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Editorial

Twin Earthquakes Devastate Southeast Türkiye and Syria: First Report from the Epicenters

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A deadly dance of the plates: *Arabia takes a step to the north*, *and Anatolia jumps to the west*

In early February, 2023, southeastern Türkiye and northern Syria were hit by a series of deadly earthquakes (two of them above magnitude 7.5) that are proving to be one of the most significant earthquake disasters of this century. These "twin quakes" caused a large number of casualties and property losses. As of press time, the death toll in Türkiye and Syria has surpassed 51 000 and the number of injured has surpassed 120 000, with the number affected >13.5 million. The toll is constantly rising and the hope of finding more survivors has rapidly faded. The USGS PAGER (United States Geological Survey, Prompt Assessment of Global Earthquake for Response) service estimates economic losses of 10–100 billion US dollars.

After a small foreshock of *M* 4.2 rattled the region on Feb. 3, the main events started at 4:17 AM on Feb. 6, 2023 (9:17 AM Beijing time), when a magnitude (*M*) 7.8 earthquake (*M* 8.0 according to GEOSCOPE Observatory, France) occurred in southeastern Türkiye, with a focal depth of 17.5 km, with 33 large and medium-sized cities within 300 km of the epicenter (USGS). Many cities and towns were devastated, as the shaking intensity, as measured by the Mercalli Intensity Scale (which measures what people remember feeling) was XI (Extreme). The USGS has instruments on the ground in Türkiye that measured ground motions as "Extreme", including ground accelerations of 0.9 (Hassa location) and 1.6 (Fevzipasa location) times the strength of gravitational acceleration. This was one of the strongest earthquakes recorded in Türkiye since the 1668 earthquake along the North Anatolian fault zone (USGS, Historic Earthquakes Worldwide). The earthquake occurred in a tectonically complex region (Fig. 1) where three plates meet, called a triple junction, and ruptured a shallow section of the crust about 190 km long and 25 km in the vertical dimension.

The main earthquake was followed 11 minutes later by a major aftershock of *M* 6.7, then at 18: 24 (11: 24 PM Beijing time) on Feb. 6, 9 hours after the magnitude 7.8 (8.0) shock, another earthquake with a magnitude of 7.5 (7.7 according to GEOSCOPE) occurred 95 km to the northeast (38.00° N latitude, 37.15°E longitude), with a focal depth of 10 km (US Geological Survey, China Earthquake Networks Center). This earthquake ruptured a segment of the crust about 120 km long, and 18 km in the vertical dimension.

Both large earthquakes were shallow and associated with various complex strands of the left-lateral Dead Sea and East Anatolian transform faults and related fault systems, which form the boundary between the Arabian, African, and Anatolian tectonic plates. The tectonic setting is complicated as near the epicentral regions, the Arabian Plate is sliding north along its plate boundary with the African Plate along the Dead Sea transform fault system, and the African Plate is plunging beneath the Anatolian Plate in the Cypriot trench (Fig. 1). The first magnitude 7.8 event (Fig. 2) was apparently on the Ölü Deniz Fay Zonu segment of the Dead Sea transform fault, a few tens of kilometers from where it intersects with the East Anatolian transform fault, making this a near-triple-junction event. However, in the location of the first shock, the two plate boundary faults (East Anatolian and Dead Sea transform faults) are parallel and only 20 km apart, making it very difficult to say at present which fault actually slipped, or if the slip is distributed along many strands of the two parallel systems. Our studies on the ground are aimed at this, and other scientific questions that will help understand how complex plate boundary fault systems work, and hopefully, save lives in the future.

The tectonic position of the Anatolian Plate where Türkiye is located is special, and the neotectonic movement is very active, with a long history of devastating earthquakes. Figure 1 shows the tectonic background, where the Arabian Plate is moving north along the Dead Sea fault zone (DSFZ), a continental transform that separates the Arabian Plate from the African Plate. Arabia is colliding with Eurasia in the northeast forming the Bitlis-Zagros collision zone between Arabia and Eurasia, but the continental block forming the Anatolian Plate (most of Türkiye) has broken off and is escaping sideways to the west away from the collision zone. This happens along two other main continental transform faults, the East Anatolian fault zone (EAFZ) in the south, and the North Anatolian fault zone (NAFZ) in the north. February's earthquake swarm was

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Figure 1. Outline map of Türkiye's tectonic structure. NAFZ. North Anatolia fault zone; EAFZ. East Anatolia fault zone; NEAF. Northeast Anatolia fault zone; DSFZ. Dead Sea fault zone; BZCZ. Bitlis-Zagros collision zone; K. Karlıova (modified from Meng et al., 2021). The East Anatolia and North Anatolia faults converge at the point where three plates (Anatolia, Arabia, Eurasia) meet near Karlıova (K), known as the Karlıova triple junction (K). The East Anatolia fault, the Dead Sea fault and the Cyprus trench meet at another triple junction near the first, *M* 7.8 earthquake, at an imprecisely defined location, where the Arabian, African, and Anatolian plates meet.

concentrated mostly along different fault segments related to the wide EAFZ and related thrust and normal fault systems, but the initial *M* 7.8 event and some of the aftershocks were apparently along strands of the Dead Sea transform fault. Aftershocks have occurred as far south as Lebanon and Israel, and along another plate boundary, that is the subduction-trench convergent boundary with the African Plate, which is being pushed or subducted beneath Cyprus then Anatolia.

The place where these plate boundaries all meet is one of the most complex plate junctions in the world, and these earthquakes are showing just how it works. The diagram below (Fig. 3) shows how part of the system works, where plate B (yellow) is Arabia, colliding with plate A (pink), forming a distributed deformation zone with many faults in between. Anatolia (plate C, blue) breaks away and escapes to the west along a southern fault (EAFZ) and a northern fault (NAFZ) causing earthquakes, and opening basins (white areas) in between, that quickly fill with lakes and sediments. Note that in these complex systems some faults and earthquakes may be strike-slip (sideways motion) in nature, whereas others may be extensional, contractional, or mixed, depending on the exact orientation of the fault rupture with respect to the plate movement direction. Note also in this simple model, the African Plate and Dead Sea transform faults are excluded, and the subduction trench above the African Plate is not shown.

If we consider the tectonic complexities of Anatolia (Türkiye), the diagram above makes it clear why we have strike-slip, or sideways moving faults in the southeast and north sides of the Anatolian Plate. Eastern regions are subjected to the collision and extrusion from being squeezed out from between the converging Arabian Plate and the Eurasian Plate (deforming the circle in Fig. 3a to the ellipse in Fig. 3b). However, the western part of the plate is also sitting above the subducting African Plate, which, as it subducts into the mantle, is also sinking backwards as it gets steeper, which is pulling the upper plate (Anatolia) towards the south, while it is trying to escape to the west.

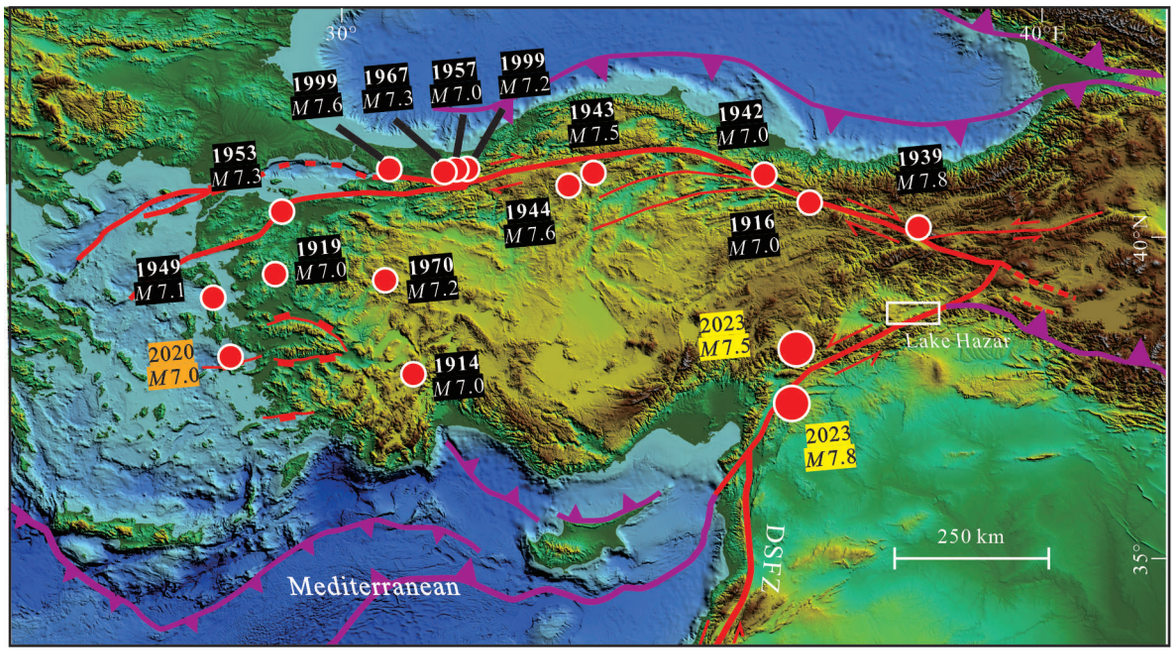

Figure 2. Distribution of earthquakes above magnitude 7 on the Anatolian plate of Türkiye (data from the US Geological Survey). The large earthquakes in the east in February 2023 occurred during slip along a system of strike-slip faults, and define a series of complex structures along the boundary between the Arabian and Anatolian plates. In contrast, a M 7 earthquake that occurred in the west in 2020 was along an extensional normal fault within the Anatolian plate, showing that the eastern and western Anatolian tectonic and deformation mechanisms are completely different.

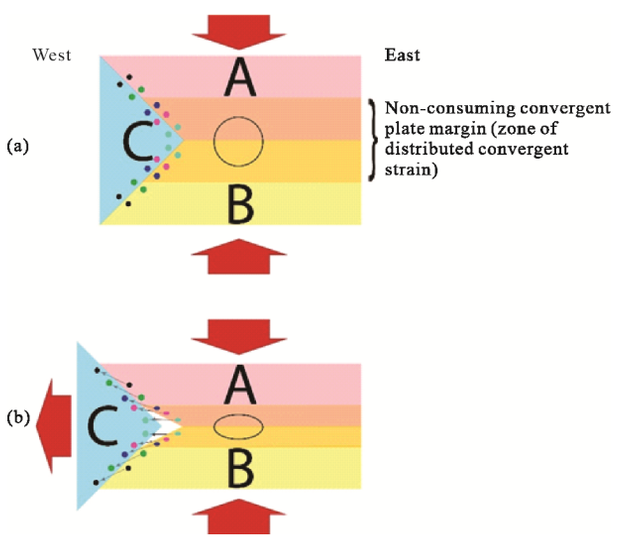

Figure 3. Karlıova (Türkiye) type triple linkage model (adapted from Şengör et al., 2021).

Therefore, in the west, we see large extensional earthquakes, like the 2020 *M* 7 (Fig. 2), because this part of the plate is deformed by the near-north-south extension related to the roll-back of the Aegean trench in the Mediterranean Sea (Meng et al., 2021). The tectonics and earthquakes along the northern part of Anatolia are dominated by the large strike-slip North Anatolia fault zone, and the middle part of the plate belongs to the structural transition zone, which is relatively stable (Fig. 2). The three tectonic systems of compression, strike-slip and extension in this area act on different positions of the Anatolian Plate at the same time, causing the country to suffer from different types of earthquakes, landslides and other geological disasters.

The general cause of this week's earthquake swarm is not much disputed. The initial *M* 7.8 earthquake fault ruptured a segment of the strike-slip fault related to the northward movement of Arabia with respect to Africa, and its collision with Eurasia, and Anatolia's escape from the eastern compression. During the collision between the Arabian Plate and the Eurasian Plate, the Anatolian Plate in Türkiye was squeezed out westward with movement accommodated along the two large strike-slip faults, the East Anatolia and North Anatolia fault zones. Arabia took a step to the north, and Anatolia responded with a jump to the west.

The first *M* 7.8 event was near the wide and complex structural triple junction formed by the East Anatolia transform fault zone, the Dead Sea transform fault zone, and the Cypriot trench (Fig. 1). After the main shock along the northern strand of the Dead Sea transform fault, the whole area became "active", as the energy released during the earthquake can be focused along the fault (as in the case of the Wenchuan Earthquake; Kusky et al., 2010). More importantly, at the edges of the area of the region that slipped during the main shocks, the stresses may be increased, and the slipped area expands along the fault, causing many aftershocks and outlining the geometry of the fault system (Fig. 4). This outward spreading of slip can also cause stresses to build-up at places where the faults end, and meet another fault such as at a triple junction, which must move in a different direction to accommodate the stress build-up, resulting in very complex patterns. The early shocks were along the NNE-striking segments of the Dead Sea transform fault (which is parallel and 20 km away from the East Anatolia transform fault in a fault-controlled valley), then the left-lateral E-W Çardak Fayı (fault) that branches off the main East Anatolian fault was activated with the *M* 7.5 event and its aftershocks, explaining the

"7" shape of the whole earthquake swarm (Fig. 4). In this case, the distribution of aftershocks after the main shock basically outlines the traces of the East Anatolia fault zone and the Dead Sea fault zone, along with related thrust and normal fault systems (Fig. 4).

While devastating, seismologists and geologists are currently researching the data recorded by seismographs and geological investigations of the neotectonics of the region, to understand the system better, and hopefully save lives in future events. The research team led by Profs. Timothy M. Kusky and Lu Wang (China University of Geosciences, Wuhan) was funded by the National Natural Science Foundation of China in

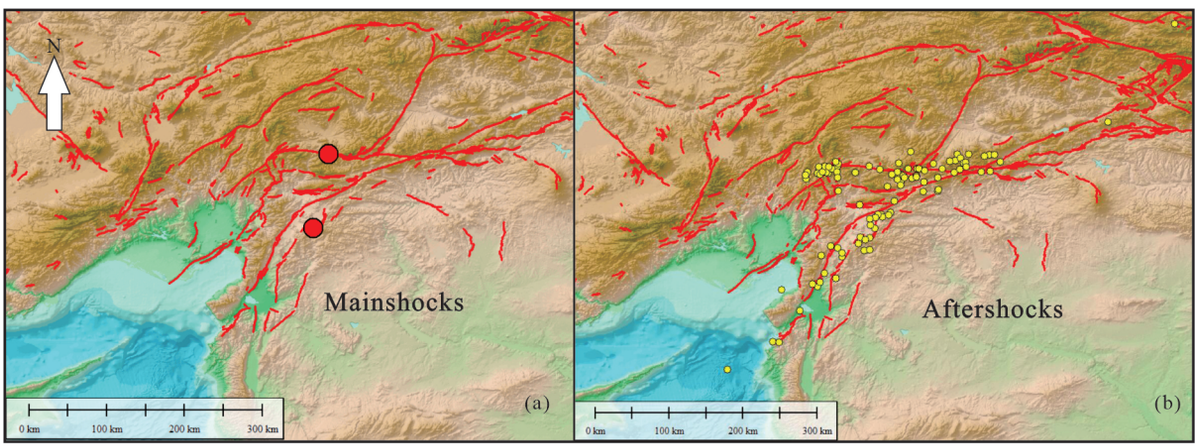

Figure 4. (a) Distribution of the main 7.8 and 7.5 earthquakes, on a map of the active faults of Türkiye (active faults from Sahin et al., 2013; General Directorate of Mineral Research and Exploration, Ankara, Türkiye). (b) Distribution of aftershocks above *M* 4.5 (data from the US Geological Survey). See text for discussion.

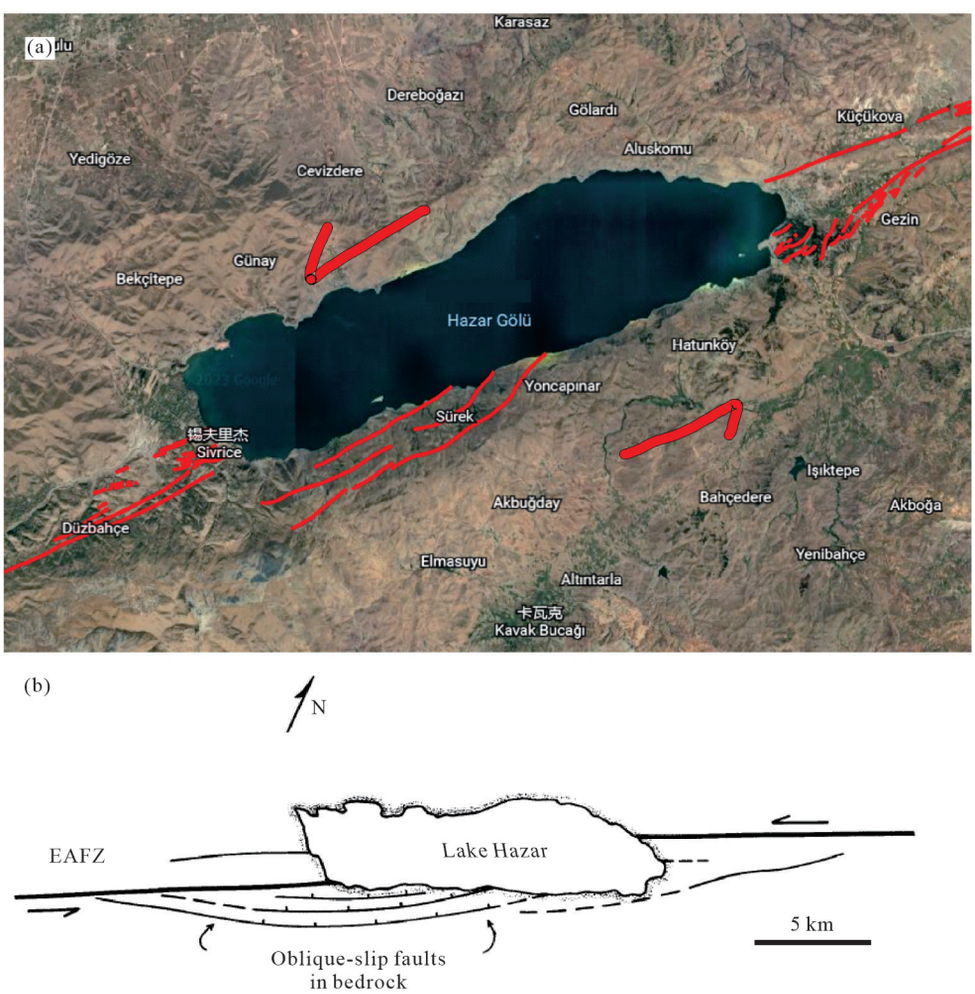

Figure 5. (a) Satellite image of Lake Hazar (from Google Earth, see the white box in Fig. 2 for the location). (b) Interpretative tectonic map of Lake Hazar, used to define pull-apart basins (Mann et al., 1983).

2019 with the support of the National Natural Science Foundation of China Tethys Geodynamic System Major Research Program Key Project "Continental Collision Lateral Escape and Formation of Initial Plate Boundaries". As part of this project a geological survey and neotectonic investigation was conducted along the active fault systems of western and eastern Türkiye (Figs. 4, 5) before the twin quakes. The vegetation coverage in this area is high, and the fault planes are rarely exposed, but the results of past seismic activity were apparent. Geomorphological evidence for the existence of a plate boundary is shown by a series of structural and geomorphic phenomena such as pull-apart basins associated with surface strike-slip faults (e.g., Lake Hazar, Fig. 5) in regions of extension along the fault system, and pop-up structures called pressure ridges in places where the main strike-slip fault bends putting different sections under compressive stresses. Historically, the concept of "pull-apart basin" was first identified in Lake Hazar along a minor step the East Anatolia fault zone (Mann et al., 1983) (Figs. 2, 5).



Figure 6. Field photographs of the traces and effects of the active ground deformation and liquefaction from the February 2023 earthquakes in Türkiye. (a) Distorted railroad tracks, due to lateral spreading along lake site where there is extensive liquefaction during intense ground shaking; (b) Lateral offset (3.84 meters) of small road on one strand of the fault, showing sinistral strike-slip displacement. Ground-break along fault in farmland, showing lateral offset and extensional pull-apart basin formation; (c) Sand that bubbled up from the substratum forming a sand volcano along the side of lake Gölbaşı, indicating liquefaction of the soils during intense ground shaking. (d) Series of sand volcanoes stemming from a deeper fracture, indicative of liquefaction of unconsolidated sediments, contributing to the structural damage in towns within the earthquake zone. (e) and (f) Aerial views of sinistral en echelon extensional fracture systems in agricultural fields, resting above deeper level fault strand. Note 4WD vehicle for scale near intersection in (e).

After the quakes, two teams from China University of Geosciences Center for Global Tectonics (CGT) were among the first scientists on the scene to conduct surveys of the fault surfaces and damage. Prof. Erdin Bozkurt (Middle East Technical University (METU) and China University of Geosciences, CGT) arrived within the first few days after the quake, investigating the surface ruptures. He reports horrific conditions, and virtually total destruction with entire towns, villages, and large parts of major cities flattened. The devastation is partly from poor construction, and also from the geological conditions where many villages were built, with many on loose soils in basins that saw much higher levels of shaking than mountainous regions on bedrock. The combination of the shaking and the properties of the soils induced catastrophic liquefaction, where the soils behave like a fluid during the intense shaking, causing thousands of buildings, and whole towns, to collapse. A little more than a week after the quakes, Ph.D. candidate Jiannan Meng flew from Wuhan, China, arriving on-scene, and as of press time, are in the midst of the first drone-assisted regional examination of the rupture area, along both the East Anatolian fault, and the left-lateral E-W Çardak Fayı fault, where the second of the twin earthquake was centered. Preliminary first-hand field observation data is shown in Fig. 6. Both have been the sites of numerous aftershocks that continue frequently at present.

The North Anatolia transform fault zone and seismic zone, which form the northern boundary of tectonically escaping Anatolia plate, is also extremely dangerous. Historically, earthquakes of magnitude 7 or above have occurred (USGS), and the sequence of earthquakes shows a clear pattern of transmission from east to west. At present, the un-slipped region with a high probability of slipping has been transmitted to the vicinity of İstanbul, the largest city in Türkiye (Fig. 2), and almost all earth scientists are concerned that there will be a large earthquake of magnitude 7 or above in the future. As the largest city in Türkiye, İstanbul is also an important hub connecting Europe and Asia. If it is damaged by an earthquake, the losses caused could be immeasurable. As most casualties in February's twin quakes were apparently caused by falling buildings and bricks, planners need to plan ahead and reinforce structures in metropolitan areas to ensure the safety of residents.

Natural disasters are ruthless, but human beings are merciful. Various countries including China have already taken action. The Chinese government immediately launched an emergency humanitarian assistance mechanism and decided to provide emergency assistance to Türkiye and Syria. The first batch will provide 40 million yuan of emergency assistance to Türkiye, including sending heavy urban rescue teams, medical teams, and providing urgently needed disaster relief materials for Türkiye. We hope that the Turkish people can receive timely assistance and rebuild their new earthquake-resistant homes as soon as possible.

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