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EXPLORING EARTHQUAKE TRIGGERING MECHANISMS: INSIGHTS FROM THE 2023 KAHRAMANMARAŞ EARTHQUAKE

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Abstract

This article investigates earthquake triggering mechanisms, drawing on established seismological theories and using the 2023 Kahramanmaraş earthquake as a case study. The discussion looks at fault stress accumulation, self-organized criticality (SOC) theory, and tidal forces as potential triggers. Finally, it raises questions about the role of lunar and solar interactions in seismic activity, indicating potential areas for future research.

Key words: earthquake triggering, stress accumulation, SOC theory, earthquake generation, fault system failure.

Introduction to Earthquake Triggering Concepts

Understanding how earthquakes are triggered is important in seismology because it involves determining which factors can cause a fault to rupture. A "trigger" in this context is usually an external or internal stimulus that causes an earthquake when fault stress reaches a near-critical level. Although tectonic shifts are the primary cause of stress accumulation (Freed, 2005), other factors such as hydrological changes (Jia et al., 2023), aftershock and foreshock sequences (Guglielmi & Zotov, 2024), and tidal forces (Li & Chen, 2024a) have been investigated for possible triggering effects.

These factors are part of the ongoing debate in seismology about which conditions may prime faults for failure. This article discusses current ideas on stress accumulation and SOC theory, followed by an analysis of tidal forces using the 2023 Kahramanmaraş earthquake as a case study. The goal is to determine which influences have a greater impact on fault systems, with the hope of encouraging further research into this topic.

Theories of Stress Accumulation and Self-Organized Criticality (SOC)

The gradual movement of tectonic plates is thought to cause stress accumulation, straining faults until they reach a critical point, at which point a rupture releases stored energy in the form of an earthquake. Ruptures happen when stress surpasses the frictional resistance along a fault plane, and this strain builds up over years, decades, or even centuries (*What Is an Earthquake and What Causes Them to Happen? | U.S. Geological Survey*, n.d.).

According to the theory of SOC, fault systems eventually reach a "critical state" where even slight variations in stress, like those caused by local seismicity or tides, have the capacity to set off more significant events (Caruso et al., 2007). According to SOC, fault systems balance close to a critical point, where the magnitude of stress perturbations and dissipations makes both large and small earthquakes equally likely (Marsan, 2005). Seismic events exhibit complex behavior rather than always following a predictable pattern, which is explained by the SOC model. It makes the assumption that the phenomenon evolved after it started. Similar to an avalanche, which can begin with a single clap and is independent of the clap's intensity. It depends on factors such as snow accumulation, slope angle, and weather conditions. The magnitude of the avalanche will increase once it begins, a phenomenon known as self-organization.

The unpredictability of SOC systems arises from the numerous variables that influence how stress propagates and dissipates within a fault system. Factors such as heterogeneities in rock composition, fault geometry, and pre-existing microfractures contribute to the chaotic redistribution of stress. Additionally, SOC systems are characterized by critical sensitivity to initial conditions: small, imperceptible changes can cascade into large-scale events, making precise forecasting nearly impossible. The stochastic nature of these interactions ensures that while the overall statistical behavior of seismicity may follow power-law distributions, individual earthquake occurrences remain fundamentally uncertain. This unpredictability underscores the inherent challenge of accurately forecasting seismic events within the SOC framework. The magnitude of an event is dependent on numerous unknowns and thus is considered unpredictable (Bak & Chen, 1991).

Here, we consider the concept of triggering as the proverbial clapping and its role in determining the characteristics of seismic events. Let's examine it on the instance of the 2023 Kahramanmaraş dual earthquake.

Case Study: The 2023 Kahramanmaraş Earthquake and Tidal Triggering

In February 2023, the Kahramanmaraş region in Turkey experienced a significant seismic event in the form of a doublet earthquake—two major earthquakes occurring in close temporal and spatial proximity.

The unusual proximity of the two separate shocks on two separate adjacent faults raises the question of whether they are separate events or simply a main shock-aftershock sequence of abnormal magnitude. Fig.1 shows the positioning of the sequence with aftershock activity along the faults. Other good examples of doublet earthquakes are the Ridgecrest event in Nevada (fig.2 and 3), and the Landers event in 1992 (fig.4).

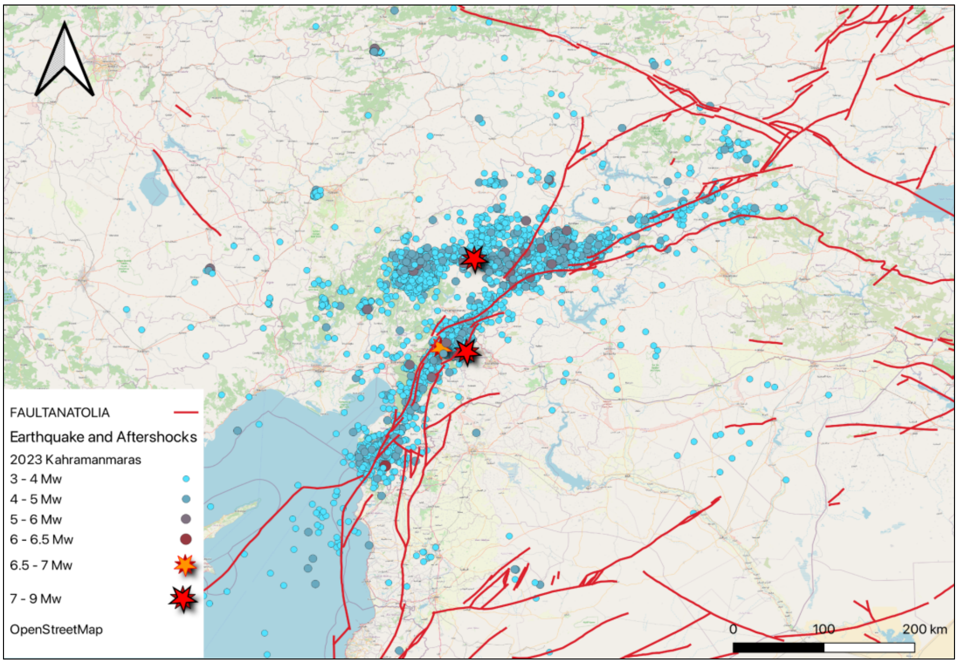

Fig.1. The spatial distribution of main shocks and aftershocks of the Kahramanmaraş earthquake doublet. Using USGS catalog, compiled with QGIS (revision, 2024).

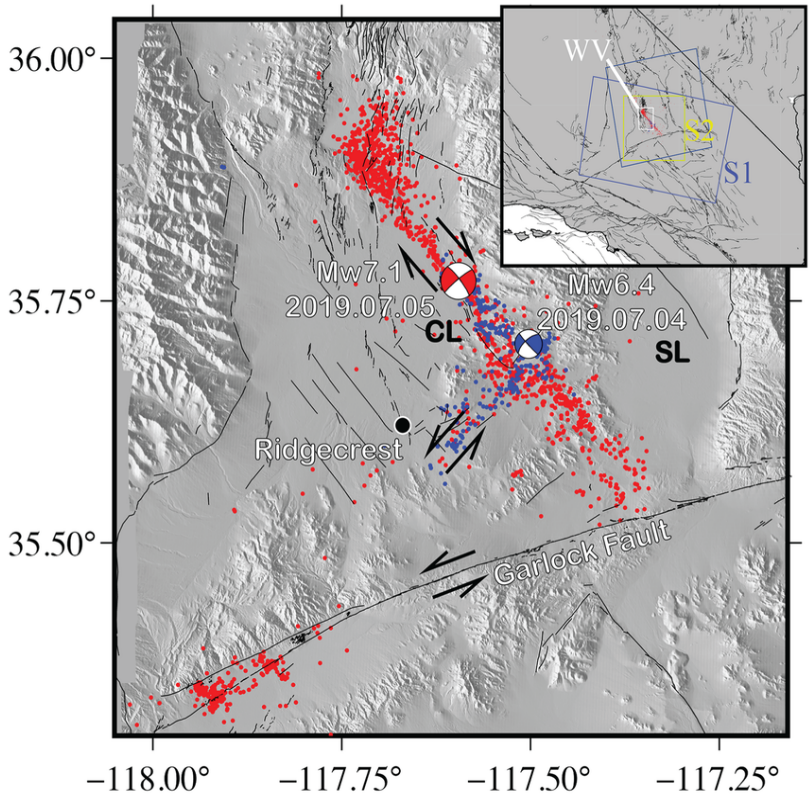

Fig.2. A map of the Ridgecrest doublet with their associated aftershocks. Colors indicate aftershocks thought to be connected with the mainshock of the same color. Each main shock has a similar moment tensor, but different focal mechanism. (Barnhart et al., 2019).

Graphic Time Series of the 2019 Ridgecrest Earthquakes as a Function of Time

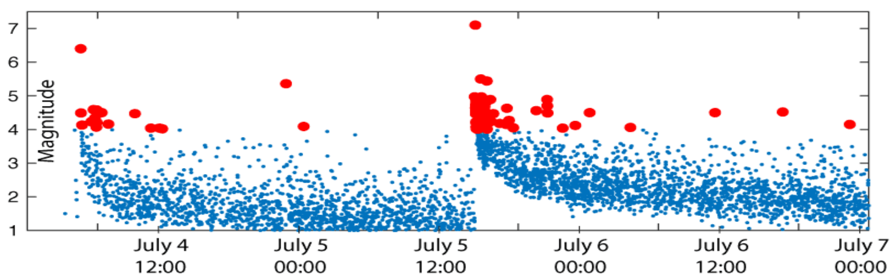

Fig.3. Time series of the Ridgecrest doublet of 2019. Red circles indicate strong shocks Mw=4+ and blue circles indicate weak earthquakes and weak aftershocks Mw=4 (Graph of 2019 Ridgecrest Earthquakes as a Function of Time | U.S. Geological Survey, n.d.). This graph shows anomalous earthquakes that appear to fall outside of the expected curve described by Omori's Law. Prompting the question of whether or not these can and should be considered triggered earthquakes or aftershock activity.

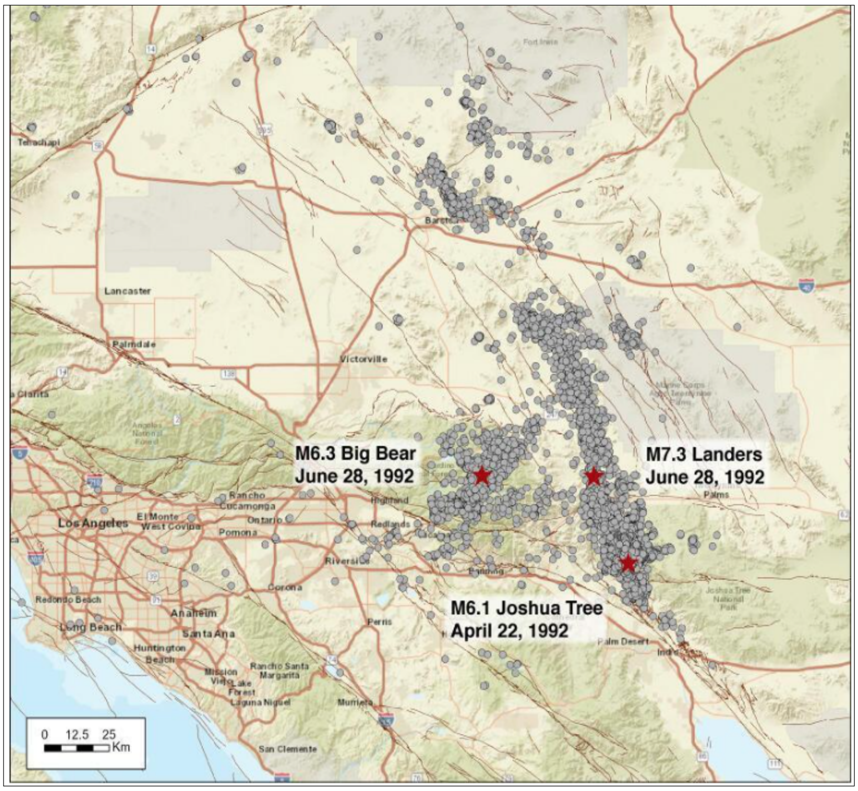

Fig.4. Landers M = 7.3 – Big Bear M-6.3 doubled event in California 1992 (Hauksson et al., 1993)

These sequences prompt the question of whether the second earthquake qualifies as an aftershock or if it should be considered a separate main event. While aftershocks are typically triggered by the stress redistribution from an initial main shock, doublets often blur these distinctions, challenging traditional classifications.

According to Omori's law, which describes the temporal decay of aftershock frequency following a main shock, aftershocks are expected to follow a predictable decline over time (Žalohar, 2018). However, in the Kahramanmaraş case and the Ridgecrest case, the large magnitude of the second event suggests it may not fit the usual aftershock decay pattern, indicating it could be another primary rupture triggered by or independent of the first. This situation underscores that while aftershocks are generally seen as triggered events, classified by the main shock as the initiating factor, doublets require a nuanced analysis to determine their specific triggering mechanisms.

The timing of the Kahramanmaraş doublet, coinciding with new and full moon phases, has spurred questions about tidal triggering (Ostrihansky & Ostřihanský, 2023). Tidal forces result from the gravitational pull of the moon and sun, exerting subtle but potentially impactful stress variations in the Earth's crust. These forces are strongest during new and full moons, as the sun and moon align, creating a combined gravitational effect. For faults on the verge of rupture, this alignment may add a minor but critical stress that tips the balance toward failure (Li & Chen, 2024b).

Some researchers argue that these tidal stresses can influence seismic activity, particularly if a fault is already critically stressed and nearing rupture. In such cases, tidal forces might act as the final trigger. However, the strength of this influence remains under debate, as discussed below.

The Debate

The idea that tidal forces could trigger significant earthquakes is controversial but not new. One viewpoint holds that while tidal forces might initiate earthquakes on critically stressed faults, they lack the strength to independently induce seismic events (Varga & Grafarend, 2018). Proponents of this view argue that tidal forces alone are insufficient and require a fault to be near its failure threshold to play any role in triggering. Others find correlations between the type of fault and earthquake and tidal cycles to find potentials for causal relations (Heaton, 1975).

Alternatively, some researchers propose that tidal forces might exert a more substantial influence, particularly when combined with other stresses, such as tectonic loading or hydrological factors (Kazarian & Mkrtchyan , 2017). They suggest that high tidal forces during lunar phases could contribute meaningfully to earthquake initiation, especially if they coincide with other favorable conditions such as fault orientation, slip, and dip (Kazarian & Mkrtchyan, 2017). On the other hand, some seismologists remain skeptical, arguing that the correlation between tidal cycles and seismic events lacks statistical robustness and may be coincidental rather than causal (*Global Earthquake Forecasting System.Pdf*, n.d.).

The Kahramanmaraş doublet, with its confirmed occurrence during lunar alignments, presents a compelling case for exploring tidal influences on seismicity. Although a direct causal link remains unproven, the observed timing invites further investigation into how celestial forces interact with tectonic stress in triggering major earthquakes. This case study underscores the need for additional research to clarify the role of tidal forces and their potential interplay with other geophysical factors.

Many more questions remain unanswered or ambiguous in order to decide if an earthquake is triggered by another earthquake or not:

- Time passed between the events
- Distance between main event
- Differences in magnitude
- Orientation of activated faults relative to the Earth’s surface
- Orientation of activated faults relative to the Moon’s and Sun’s ecliptic planes

- Differences in focal mechanisms of main and subsequent events
- Different orientational distribution of primary and secondary aftershocks

All of these questions and answers would influence the classification of each doubled event as an aftershock, triggered event, or stand-alone earthquake. The main conceptual difference between them is their level of connection to the main shock. Previously, we observed a close relationship between main and subsequent stand-alone events in the case of intraplate Ridgecrest and Landers earthquakes in Nevada and California. The Kahramanmaraş doubled event shows that this phenomenon is probably more common than previously thought.

From a different angle, the fact that this double event coincided with the full moon raises questions about whether the triggering effect was caused by a combination of various forces or by stress distribution following the initial event. Close examination of other strong earthquakes in the region should bring more answers on this matter.

Our comparable analysis shows that these 3 doubled events predominantly exhibited strike-slip faulting, where tectonic plates or crustal blocks slide past one another horizontally.

Many other instances of doublets also exist. Here is a non-comprehensive list of events that should be accounted for moving forward:

- Sumatra Earthquakes (2004 and 2005)
- New Zealand, Christchurch Earthquakes (2010 and 2011)
- El Salvador Earthquakes (2001)
- California Loma Prieta and Subsequent Events (1989)
- Papua New Guinea Earthquake Doublet (1971, 1975)
- 2010 Maule and 2014 Iquique Earthquakes (Chile)
- 2006 and 2009 Sunda Megathrust Earthquakes (Sumatra, Indonesia)
- 2009 Samoa-Tonga Earthquake Doublet (Pacific Ocean)
- 2012 Indian Ocean Earthquake Doublet.

Discussion and Conclusion

The complex interactions between variables affecting earthquake dynamics are highlighted by the 2023 Kahramanmaraş doublet. This study emphasizes the possible contributions of external triggers like tidal forces, even though tectonic stress continues to be the primary force causing seismic events. The temporal alignment of the doublet with lunar phases is intriguing, implying that tidal stresses may act as a catalyst when faults are already close to failure. However, the evidence remains inconclusive, requiring further investigation.

This case calls into question traditional seismic event classifications, such as aftershocks versus independent earthquakes, and suggests a more nuanced understanding of doublet earthquakes. Future research on the interactions between fault mechanics, tectonic loading, and external forces may help us better understand seismic triggers. Key questions—ranging from fault orientation relative to celestial planes to differences in focal mechanisms—demand rigorous exploration.

In the end, the Kahramanmaraş sequence emphasizes how complex earthquake triggering is. A deeper understanding of how celestial forces and geophysical conditions combine to influence seismicity could enhance our predictive capabilities, shedding light on whether such phenomena are coincidence or causality. Reducing the risk of earthquakes may be greatly aided by incorporating these insights into seismic forecasting models.

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ԵՐԿՐԱՇԱՐԺԻ ՀՐԱՀՐՄԱՆ ՄԵԽԱՆԻԶՄՆԵՐԻ ՈՒՍՈՒՄՆԱՍԻՐՈՒԹՅՈՒՆ. ՊԱՏԿԵՐԱՑՈՒՄՆԵՐ 2023 ԹՎԱԿԱՆԻ ՔԱՀՐԱՄԱՆՄԱՐԱՇԻ ԵՐԿՐԱՇԱՐԺԻՑ

Ղազարյան Հայկ

Ամփոփում

Այս հոդվածը ուսումնասիրում է երկրաշարժերի առաջացման մեխանիզմները՝ հիմնվելով հաստատված սեյսմոլոգիական տեսությունների վրա՝ որպես դեպքի ուսումնասիրություն կիրառելով 2023 թվականի Քահրամանմարաշի երկրաշարժը: Քննարկվում է հողի լարվածության կուտակումը, ինքնակազմակերպված կրիտիկականության տեսությունը (Self Organised Critically) և մակընթացային ուժերը որպես հնարավոր առաջացնող գործոններ: Վերջապես, բարձրացվում են հարցեր լուսնային և արեգակնային փոխազդեցությունների դերի մասին սեյսմիկ ակտիվության մեջ, նշելով ապագա հետազոտությունների հնարավոր ուղղությունները:

ИЗУЧЕНИЕ МЕХАНИЗМОВ ВОЗНИКНОВЕНИЯ ЗЕМЛЕТРЯСЕНИЙ: ВЫВОДЫ ИЗ ЗЕМЛЕТРЯСЕНИЯ В КАХРАМАНМАРАШЕ 2023 ГОДА

Казарян Айк

Резюме

В данной статье исследуются механизмы триггеров землетрясений, опираясь на признанные сейсмологические теории, с использованием землетрясения в Кахраманмараше 2023 года в качестве примера. Обсуждаются накопление напряжения в разломах, теория самоорганизованной критичности (Self Organised Critically) и приливные силы как возможные триггеры. В заключение поднимаются вопросы о роли лунных и солнечных взаимодействий в сейсмической активности, указывая на потенциальные направления для будущих исследований.