3D Analysis of Scattering Attenuation Before and After the February 6, 2023, Earthquake Doublet in Türkiye

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The February 6, 2023, Earthquake Doublet in Türkiye

On February 6th, 2023, an earthquake of Mw 7.8, known as the Kahramanmaraş earthquake, struck between southern Turkey and northern Syria. The strike-slip event ruptured multiple southwestern segments of the East Anatolian Fault System (EAFS). It was followed by a severe series of aftershocks, as the Mw 7.6 Elbistan earthquake, occurred just nine hours from the Kahramanmaraş event, rupturing an east-west trending fault near the main EAFS. The Mw 6.4 Antakya aftershock occurred along a bifurcation of the EAFS.

Aim of the study

Seismic attenuation is a powerful tool to look at variations in the crustal properties, being strongly controlled by structural irregularity and heterogeneities: fractures, temperature, and pressure variations can cause an increase or a decrease in the amplitude of seismic wave amplitude**.** Hence, seismic attenuation imaging can provide us with information about the areas with changes in the crust before and after the February 6th 2023, earthquakes.

The **overall attenuation** is given by:

$$Q_{tot}^{-1} = Q_s^{-1} + Q_i^{-1}$$

where Q_i^{-1} and Q_s^{-1} are the quality factors due to the **scattering loss** and the **absorption.**

Scattering Imaging: Peak Delay Method

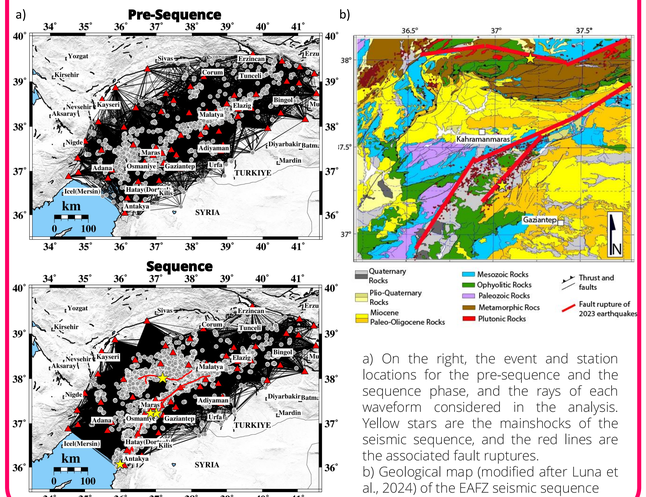
Absorption Imaging: Coda Attenuation

Total Attenuation: Coda Normalization

Two datasets have been used:

- a pre-sequence phase, January 2020 - February 5, 2023 (~48000 waveforms)
- a sequence phase, 6 February 2023 – 31 May 2023 (~238000 waveforms)

Fault plane solutions for the main events indicated that both the Mw7.8 and Mw7.5 earthquakes are associated with left-lateral strike-slip faults.



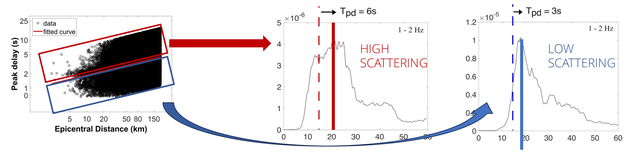
a) On the right, the event and station locations for the pre-sequence and the sequence phase, and the rays of each waveform considered in the analysis. Yellow stars are the mainshocks of the seismic sequence, and the red lines are the associated fault ruptures.
b) Geological map (modified after Luna et al., 2024) of the EAFZ seismic sequence

Scattering imaging – Peak Delay

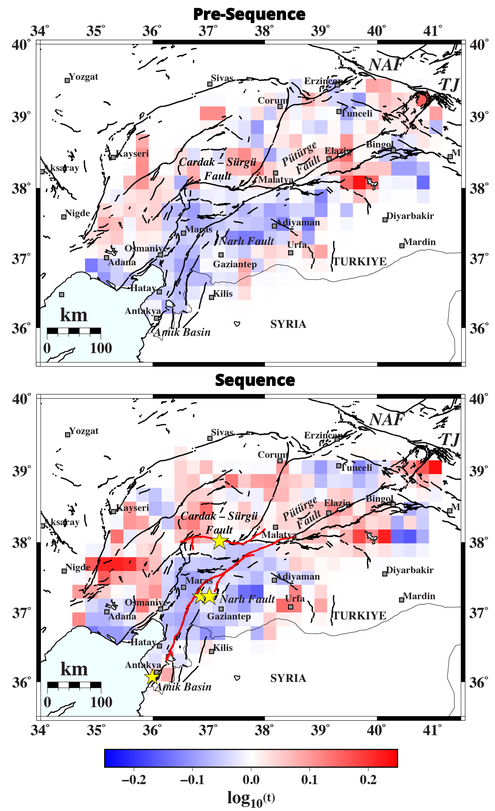
Peak Delay is defined as the time lag between the S-wave arrival and the maximum amplitude of the arrival. Energy loss and amplitude attenuation are due to the presence of heterogeneities (e.g., faults)

The difference between the peak-delay time of the i-th waveform at a certain hypocentral distance and the fitted straight line gives the amount of scattering accumulated along the raypath:

$$\Delta log_{10} t^{PD}(f) = log_{10} t_i^{PD}(f) - log_{10} t^{PD}(f)$$



To map the peak delay, we performed a weighted average at each block (block size: 20km x 20km) via the regionalization approach. The cells crossed by more than 5 rays are displayed.



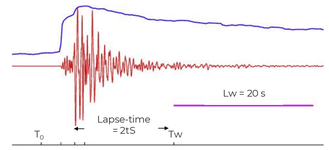
- Scattering anomalies mark the main tectonic structures and geological barriers
- There is a clear impact between the north (high scattering - Quaternary Sedimentary Rocks) and south (low scattering – Ophyolitic Rocks) sectors of the EAFS
- The high/low scattering anomaly stops at Pütürge Fault (center of the map)
- Strong contrast in scattering between the North Anatolian Faults (NAF) – around the Triple Junction (TJ) and EAF due to main lithological differences
- The Cardak – Sürgü Fault (center of the map) recorded a change from low to high scattering between the two phases

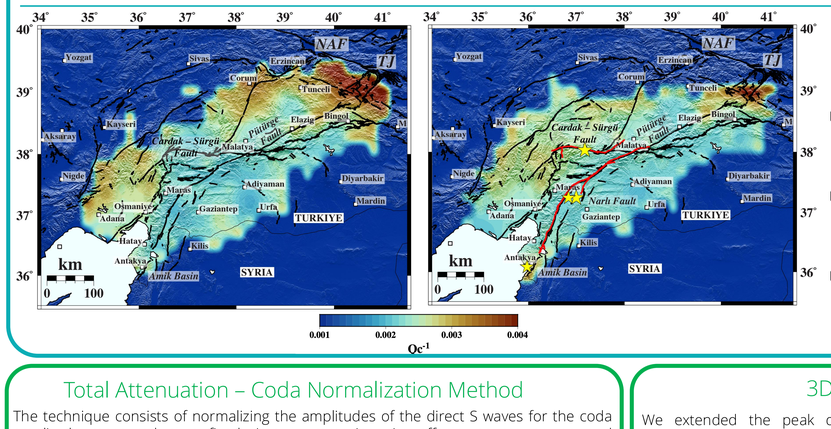
Seismic attenuation imaging – Coda Waves Attenuation

Coda waves are after-body waves (S arrival) and contain information about heterogeneities and fluids encountered from the seismic waves during their path in the earth's crust. The parameter to quantify the shape of the decay curve is the coda attenuation Qc^{-1}:

$$E(t,f) = S(f) t^{-1.5} exp - \left(\frac{2\pi f t}{Q_c}\right)$$

where S(f) includes both source and site terms, and Qc^{-1} is the frequency-dependent inverse coda quality factor. Taking the logarithm of E(t,f), we can measure Qc using a straight-line fitting.



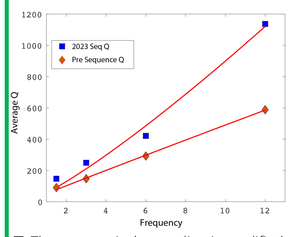


To map the Qc^{-1}, we performed a weighted average at each block (block size: 20km x 20km) via a regionalization approach. The cells crossed by more than 5 rays are displayed.

- High and low absorption anomalies generally correspond to the main high and low scattering patterns.
- Regions of high absorption are primarily located near the Triple Junction, particularly in the vicinity of Bingöl and Tunceli.
- The Amik Basin exhibits consistently high absorption, both prior to and during the seismic sequence.

Total Attenuation – Coda Normalization Method

The technique consists of normalizing the amplitudes of the direct S waves for the coda amplitude measured at a fixed time t_c, removing site effects, source power, and instrumental response.



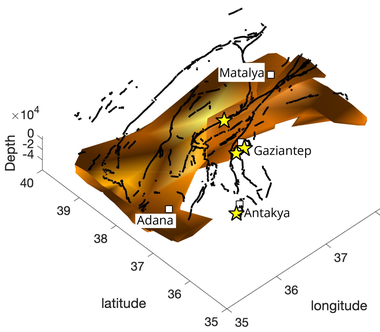
Parameters	Values
Geometrical spreading g(r)	$g(r) = \begin{cases} R^{-1.0} & if\ R \le 30 \\ R^{-0.9} & if\ 30 < R \le 50 \\ R^{-0.8} & if\ 50 < R \le 70 \\ R^{-0.7} & if\ 70 < R \le 90 \\ R^{-0.6} & if\ 90 < R \le 100 \\ R^{-0.5} & if\ R > 100 \end{cases}$
Coda Wave Lapse Time	2 tS
Body Window length	5s
Coda Window length	10s

- The geometrical spreading is modified after Wang et al. (2024)
- The values of Q(f) are considerably lower than the ones of Wang et al. (2024) and Izgi et al. (2024)
- This difference can be related to differences in the size of the dataset and the target area

	$Q(f) = Q_0 f^n$
Pre-Seq	$52\ f^{0.97}$
2023 Seq	$56\ f^{1.2}$
Wang et al. 2024	$103\ f^{0.71}$
Izgi et al. 2024	$75\ f^{0.71}$

3D Preliminary Results

We extended the peak delay analysis in 3D. Here, the ray path for the regionalization is defined using the velocity model from Acarel et al. (2019).



Here, we plotted only the peak delay > 0.02. The preliminary results of the pre-sequence phase confirm the results of the 2D, with a clear division between the north and south sectors of the EAF.

Main results and Conclusions

- Peak delay demonstrates a strong correlation with geological domains and fault networks (Gabrielli et al., 2022, 2023), while high absorption anomalies are generally following the placement of high-scattering ones
- While the Narlı fault, where the Mw7.8 originated, does not witness changes in attenuation, the Cardak – Sürgü Fault, where the Mw7.5 occurred, increased in scattering and absorption, probably due to an increment in fracturing during this phase of the sequence
- High scattering stops at the Pütürge Fault in both sequences, suggesting that this fault has not experienced a complete rupture, as also indicated in other studies (e.g., Cheloni and Akinci, 2020; Akinci et al., 2024).
- North-East zone (around Bingol – Tunceli, cities close to the Triple Junction) is strongly influenced by lithological differences (metamorphic massif in contrast with volcanic mio-pliocenic rocks) as seen both in scattering and absorption imaging.
- Further analyses on the Total Attenuation and the associated geometrical spreading will be done; a detailed study of the scattering for the EAF in the Gaziantep area will be performed, to look at possible variation using a more detailed grid.

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