there, and hence exposed to seismic hazards.

Here we note that the devastating quakes and subsequent aftershocks have highlighted—and on some sections of the faults increased—a well-known seismic risk in the entire region, as indicated in the European Earthquake Hazard Map[4]. If we are to prevent a repeat disaster, it is key to reduce vulnerability and build resilience.

Devastation beyond expectations

The two events in February exceeded expectations not only in magnitude but also in terms of the damage they caused. One reason lies with rupture length. Observations and pre-instrumental historical records have shown that earthquakes in East Anatolian Fault Zone exhibit a high variability in magnitude, involving moderate (Mw 6+) and sporadic large (Mw 7+) earthquakes, which typically unzip—partially or completely—different segments of the East Anatolian Fault Zone separately[2]. However, the earthquake doublet on 6 February 2023 ruptured several of these segments in one go, producing larger slip than the deficit accumulated since the last large events. In hindsight, we know that such "superevents" might be part of a supercycle that transcends

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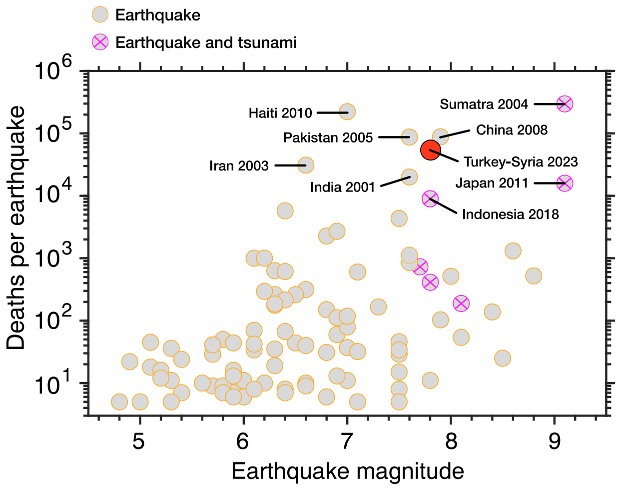

Fig. 1 Deaths from earthquakes since 2000. The toll of the Turkey and Syria quakes is one of the highest of any previous magnitude-7.8 event, and the fifth worst earthquake since 2000 (ref. [1]).

ordinary seismic cycles[5]. Supercycles are somewhat linked to the long-term fault memory, where the probability of a large earthquake reflects the accumulated strain rather than elapsed time[6]. Advances in understanding supercycles would be important for seismic hazard assessment, as they may help explain observed mismatches between deformation-model-based paleoseismology and those based on geodetic and other datasets.

Secondly, for the main quake, the rupture extended over about 300 km, with surface rupture displacements of up to 5 m (Fig. 2b). The magnitude-7.6 aftershock occurred on two branches of the East Anatolian Fault Zone—the Surgu and Cardak faults. Although the aftershock resulted in a shorter rupture of about 100 km, it led to larger land displacements of up to 7–8 m. The source time functions of both events—describing the rate of energy release with time after earthquake initiation—is provided by the US Geological Survey (USGS)[7] and shown in Fig. 2c. For the mainshock, the apparent complexity of the source time function is identified by many peaks reflecting the interaction between different fault segments. On the other hand, the source time function of the magnitude-7.6 aftershock shows a relatively simpler rupture with a single major pulse of ~30 s duration (Fig. 2c). Because the two earthquakes propagated all the way up to the surface, ground shaking was intensified in the areas surrounding the two faults. Comparing the two events also illustrates that larger earthquakes do not necessarily produce much stronger ground accelerations—which ultimately lead to damage; instead, they affect a wider area.

Another factor that made this earthquake particularly devastating was the size of the affected area, with two large earthquakes occurring in neighbouring fault zones. Surprisingly, the largest aftershock in the 2023 Kahramanmaraş Earthquake Sequence was relatively similar in magnitude to the main shock. Typically, the biggest aftershock is around 1.2 magnitudes smaller than the primary earthquake, a relationship known as Bath's Law. However, as the two Kahramanmaraş events ruptured two different faults, the magnitude-7.6 quake can arguably be classified as a secondary main-shock on a different fault that was triggered by the first magnitude 7.8 earthquake. Hundreds of aftershocks of varying magnitudes continue to shake the devastated region (Fig. 2b, d). They are damaging the unstable buildings and other infrastructure further, and hamper rescue and relief efforts at the same time.

Finally, according to early stress calculations, the increase in stress induced by the main-shock magnitude-7.8 rupture was largest close to the location of the subsequent magnitude-7.6 aftershock. The main magnitude-7.8 rupture might therefore have brought the magnitude-7.6. aftershock closer to failure, and provided the final kick to an already critically stressed fault[7,8]. Worryingly, as a result of those two events, the end zones of both events are now significantly stressed.

In light of these concerns, we suggest that risk-management practice urgently needs to be updated with a quantification of how stress transfer in the region has modified hazard probabilities. Likewise, we must work out by how much main-shocks have changed the fragility of buildings and increased their vulnerability to aftershocks.

The factors discussed above contributed to hazard and exposure. Risk and damage are, however, influenced by a third factor: vulnerability. In war-battered Syria, vulnerability was particularly high, but as it turns out, many buildings in Turkey, some of them relatively new, were not constructed to withstand a large earthquake. That the main shock occurred at 4.17 am local time, when most people are indoors and therefore in danger, added to the catastrophic outcome.

Learning from disaster

When a major disaster strikes, the focus in the first few days is on rescue efforts and on the tremendous loss, both of lives and property. But as emergency response turns to longer-term recovery, we must focus on how to avoid repetition.

The ultimate reason for the devastation was clear in the mangled ruins: unreinforced brick masonry, low-rise concrete frames, lift slab, and non-ductile concrete. Severe damage was amplified because most existing buildings are low-rise brick structures that are constructed very close to each other[9]. Such devastation is reflected in the saying: earthquakes do not kill people, buildings do.

In Syria—at war for more than 10 years now—building codes were not a priority, and structures were built and rebuilt with whatever was available. In Turkey, vulnerabilities persist despite the existence of an appropriate earthquake-resistant building code. Now aid must focus on the priorities of local people. Identifying and reducing vulnerability and building long-term resilience is key to a safer future. In order to increase earthquake resilience, building codes need to both exist and be followed. Yet depending on social and political circumstances that may be difficult. Nevertheless, a poorly regulated construction industry in a region with known seismic risk is the real killer[10]. Part of the solution might be to develop cost-effective tools and consumer awareness campaigns that empower citizens to verify the safety of the properties they consider buying or renting.

Where next

The Kahramanmaraş Earthquake Sequence is the latest of a long list of examples where fault systems have produced cascade of earthquakes over periods of hours to decades. We can expect elevated seismicity in the affected region for years, even decades.

Historical and recent seismicity on the East Anatolian Fault is not so different from the activity on the North Anatolian fault, the site of several large earthquakes between 1939 and 1967. Over the last century, the Turkish part of the North Anatolian Fault has produced a remarkable sequence of large earthquakes. These events have left an earthquake gap south of Istanbul beneath the Marmara Sea, a gap that has not been filled in 250 years[11]. We do not know when this fault will rupture, but the risk is rising.

Another region of concern surrounds the Dead Sea Fault, the segment of the East Anatolian Fault south of the February 2023 subsurface rupture. The long historical record of earthquakes indicates that the Dead Sea Fault hosted several earthquakes of magnitude above 7 along its full length, including the

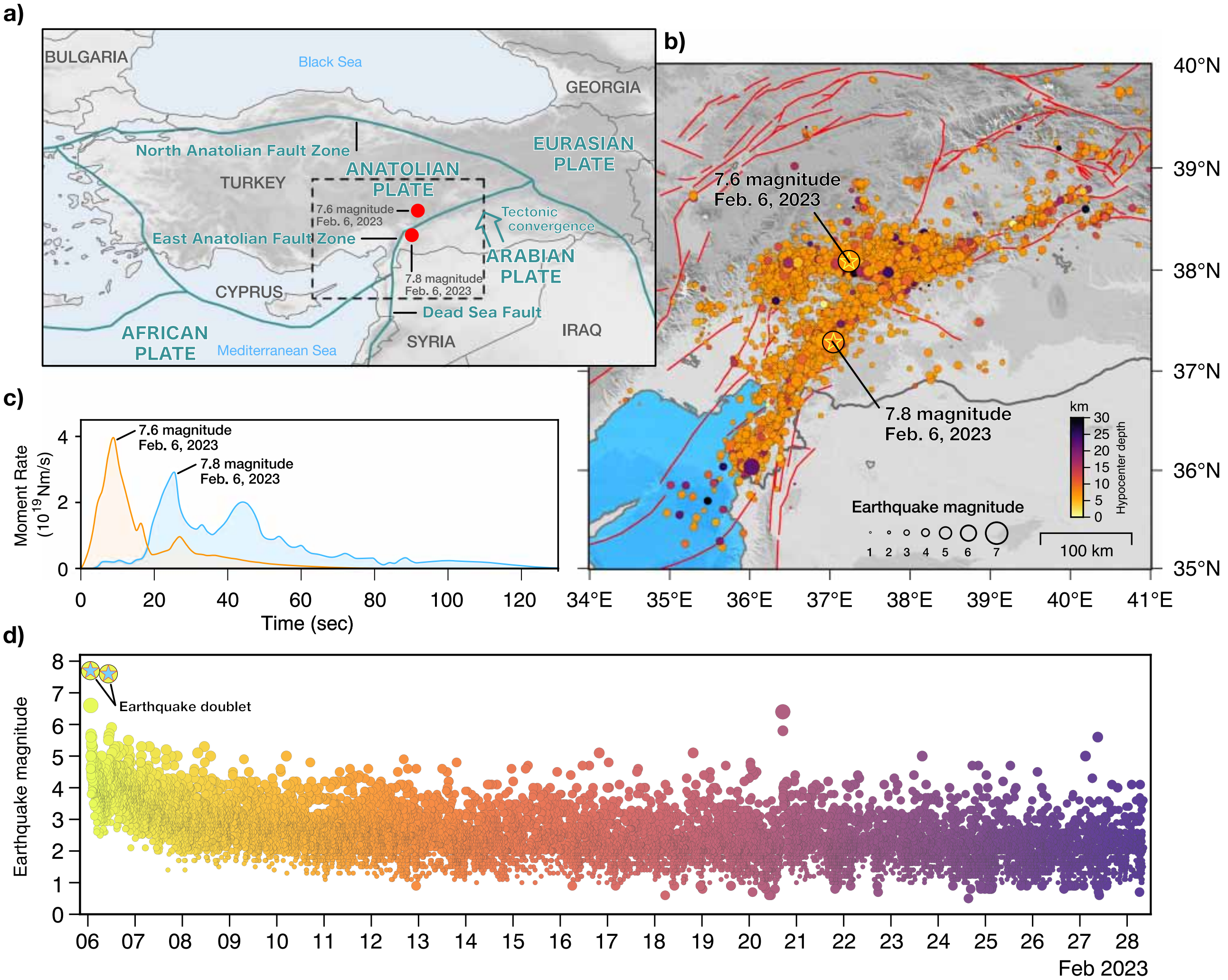

Fig. 2 Tectonic setting and seismicity caused by the 2023 Kahramanmaraş Earthquake Sequence. a The inset map shows the large-scale geodynamic context indicating the two main strike-slip faults that delineate the Anatolian block: the East Anatolian Fault and the North Anatolian Fault. Known and mapped surface traces of the main faults are shown as dark grey lines. **b** First month of relocated seismicity as a function of magnitude and depth, including the main two events and aftershocks. Fault lines are indicated in red. **c** Source time functions of both events of the main two events are provided by the US Geological Survey (USGS)[7]. **d** Temporal evolution of seismicity in the month of February 2023. The yellow-to-purple colour scheme indicates the temporal evolution of seismicity. The two stars indicate the earthquake doublet. The seismic catalogue is provided by the Disaster and Emergency Management Authority of Turkey (AFAD).

859 AD earthquake in the Sergilla segment, the 1157 AD earthquake in the Apamea segment, and the 1408 AD earthquake in the Lattakia segment[12]. The seismic behaviour of the northern segment of the Dead Sea Fault appears to involve long periods of seismic quiescence abruptly interrupted by infrequent, large earthquakes. The northern segment of the Dead Sea Fault calls for special attention, as this segment is a well-identified seismic gap with no large earthquake for over 850 years[12]. With an average slip rate of 7.0 mm per year, this fault would have accumulated a slip deficit of almost 6 m. As a result, we argue that this long seismic quiescence possibly represents a high level of seismic hazard in Syria and Lebanon.

To conclude, this is time for a rapid re-appraisal of earthquake risk in the region. It will then be up to policymakers to work on enforcing building and seismic codes, use of quality material and skilled workmanship as well as building insurance.

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Author contributions
L.D.Z. Prepared the manuscript, conceptualized the first draft, and created figures. J.P.A. contributed to manuscript writing and revision.

Competing interests
The authors declare no competing interests. L.D.Z. is an Editorial Board Member for *Communications Earth & Environment*, but was not involved in the editorial review of, nor the decision to publish this article.

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