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Preliminary Analysis of the Aftershock Sequence of the February 6, 2023, Turkey Earthquake

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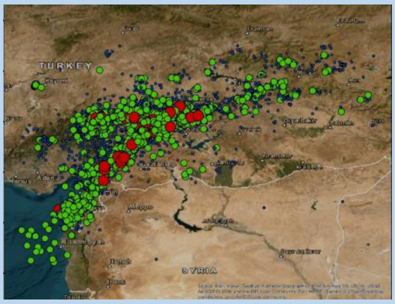
Abstract: The February 6, 2023, Turkey earthquake with a moment magnitude (Mw=7.8) will be recognized as one of the most powerful earthquakes to strike a large metropolitan area in recent memory. This quake occurred in southern Turkey near the northern border of Syria along the southern western branch of the East Anatolian Fault (EAF). This major event was followed by numerous significant aftershocks, with 14,107 earthquakes occurring as of March 5, 2023. Preliminary data analysis in this study of aftershocks a month after the main earthquake (Mw=7.8) implies that the majority of the aftershock sequence was focused near the epicenter of the main shock displaced numerous fault segments within the EAF zone and can have indirect effects on neighboring fault systems. As a result, notable earthquake activity was observed along the northern section of the Dead Sea Transform (DST) fault system in Syria, Lebanon, and Palestine. According to statistical seismological analysis, 81% of aftershocks with magnitudes less than 3 occurred after the main shock, while 38 aftershocks with magnitudes 5 or greater occurred within the first 6 days, which includes 7.5 and 6.8 magnitude shocks. The depth distribution of the large main shocks and the aftershocks was located at shallower crustal depth. The aftershock sequence is mostly distributed in the first 15 km of the earth's crust, with significant occurrences occurring between 5 and 19 km deep. The expected aftershock scenario of such a large earthquake is to continue for several months or longer, possibly years. The interaction of the EAF and the DST fault is strongly recommended as an important research issue since it may well provide insights into the general tectonic activity and assist in better predicting future earthquakes in the region.



Keywords: the 2023 Turkey earthquake, East Anatolian Fault (EAF), Dead Sea Transform (DST), foreshock, aftershock, focal depth.

Introduction

On 6 February 2023, a disastrous earthquake with Mw 7.8 took place in the southwestern part of Turkey (1-2). Various regional seismic networks recorded the major shock that caused extensive damage and devastation (3). The surface rupture that appeared with the main shock followed the East Anatolian Fault (EAF) zone (Figure 1). It is one of the seismically active and well-known strike-slip faults on the Earth extending along the Anatolia-Arabia plate boundary (4-5). The EAF is the second major fault system in Turkey which is mainly controlled by the continuing northward motions of the African and Arabian plates concerning the Eurasian plate (6-8). The first important one is the North Anatolian Fault (NAF) zone (Figure 1). The EAF extends for around 700 kilometers from a triple convergence in the northeast where the Anatolia, Arabia, and Eurasia plates meet (9). It continues to the southwest until it meets another ripple convergence at the conjunction of the EAF, the Cyprus subduction arc, and the Dead Sea Transform fault (Figure 1), which is a transform boundary between the Arabian and Sinai plates as they converge into Eurasia (10-13). Devastating earthquakes occurred on the EAF during both historical and instrumental periods (14-17). The studies of earthquake source mechanisms show that the faulting along the eastern part of the EAF is dominated by a stress regime with horizontal maximum and minimum compressional stresses, characterized by pure left-lateral strike-slip faulting (18-19). The EAF displays seismicity patterns with gaps, localized clusters, and sections with diffuse activity. This complexity partly results from the geometry and the direction of the plate motion (20).

Following a major earthquake event, seismologists and geologists conduct extensive research to gather data on the occurrence of aftershocks. These seismic events are typically classified as aftershocks if they occur within a certain radius of the main earthquake epicenter and within a specific period. This data is critical in understanding the nature of the earthquake and the potential risks it poses to the affected region.

In this paper, we present a preliminary analysis of the aftershock activity associated with the February 6, 2023, Turkey-Syria earthquake along the segments of the EAF as revealed by Bögazici University Kandilli Observatory and Earthquake Research Institute (1), Turkey's Disaster and Emergency Management Authority (2), and from the Palestinian Seismological Observatory (3).

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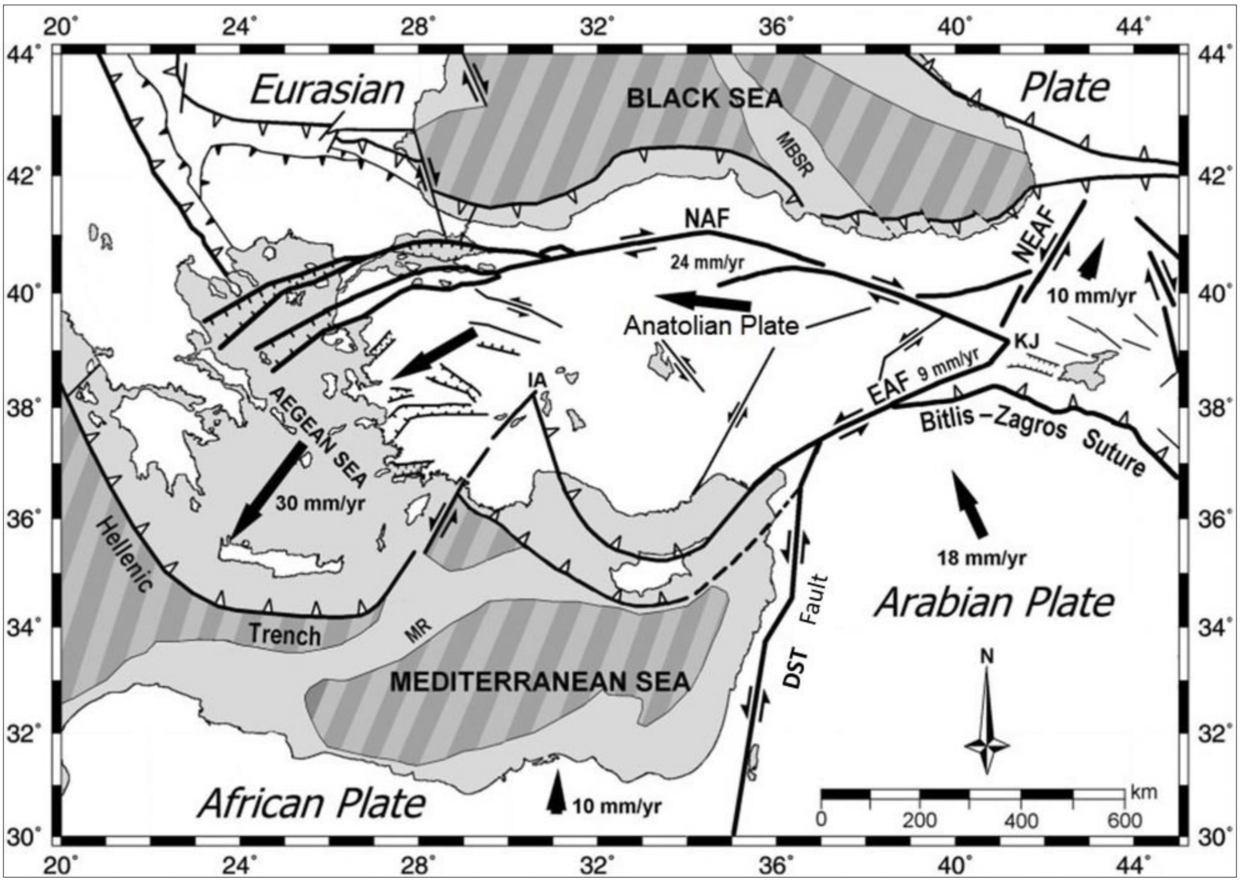

Figure (1): Tectonic setting map of the East Anatolian Fault (EAF) zone modified after (21).

Data Analysis

Seismic Activity Before the Main Shock

The seismic activity before the main shock is an important feature that could be observed for comparison when we consider a statistical picture of the evolution of seismicity as a function of time. Foreshocks are shifts in the earth's crust that occur before a major earthquake, and they can provide warning signs to people in the area. Turkey experienced a series of foreshocks that preceded the major earthquake on February 6, 2023. Figure 2 shows the seismic activity data for the period July 4 to February 5, 2023, a month before the main shock (Mw 7.8).

People in the area likely felt the foreshocks as minor tremors or vibrations, but they were a precursor to the bigger earthquake that was to follow. These events can be difficult to forecast, but seismic tracking can frequently notice pressure changes that indicate an earthquake is impending. Turkey's reaction to these foreshocks would be determined by their severity and the degree of preparedness. Officials should ideally have an evacuation plan in place and use the foreshocks to evacuate and alert people in susceptible areas. They would also work to strengthen existing structures and facilities to minimize the earthquake's harm. Overall, the foreshocks that anticipated the 2023 earthquake in Turkey may have helped to lessen its effect by giving those in the region early warning signals. However, local authorities' readiness and finances, as well as the magnitude of the earthquake itself would determine the efficacy of any reaction.

Aftershocks Analysis of the February 6, 2023, Turkey Earthquake

An aftershock is an earthquake that occurs following and near the epicenter of the main large-magnitude earthquake. Because aftershocks are common and follow a typical pattern, scientists can provide information regarding how they might affect areas that have recently experienced a large earthquake. These observations, which sometimes take the form of forecasts, are not predictions, but rather a tool for emphasizing plausible scenarios defining the number and magnitude of earthquakes that may occur in the months after the major shock.

Previous attempts were made to figure out more about the seismic behavior of the EAF by analyzing aftershock sequences focused near the epicenter of the large shocks, which displaced multiple fault segments inside the EAF zone and ruptured an adjacent fault segment (21-25). They can be used to get a better understanding of the fault structure and stress changes in the affected region. Thus, analyzing the aftershock sequence of the February 6, 2023, Turkey earthquake provides important insights into the behavior of the Earth's crust following a significant seismic event. The aftershock sequence following the February 6, 2023, Turkey earthquake consists of numerous earthquakes of varying magnitudes (Figure 3). The largest and most significant aftershock occurred on February 6, 2023, with a magnitude of 6.8 and a magnitude 7.5 earthquake. These significant events

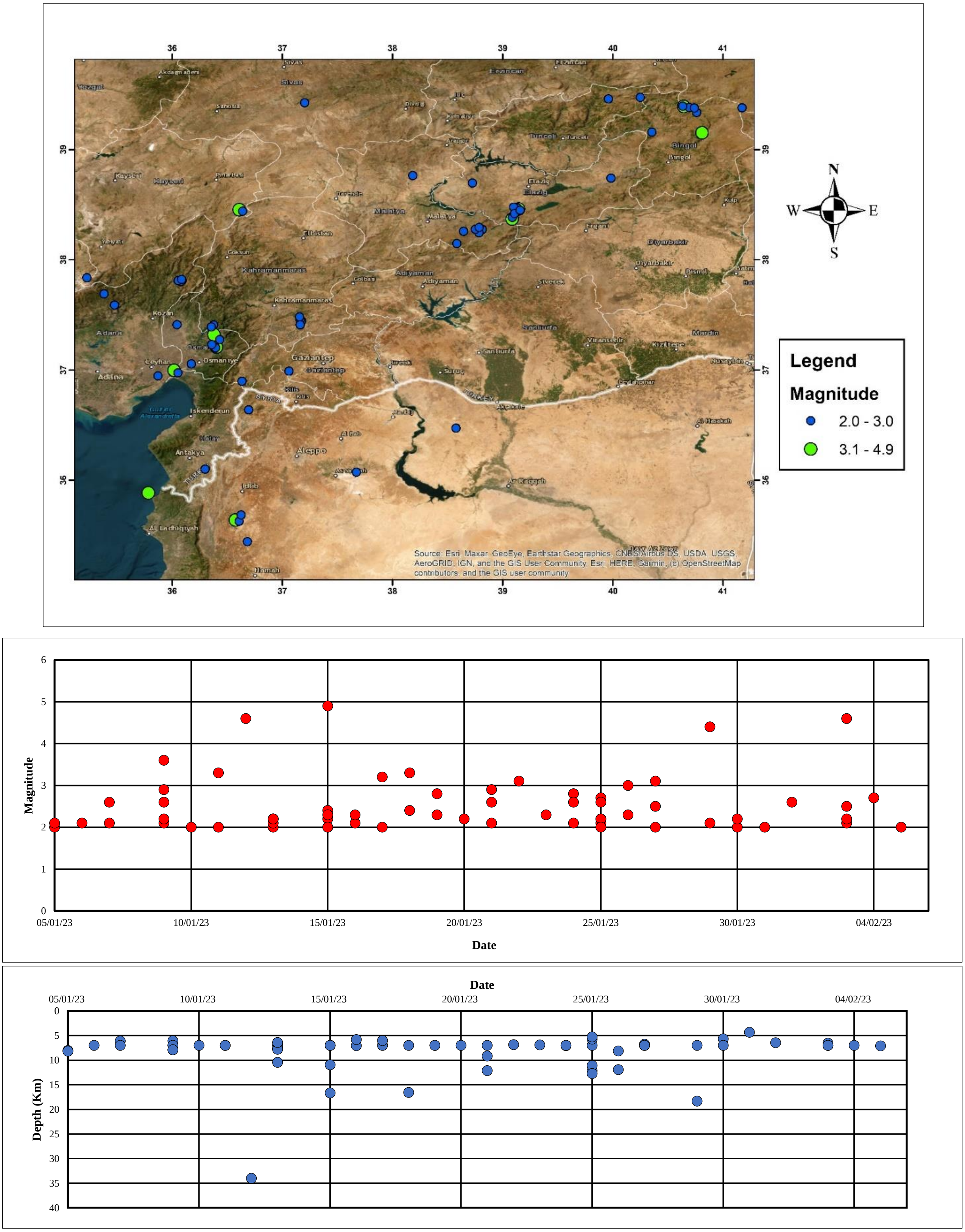

Figure (2): Distribution map of seismic activity one month before the major shock, with depth and magnitudes of events plotted over date.

were followed by many significant aftershocks, as of March 5, 2023, 14,107 aftershocks occurred (1-3). Out of them, 423 events with magnitudes, more than 4 occurred, among these 38 aftershocks of magnitude 5 or greater were recorded within the first 6 days following the main shock (Figure 3), while 81% of the total aftershocks with magnitudes less than 3 (11385), and 2299 earthquakes of magnitude between 3 and 4. The location of the aftershocks indicates that they are occurring along the same fault as the main earthquake, which is the EAF (Figure 1), and ruptured a neighboring fault segment. This fault is known for producing large earthquakes and is part of the complex tectonic regime of the Mediterranean region (14- 17).

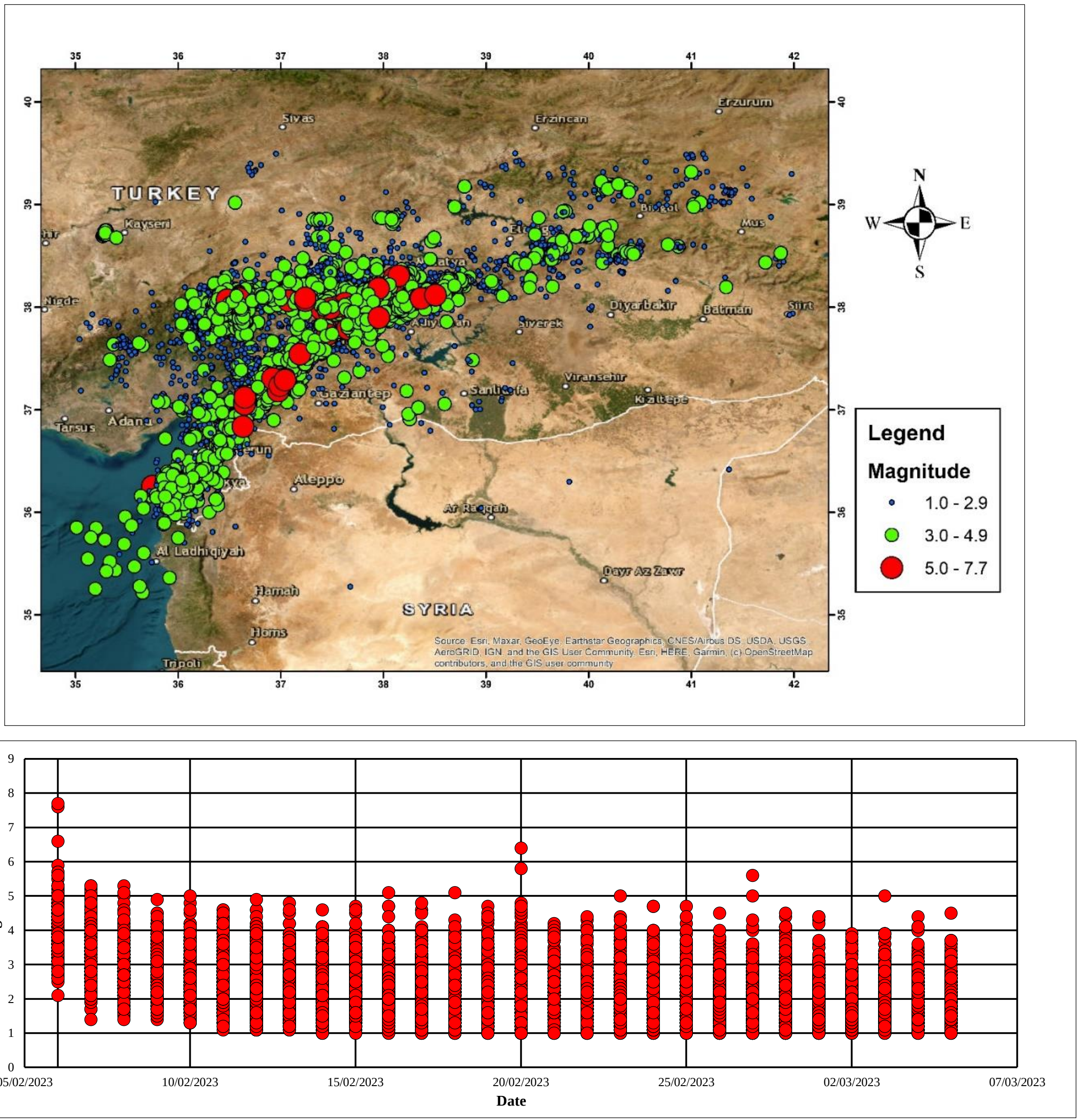

Figure (3): Aftershock epicentre distribution map, with shock magnitudes shown against time.

The aftershock sequence appears to be following the typical pattern of decreasing frequency and magnitude with time since the main shock, but the seismic activity is still higher than usual for this region. Therefore, it is possible that more significant aftershocks could occur in the coming months. Hence, this means that the region affected by the February 6, 2023, Turkey earthquake remains at risk of experiencing more seismic activity, including potentially significant aftershocks. The temporal variation of the aftershock sequence indicates that the crustal system is still adjusting to the stress changes caused by the main shock and that there is still a significant amount of residual stress within the region.

Focal Depth Distribution Along the Aftershocks of the February 6 Earthquake Zone

The depth of the main shock Mw 7.8 of the February 6 earthquake was nearly (9 km). The depths of the following aftershocks lie above a depth of 15 km, and most of them (96%) are located within a band zone between 5 km and 15 km depth, as can be seen in (Figure 4). The upper 5 km of the crust shows a low seismic activity. However, most hypocenters are located closer to the surface, where most of the aftershocks lie above a depth of 10 km. The deepest earthquake of the entire sequence has been determined here with a depth of around (45) km.

It appears that the depth of aftershocks following the February 6, 2023, Turkey earthquake is concentrated in the crustal layer of the earth's surface, between 10 and 20 kilometers deep. The largest aftershocks have been located at a depth of approximately 15 km. This is expected for earthquakes located near the boundary of the Anatolian and Aegean plates, where stress builds up due to the movement and collision of these plates (20). The depth of aftershocks can provide important insight into the geometry and type of fault responsible for the earthquake, as well as the behavior of the rocks and structures affected by the earthquake. In addition to understanding the behavior of rocks and structures, the depth distribution of aftershocks can also provide insight into the potential for future seismic activity in the region. It is worth noting that the depth of an earthquake event can significantly affect the occurrence and magnitude of aftershocks.

In general, shallower earthquakes tend to produce more aftershocks, with higher magnitudes. However, this is not always the case, and other factors, such as the orientation and geometry of the fault play a role.

Data Discussion

On February 6, 2023, a magnitude 7.8 earthquake occurred in southern Turkey near the northern border of Syria. The earthquake was followed 11 minutes later by a magnitude 6.8 aftershock and approximately nine hours later by a magnitude 7.5 earthquake located to the northwest of EAF. These significant magnitude earthquakes resulted from strike-slip faulting at shallow depths. The event ruptured either a near-vertical left-lateral fault striking northeast-southwest, or a right-lateral fault striking southeast-northwest. The preliminary location of the earthquake places it within the vicinity of a triple junction between the Anatolia, Arabia, and Africa plates (1-3). The February 6, 2023, Turkey earthquake has been followed by a series of aftershocks, ranging mainly in magnitude from less than 2 to 5.4. The depth distribution of these aftershocks has been predominantly focused on the crustal layer of the earth's surface, which is approximately 10-20 km deep. This is consistent with other earthquakes in the region, as Turkey is geologically complex and located near the boundary of the Anatolian and Aegean plates. The largest aftershocks have been located at a depth of approximately 15 km. The depth of aftershocks is an important factor in understanding the behavior of the rocks and structures affected by the earthquake. Aftershocks typically occur at shallower levels as time passes, suggesting that the earth has adjusted to the new configuration of stresses produced by the main shock.

The depth distribution can also provide information on the type of fault responsible for the earthquake, as different types of faults exhibit different depth distributions. It is also important to note that the depth distribution of aftershocks following the February 6, 2023, Turkey earthquake may evolve over time. The immediate pattern of aftershocks can be affected by local variations in rock properties and stress conditions. Furthermore, the pattern of aftershocks can change as the crust adjusts to the stress changes caused by the earthquake. Aftershocks may also trigger other earthquakes in the region, or they may release stress and reduce the likelihood of future earthquakes (21-25).

On the other hand, the mechanism and location of the earthquake are consistent with the earthquake having occurred on either the East Anatolia Fault zone or the Dead Sea Transform fault zone. The East Anatolian fault accommodates the westward extrusion of Turkey into the Aegean Sea, while the DST accommodates the northward motion of the Arabian Peninsula relative to the Africa and Eurasia plates (20).

However, it is important to note that earthquakes in the region can have indirect effects on neighboring fault systems. A large earthquake in one area can cause stress changes in the crust that could trigger earthquakes on nearby fault systems. In this sense, the occurrence of a significant earthquake Mw 7.8, such as the February 6, 2023, in Turkey was followed by two large earthquakes with a magnitude of 6.8 and a magnitude of 7.5 (1-3) could potentially increase the likelihood of earthquakes on the Dead Sea Transform fault system or other nearby faults.

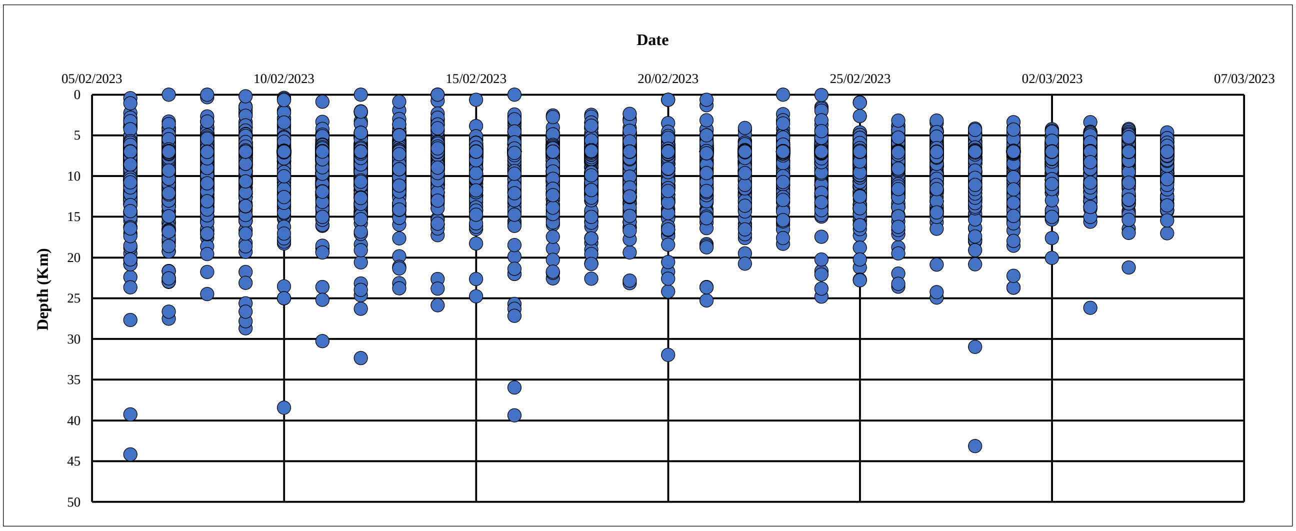

Figure (4): Aftershock depth distribution with time.

Indeed, notable seismic activity was documented during the first week of the February 6 main earthquake, along the Dead Sea Transform (DST) fault system in Syria, Lebanon, and Palestine (Figure 5). Many Palestinians in different urban and ruler regions of the West Bank felt some events that happened south of Nablus and north of Tubas city in Palestine (3). In a broad sense the February 6, 2023, Turkey earthquake is unlikely to have a direct effect on the Dead Sea Transform fault system, which is located several hundred kilometers to the south of Turkey. However, there is a possibility that the earthquake could indirectly contribute to an increase in seismic activity in the region. Different studies examined the seismicity patterns of the EAF and the DST and found evidence of seismic coupling between the two faults (26-29). Results showed that the EAF and the DST have similar and common tectonic characteristics, which can result in significant seismic activity. The presence of these similar features suggests that the faults may interact with each other in complex ways, leading to the transfer of stress and triggering of earthquakes. The researchers used a combination of seismological, GPS data, and kinematic modeling to show that the EAF and the DST interact with each other through a series of smaller, connecting faults.

Therefore, it is important to continue monitoring seismic activity in the region, including the DST, to understand any changes that may occur because of the Turkey earthquake or any other seismic events in the area. Such monitoring can help to better risk assessment of earthquake hazards and to develop preparedness and response plans for the affected areas. As a result, it is of prime importance to install more broadband and short-period seismic stations to expand the Palestinian seismic network for more coverage in the West Bank regions of potential seismic activity. Monitoring seismic activity in the region, including the DST, is crucial to evaluate any changes that may occur following the February 6, 2023, Turkey earthquake or any other seismic events to develop effective strategies for earthquake risk mitigation throughout the wider area.

Conclusions

Both historical and instrumental records reveal that destructive earthquakes have affected the EAF zone for almost 2,000 years. Aftershocks are smaller earthquakes following the main shock. They are caused by the readjustment of the Earth's crust due to the changes in stress caused by the main shock. The hypocenter of an aftershock is typically located near the rupture zone of the main shock. Thousands of aftershocks of varying magnitudes continue to shake the devastated region of the February 6, 2023, Turkey earthquake (Mw=7.8), among them are shocks of magnitudes 7.5 and 6.8 have been documented within the first day caused further damaging or destroying buildings, roads, railways, and other infrastructure while hampering rescue and relief efforts. Meanwhile, scientists across the world are examining data from these occurrences to figure out what happened and how they might help. The distribution of aftershocks can provide valuable information about the characteristics of the main shock, such as the location and size of the fault that ruptured. Aftershocks are usually more numerous near the main shock epicenter and decrease in frequency and intensity with distance. The spatial distribution of aftershocks can also help seismologists understand the geometry of the fault that ruptured and the direction of the fault slip.

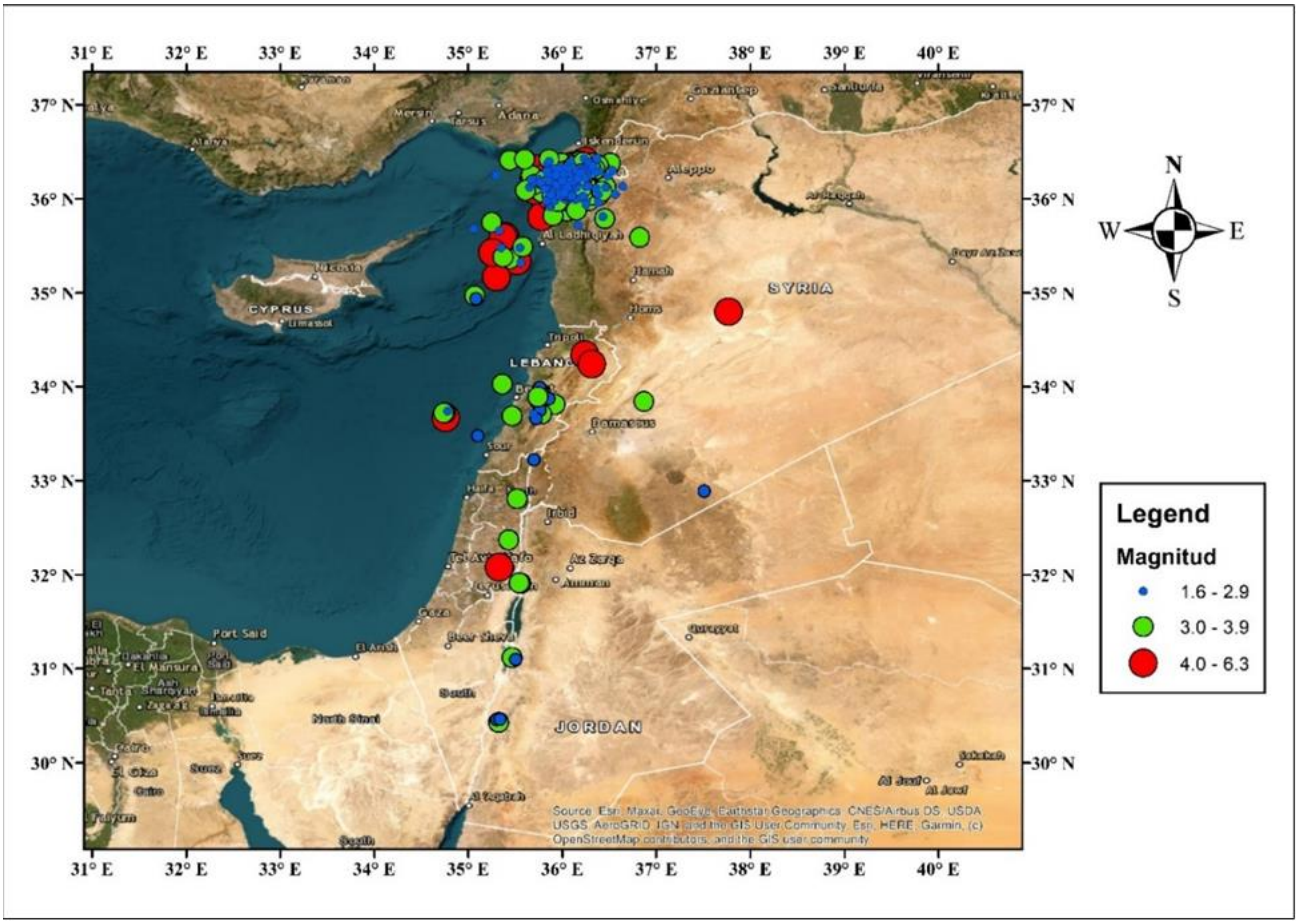

Figure (5): Epicentre distribution map of events along the Dead Sea Transform (DST), a month after the occurrence of the February 6, 2023, Turkey earthquake.

The purpose of this work was to investigate the promoting aftershock sequence of the February 6, 2023, Turkey earthquake because of stress transfer. This can provide us with tools and insights that can help us anticipate the distribution of future aftershocks and assess the potential of following large shocks. As more data from Turkish seismic networks, geological reconnaissance, satellite images, and international collaboration become available, it should be able to improve these evaluations. However, we believe that the magnitude 7.8 earthquake actated a second major shock of magnitude 7.5, and the distribution of minor aftershocks is consistent with these two major shocks. It is important to keep monitoring the depth distribution of aftershocks to gain a better understanding of the region's current seismic activity and predict the possibility of future earthquakes. The distribution of the depth can also help seismologists and geologists comprehend the complex tectonic processes that occur beneath the earth's surface. Consequently, understanding the location and depth of aftershocks is crucial for emergency responders and local officials to prepare for potential future earthquakes and plan effective response strategies. The outcomes of this study highlight the need for monitoring and reporting aftershocks after a big earthquake. Researchers can gain a better understanding of earthquake dynamics by studying aftershock patterns and potential hazards. The information can be used to inform disaster response strategies, perhaps saving lives, and reducing the long-term consequences of natural disasters.

Furthermore, the regional geological surroundings of the earthquake must be considered. The eastern Anatolian fault, a strike-slip fault in eastern Turkey, caused the earthquake in our study. The Dead Sea Transform fault is part of a larger tectonic network that crosses the eastern Mediterranean. The interaction of these faults is an interesting area of research since it may provide insights into the region's general tectonic activity and aid in better predicting future earthquakes.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The earthquakes data used to generate these findings are available in AFAD, KOERI, and PSO.

Author's contribution

The study was conceptualized and written by the first author. The statistical analysis was carried out by the second author. Both authors evaluated the findings and approved the final manuscript version.

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Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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