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Large, distant earthquakes can trigger microseismicity in Costa Rica

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For the first time in Costa Rica, scientists document that earthquakes can communicate with faults, even at a distance of more than a thousand kilometers.

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When large earthquakes strike, smaller magnitude events called aftershocks occur — but why? Aftershocks are a response to an increase in static stresses induced by sudden slip during a mainshock. These smaller events generally illuminate the rupture area of the main event, and thus tend to occur within a range of about one to two fault lengths. For instance, if the rupture length is 100 kilometers, then aftershocks most often occur within a radius of 100 to 200 kilometers. Such aftershock behavior has been very well characterized by

Although the underlying physics that governs dynamic triggering of seismicity is not well understood, results from numerical simulations and laboratory experiments have highlighted several processes (e.g., permeability enhancement, granular flow, viscous creep, rate and state friction and others) as plausible mechanisms driving the triggering process. In one proposed mechanism, fault heterogeneities (also called asperities) may focus transient energy from surface waves, thus inducing local stress perturbations (Langer et al., 2015). In other words, as energy from surface waves passes by a bump on a fault, the local stress can be changed.

Scientist have observed and documented dynamic triggering in multiple regions all over the world, from Southern California (e.g., Aiken and Peng, 2014; Fan et al., 2020) to Northern China (Peng et al., 2010), and even Antarctica (Peng et al., 2014). Overall, data show that surface waves are responsible for triggering seismicity at great distances. Among the surface waves, Rayleigh waves are more efficient at triggering than Love waves. Regions experiencing extension, like geothermal fields, are more prone to dynamic triggering than regions experiencing compression, like subduction zones (Brodsky and van der Elst, 2014).

During the passing of surface waves, locally triggered earthquakes generally occur instantly or within a few minutes after their arrival. The subsequent cascade of microseismicity (small magnitude seismicity) may last for hours or even days. In Costa Rica, the dynamic triggering of earthquakes by distant events has not been documented — until now.

...ck events with magnitudes greater than or equal to 7.5 (Figure 1). We ...023 American Geophysical Union Annual Meeting ...Francisco, California.

In our investigation, we evaluated the seismic records of all stations operated by the Volcanological and Seismological Observatory of Costa Rica at Universidad Nacional (OVSICORI-UNA) between 2010 (when the digital era of the observatory began) and 2023.

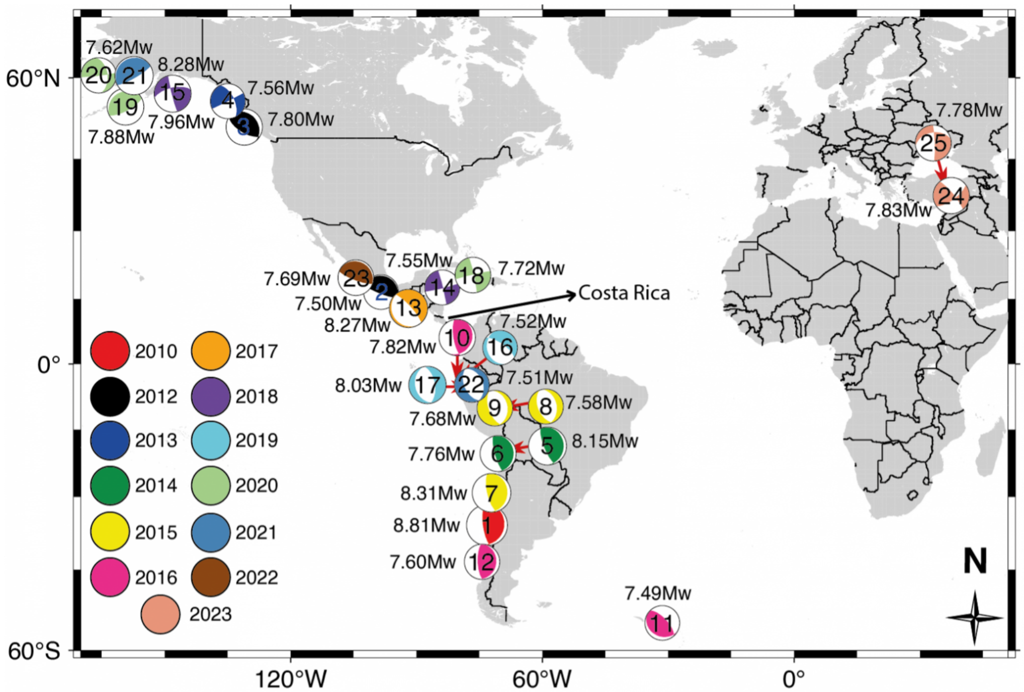

Figure 1. Spatial distribution of mainshocks with magnitude greater than or equal to 7.5 examined for dynamic triggering in Costa Rica. Each event is represented by its focal mechanism (also called a beachball diagram in reference to the average representation of the fault's geometry). The events are also color coded by year of occurrence. Credit: Hajaji and Chaves, 2024, CC BY-NC-ND 4.0

Among the 25 analyzed events, we noticed an increase in the local microseismicity following events 14 and 24. Event 14 corresponds to a

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...ismicity. Therefore, the question of why larger and closer teleseismic ...ity in Costa Rica is an avenue for future research.

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The Honduras event triggered microseismicity that was focused along the Tenorio Volcano of northern Costa Rica, generating events with magnitudes between 0 and 3.0. The Türkiye-Syria earthquake last year resulted in microseismicity with magnitudes between 0 and 4.4 along the subduction zone in southern Costa Rica immediately after the event (Figure 2).

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We quantified the sudden increase in local earthquakes following three approaches: 1) visual inspection in the time and frequency domain, 2) computing the statistic, as done in previous studies (e.g., Fan et al., 2020) and 3) evaluating the probabilistic power spectral densities, or PPSDs (MacNamara and Bulland, 2004) for all stations available in Costa Rica hours before and after the passing of the regional and teleseismic surface waves.

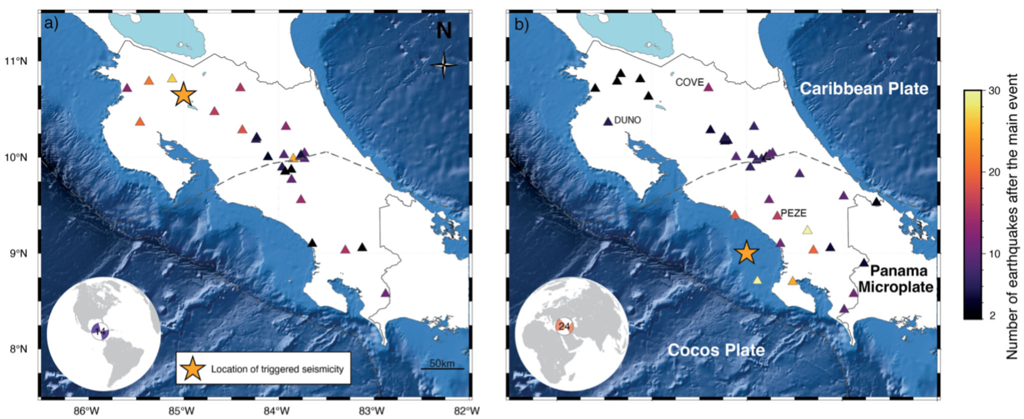


Figure 2. Seismicity in Costa Rica dynamically triggered by the passing of surface waves from a) the Honduras earthquake and b) the Türkiye-Syria earthquake, respectively. The star in each panel shows the location of triggered seismicity. The triangles represent the seismic stations used in the study. The triangle color coding represents the number of triggered earthquakes detected at each station after the arrival of the surface (Rayleigh) waves and the following two-hour period. Seismic stations DUNO, PEZE and COVE are labeled. Credit: Hajaji and Chaves, 2024 CC BY-NC-ND 4.0

These signals contrast with teleseismic events' long period, high amplitude ... uency signals produced by large mainshocks rapidly attenuate, or fade away, and cannot be measured hundreds to thousands of kilometers from the source. Earth essentially works as a low pass filt...

Thus, for all events analyzed in this study (Figure 1), we filtered the signals. We kept only high frequencies generated by local seismicity, which let us look for the presence of nearby earthquakes that correlate temporally with the arrival times of the surface waves. Figure 3 shows an example of this analysis for the Türkiye-Syria earthquake. We focused on the vertical components recorded by three different stations (COVE, PEZE and DUNO shown in Figure 2). The triggering is most evident in the frequency domain, as highlighted by the "sparks" or bright vertical lines in panels c, g and k (Figure 3).

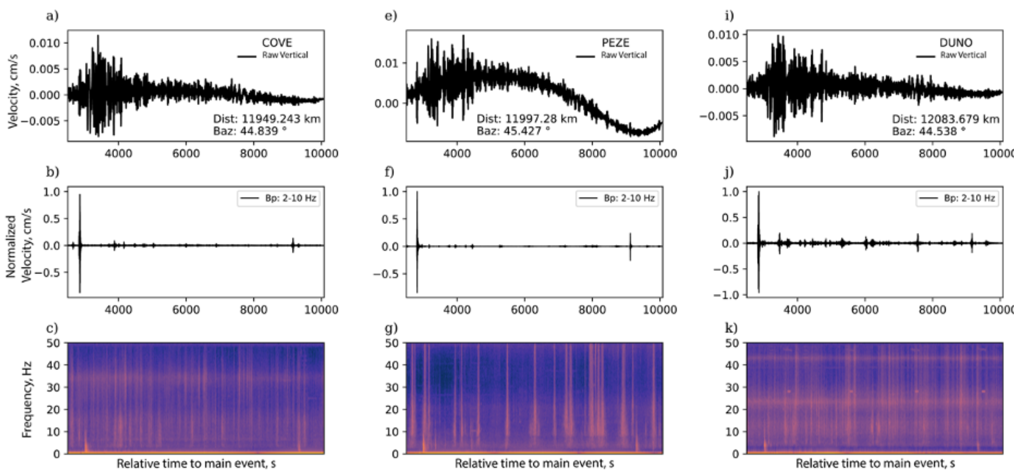
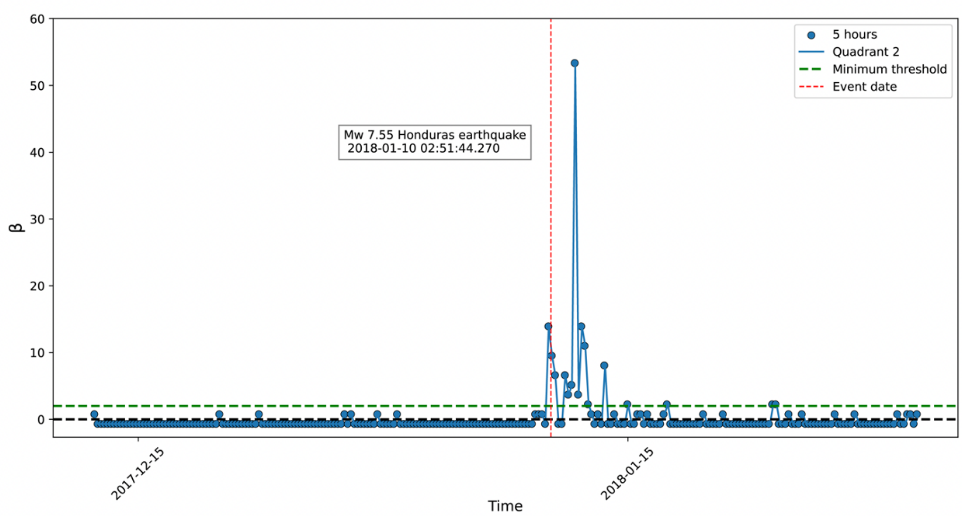


Figure 3. Seismic signals of the Feb. 6, 2023, magnitude 7.8 Türkiye-Syria earthquake were recorded by stations in Costa Rica. The three columns correspond with three different stations: COVE, PEZE and DUNO, respectively. The top row shows vertical component of the seismic records for each station. We show the vertical component for two main reasons. First, there are amplitude problems in the horizontal components for some stations, and so we decided to homogenize by only showing the vertical component. Second, the P-wave from local microearthquakes is clearer in the vertical component. Panels b, f and j show the same vertical component that has been filtered between 2 and 10 Hz. Panels c, g and k show the spectrogram as a function of time resulting from the Fourier transform of the original seismogram. The bright orange

or equal to two is typically considered an indicator of a seismicity increase at the 95% significance level (e.g., Aiken et al., 2018).

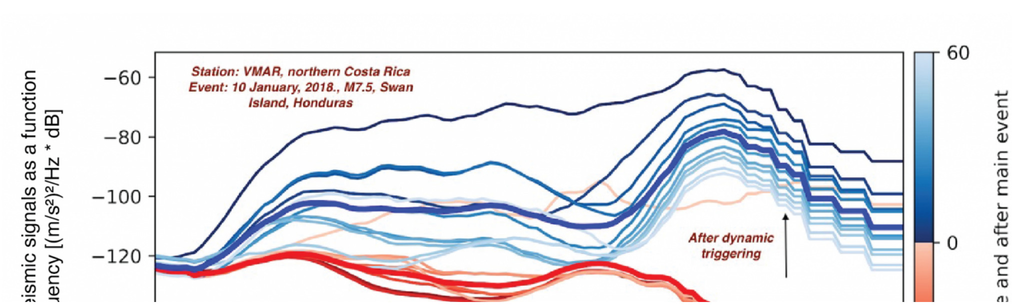
By computing β, we made two important observations. First, β exceeds values of 25 and 50, correlated temporally with the occurrence of the Honduras earthquake and the Türkiye-Syria earthquake, respectively (Figure 4). This lends further support that Costa Rican microseismicity was dynamically triggered by these large magnitude events located at regional and teleseismic distances. Second, a β of two is a very low value for a region with a high background seismicity rate, like Costa Rica. This is particularly evident in Figure 4b (green dashed line at β=2).



Probabilistic Power Spectral Density

The Probabilistic Power Spectral Density (PPSD) is a concept used in signal processing, seismology, and other fields. It extends the traditional Power Spectral Density (PSD) analysis by incorporating the probabilistic distribution of spectral amplitudes. The PPSD shows how the power of a signal is distributed over different frequencies and offers a more detailed view by accounting for the variability of the signal's power over time.

We used this concept of PPSD to analyze the seismic records from all OVSICORI's seismic stations that were available hours before and after the occurrence of the 2018 magnitude 7.5 Honduras earthquake and the 2023 magnitude 7.8 Türkiye earthquake. Specifically, during the 60 minutes before the P-wave arrival (red curves in Figure 5), we computed PPSD every 900 seconds. We followed the same procedure during the 60 minutes after the arrival of surface waves (blue curves in Figure 5).



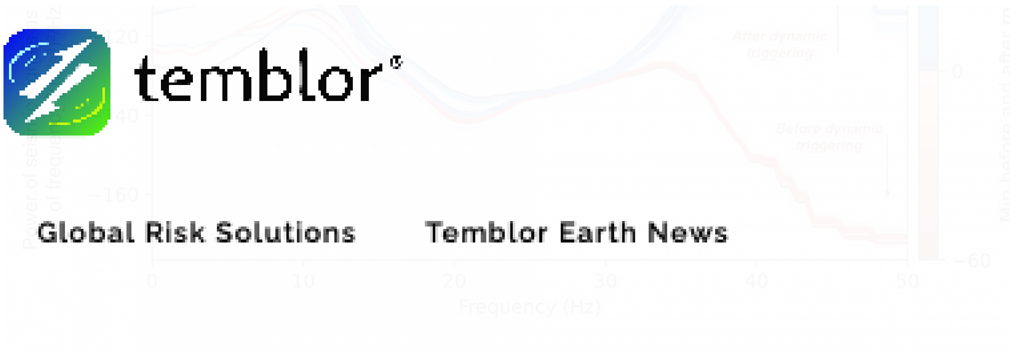


Figure 5: PPSD analysis carried out for a) station VMAR in northern Costa Rica for the Honduras earthquake in 2018 and b) station PEZE in southern Costa Rica for the Türkiye-Syria earthquake in 2023. For both events, we computed PPSDs every 900 seconds during the 60 minutes before the P-wave arrival (red curves) and every 900 seconds during the 60 minutes after the arrival of the surface waves (blue curves). Notice that dark blue lines indicate PPSDs computed immediately after the arrival time of the surface waves, whereas light blue represents PPSD calculations performed for data collected after more time had elapsed. The reverse is shown for the red curves, where darker red indicates one hour before the P-wave arrivals and lighter red indicates proximity to the P-wave arrival times. Credit: Hajaji and Chaves, 2024, CC BY-NC-ND 4.0

What can we learn?

For both events analyzed here, the implications are different. In the case of the 2018 Honduras earthquake, dynamically triggered seismicity occurred in the Tenorio Volcano and surrounding volcanic field. The sequence of events lasted several days before dying out.

However, an alternative scenario could have occurred: the cascade of events could have led to a change in the internal dynamics of the volcano, releasing pressure and culminating in an eruption that could have affected lives and public infrastructure. For instance, the geothermal field next to the volcano produces energy for the country. In Costa Rica, where the 99% of the energy produced is green, this scenario would be a game changer if energy production for the country were reduced. This would affect public and private infrastructure, and consequently, the growing economy.

For the second example, the 2023 Türkiye-Syria earthquake triggered this region, subducting sediments could be lubricating the fault, introducing different material properties and rheologies that might be susceptible to minor strain changes compared to the central and northern subduction zones (DeShon et al., 2006; Bangs et al., 2016; Edwards et al., 2018).

Of concern, in this region, the Osa Peninsula last experienced a magnitude 7.4 earthquake in 1983, which produced significant damage (Tajima and Kikuchi, 1995). With an estimated recurrence time of about 40 years, an event of similar magnitude may be impending. Recent seismological observations have shown how big ruptures like the 2011 magnitude 9.1, Tōhoku, Japan earthquake or the 2014 magnitude 8.2 Iqueque, Chile earthquake were preceded by distinct spatial and temporal patterns of microseismicity (Lay et al., 2014). However, we do not yet understand if a cascade of dynamically triggered microseismicity can also lead to a larger earthquake rupture in a critically stressed region. But it is a concept that should be considered, both in risk assessment and in future research.

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