

Reply Anonymous Referee #1

Thank you for passing on the review of our manuscript on the Elazig-Sivrice earthquake and comments. We have taken great care to address all of the concerns. The detailed one-by-one response to the comments is included below (the review itself is in black, and our responses are in green).

The study presents a detailed analysis and interpretation of the 2020 January 24 Mw6.7 The Elazig-Sivrice earthquake. The study presents a full geodetic and seismo-logical analysis of the source rupture and the peripheral seismicity including foreshocks and aftershocks.

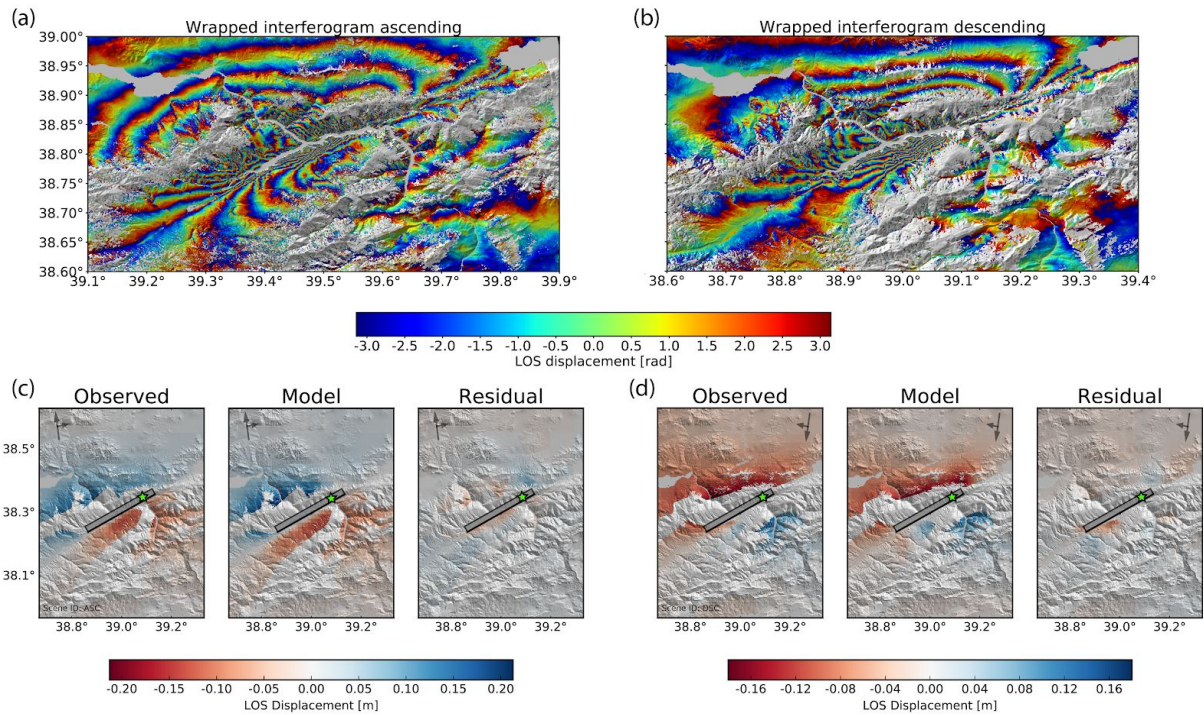
Coulomb stress and seismicity pattern – Interestingly, the south part of the fault has no aftershocks. This seismic quiescence is puzzling even more due to the prediction of the Coulomb stress analysis and the symmetry in the InSar data from both sides of the fault supporting that surface deformation took place at the south. Do you have explanation for that behavior?

The observation that the location of almost all aftershocks is north of the fault trace, is in good agreement with the focal mechanism solution and finite-fault modeling that point to an NNW dip of the fault plane. In a surface projection, an NNW fault dip offsets the rupture area at depth to the NNW. We show the centroid depth distributions of the aftershocks in Fig. 3, C1, C2, and C3.

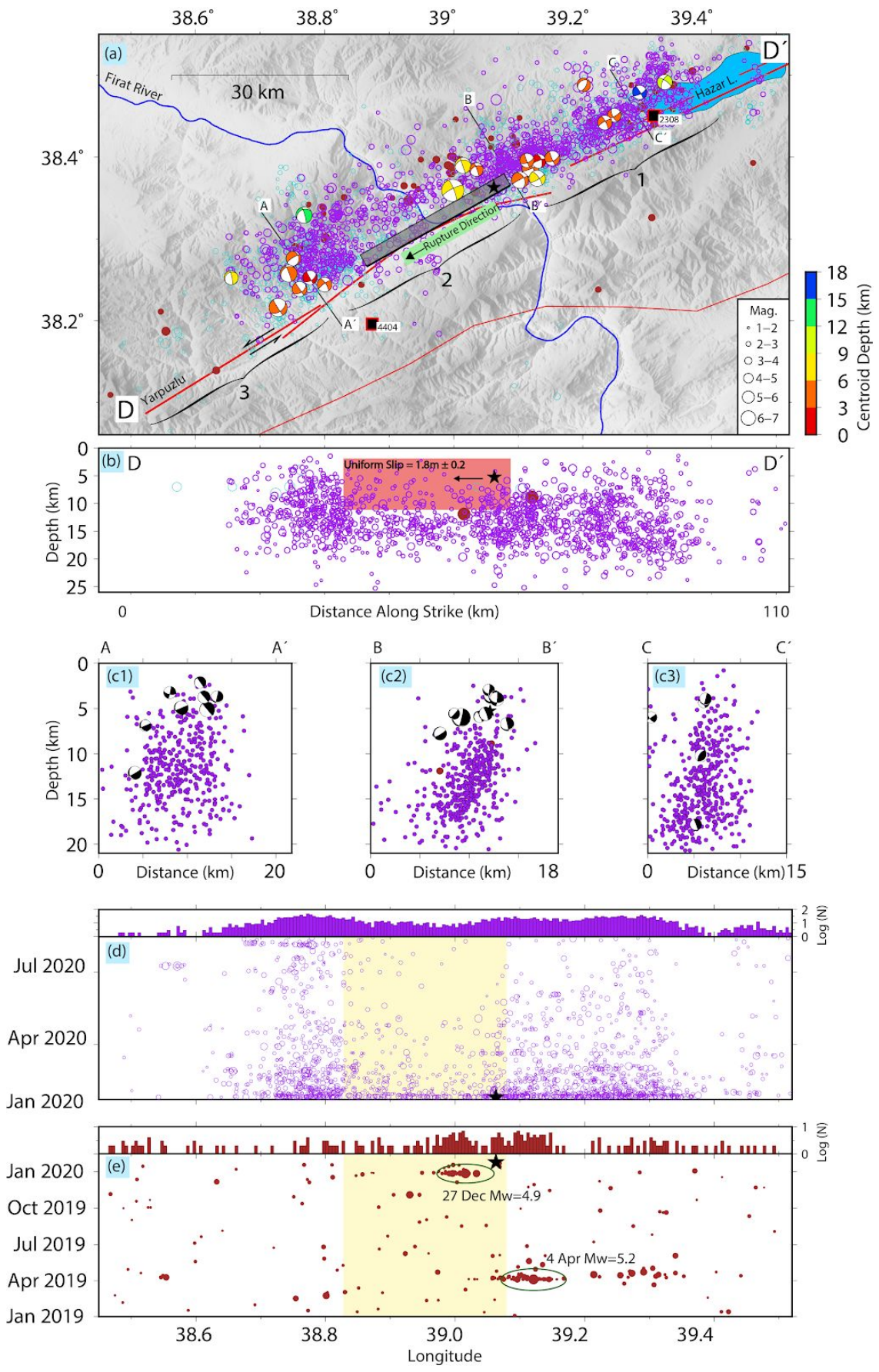
The surface displacement measured by InSAR shows surface deformation on both sides of the fault, but at depth, the deformation will also be largest close to the rupture plane and again would show an offset to the NNW in a surface projection.

We have also updated the former figure 3 (Figure 5 in the new version) and figure 2 (Figure 3 in the new version) to show this result more clearly.

We also have added new sentences about the limitation of Coulomb stress modelling.



Former Fig. 2, panel c (Figure 3 in the new version): InSAR surface displacement maps covering the epicentral area. a) Masked and wrapped interferograms spanning the coseismic of the Elazığ-Sivrice earthquake: a) Ascending 21.-27. January, b) Descending 22. - 28. January). c and d) Ascending and descending subsampled surface displacements as observed, modeled and with the data residual. The grey filled box in c and d shows the surface projection of the modeled source, with the thick-lined edge marking the upper fault edge. The green star shows the epicenter of the Elazığ-Sivrice earthquake.



Former Fig. 3 (Fig. 5 In the new version). Spatiotemporal evolution of the 2020 Mw 6.8 Elazığ-Sivrice earthquake sequence (black stars always denote the mainshock, purple and cyan circles show aftershocks and filled brown circles show foreshocks). a) Spatial distribution of seismicity at the Pütürge segment, located between the Hazar Lake and the Yarpuzlu bend, showing the path of Fırat River (blue line). Red lines show main faults (after Basili et al., 2013). Circles represent the epicentral locations of fore- and aftershocks (purple circles show 18 days of relocated aftershocks from Melgar et al., 2020 and cyan circles show AFAD catalog MI 1+ and azimuthal gap less than 120°, last accessed 15 August 2020). The grey filled box shows the surface projection of the modeled source, with the thick-lined edge marking the upper fault edge. Focal mechanisms of the mainshock, 2 foreshocks and 19 aftershocks (focal spheres, color scale according to centroid depths) shown based on our moment tensor inversion. Black squares denote locations of the closest strong motion stations with their code. b) Depth cross-section along the profile DD' of relocated aftershocks (after Melgar et al., 2020) and events larger than MI 4 (cyan) from AFAD catalog. The light pink rectangle shows the main rupture area and the dark vector shows the direction of the main rupture propagation, as resolved in this study. (c1-3) Depth cross-sections along profiles AA', BB' and CC', respectively (dip and width of all cross-sections are 90° and 20 km, respectively), showing the focal mechanisms of largest events (cross section projection). d) Temporal evolution of the aftershocks (MI 1+ and azimuthal gap < 120°) versus longitude; the upper histogram shows the longitude versus the number of events N. The light yellow patch covers the longitudes ruptured in the Elazığ-Sivrice based on our finite-source modelling. e) Temporal evolution of the foreshocks (same style as panel d).

Specific comments:

1- L. 24: Please use quantitative rather than “small” for the described foreshock cluster:

Thank you for this suggestion. We rephrased the abstract and manuscript, being quantitative. There are indeed two foreshock clusters, with maximum magnitudes of 4 April Mw 5.2 and 27 December Mw 4.9.

We have added new sentences in line 4 of the abstract and we removed “small” in line 24.

“...Two foreshocks with $M_w \geq 4.9$ and clusters of seismicity ($M_I \leq 3$) located in the proximity of the main rupture’s hypocenter...”

2- L. 29: Please explain how the statement for shallow locking depth corresponds with the seismicity range presented in Fig. 1 (0 – 30 km).

We believe that the instrumental and historical catalogs (Fig. 1) have a poor depth accuracy to discuss the shallow locking hypothesis by Cavalié and Jónsson (2014). Our statement is only based on the analysis of the Elazığ-Sivrice earthquake and supports this hypothesis. We have added the following sentences in the discussion section:

“Estimated locations of historical and instrumentally recorded seismicity in the period 1900-2019, before the Elazığ-Sivrice earthquake sequence, show that they cover a large depth range from 0 to 30 km with no apparent pattern (Fig. 1). It seems changes of fault coupling with depth have a limited effect on the seismicity pattern. However the accuracy of the hypocenter depths is limited, particularly for the early times in this period, and maybe these locations lack the required depth resolution.”

3- L. 118: Please explain the usage of strong motion sensors to capture the low-frequency signal:

The low-frequency signals are used for the moment tensor inversion using regional and teleseismic broadband data. The resolved source geometry is then used to constrain the finite fault modeling. Here, we use higher frequencies (0.08-0.20 Hz) from strong motion sensors in the near field, to capture details of the rupture process. InSAR is important for finite-fault inversion to fix the lower-frequency image of the source and provides spatial resolution and constrains the fault position. Seismic data, especially near-field strong motion data is essential to resolve the temporal change in detail and provide better resolution (Anderson, 2003; Ide, 2007).

We have added the following sentences with references in the mainshock and method sections to clarify this issue and also the criteria that we selected the modeled stations:

In the mainshock section:

"...Considering the signal-to-noise ratio, timing error, data availability, and azimuthal gap, we have selected six recordings of strong-motion stations of the AFAD network to be included in our optimization (Fig. 2). To capture the rupture process in space and time (Anderson, 2003; Ide, 2007), we use bandpass-filtered velocity records between 0.08 - 0.2 Hz "

and in the method section:

"Using combinations of different types of data-sets together helps to control different parts of the fault model (Ide, 2007). The InSAR data set together with the strong motions data allow to constrain the average slip, which can be less well constrained by either seismic or InSAR data alone (Ide, 2007)"

Anderson, J. G. (2003). Strong-motion seismology. *International Geophysics Series*, 81(B), 937–966.

Ide, S., 2007. Slip inversion. In: Kanamori, H. (Ed.), *Earthquake Seismology. In: Treatise on Geophysics, vol.4*. Elsevier, Amsterdam, the Netherlands. ISBN978-0-444-51932-0, pp.193–224.

4- L.131: Did the earthquake rupture to the surface? This is not clear.

Thanks for pointing out the lack of clarity. The mainshock did not reach the surface with significant rupture. We see some disrupted fringes in the interferograms but these motions are very small compared to the average fault slip. Also, the modeled uppermost edge of the rupture at ~2.5 km depth, explains the lack of surface rupture. Now we have added new clear sentences as following in the mainshock section and with new references suggested by reviewer #2.

Furthermore, we have added the new sentence which mentioned the recently published study and their results about the absence of clear surface rupture (Pousse-Beltran et al. (2020)).

“... no significant surface rupture is reported by the General Directorate of Mineral Research and Explorations of Turkey (MTA, 2020) nor apparent in optical satellite imagery (Pousse-Beltran et al., 2020). There is a pronounced slip deficit above the mainshock rupture, leading to, if any, very weak fault motion in some parts of the fault’s surface trace (Pousse-Beltran et al., 2020).”

MTA. (2020). Preliminary field and evaluation report on 24 January 2020 Sivrice (Elazig) Mw 6.8 Earthquake, General Directorate of Mineral Research and Explorations of Turkey (MTA), Ministry of Energy and Natural Resources, Ankara, 48 pages (<https://www.mta.gov.tr/>).

L., Pousse-Beltran, Nissen, E., Bergman, E. A., Cambaz, M. D., Gaudreau, É., Karasözen, E., & Tan, F. (2020). The 2020 M_w 6.8 Elazığ (Turkey) earthquake reveals rupture behavior of the East Anatolian Fault. *Geophysical Research Letters*, 47, e2020GL088136. <https://doi.org/10.1029/2020GL088136>

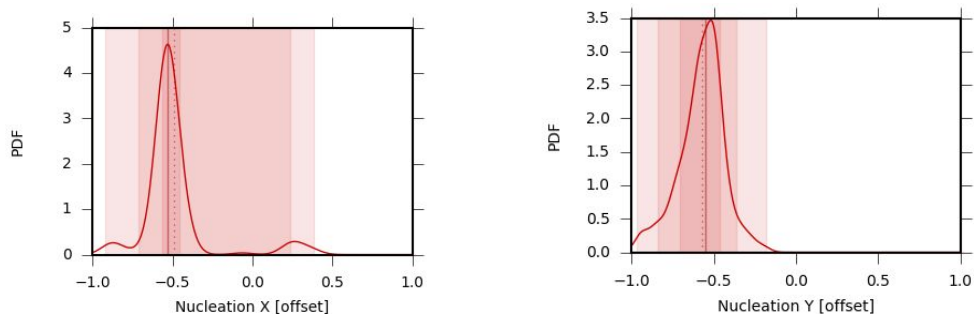
5- L. 206: It is not clear to me how did you conclude that the mainshock nucleated from the topper part of the fault plane from Fig. 3b. Please elaborate.

Thanks for pointing out the lack of clarity. In our finite fault modeling, we consider the fault as a rectangular plane. We optimized for the nucleation point, with variable locations on the faults along-strike and in depth. The finite fault inversion results show both that the rupture nucleated (1) at shallow depth and (2) ENE of the main ruptured area.

We apologize for the missing information on the resolution of the nucleation point and included a plot in Figure S13 to show the distribution of the hypocentral parameters. we provide the detailed output reports for all inversion runs in a separate online report at:

<https://data.pyrocko.org/scratch/grond-reports/2020-elazig-sivrice/#/>

We also clarify in former figure 3 (Fig.5 in the new version). They clearly show a shallow hypocenter of about 5 km, which is in the upper part of the fault plane with the confidence of 1 km (The uppermost edge of the fault plane is modeled at ~2.5 km depth and the width of the fault plane is ~9 km).



Missing information in the former figure S 13.

We have added the following sentences in the methodology and discussion sections to clarify these criteria. We also improve the former fig 3 (Figure 5 in the new version).

In the methodology section:

“In the finite-fault modelling, we assume a planar rectangular rupture area with uniform slip, similar to the model by Haskell (1964). It is defined by 14 parameters: centroid time, three coordinates for position of the rupture plane, width, length, the two angles strike and dip, two coordinates for the nucleation point on the plane, slip rake angle, slip amount, rupture velocity, and rise time.”

In the discussion section:

“Our results show a shallow nucleation point at about 5 km depth, which is in the upper part of the fault plane (Fig. 5), formally with a very small confidence interval of 1 km. Mai et al. (2005) showed that most strike-slip earthquakes nucleate near the bottom of the rupture plane. The Elazığ-Sivrice earthquake could be contrasting this tendency, but it is also possible that this result is an artifact of our inversion. From our experience with the nucleation point parameter from other examples, we think that a depth bias is likely due to oversimplification of the earth and source models.”

6- Fig. S5 – This is a very nice presentation of a unilateral rupture. I think it should be included in the main text. Please also consider presenting the seismic traces with azimuth to support the apparent duration measurement.

Thanks for the positive feedback. We agree to include this figure in the main text and we have added a new plot to also include the seismic traces.

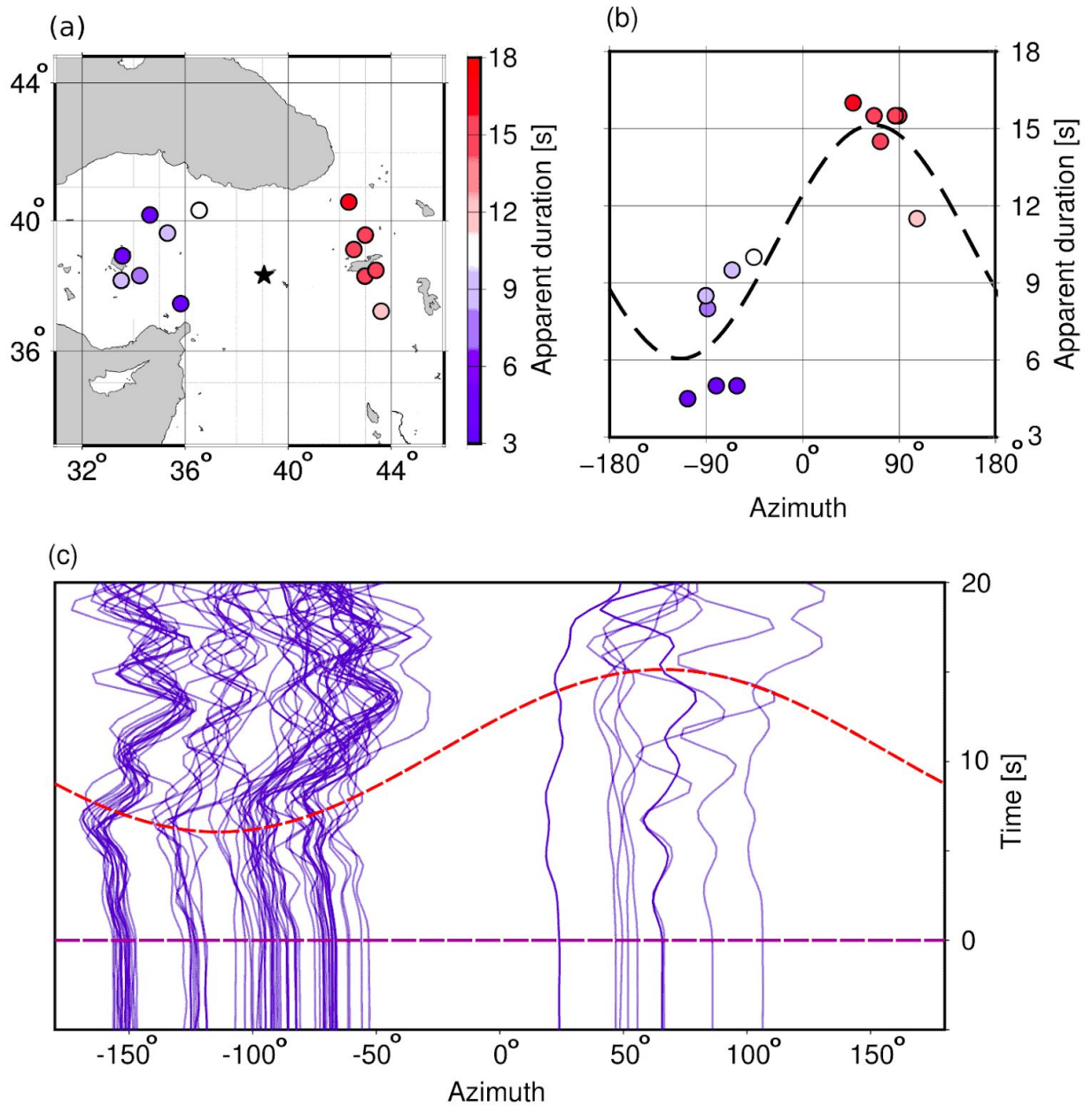


Figure 4: Mainshock apparent rupture durations (unit in seconds) at regional seismic stations. a) color-coded in map view. b) as a function of azimuth. c) Seismic traces used for apparent rupture duration sorted by azimuth.

Best regards,
 Mohammadreza Jamalreyhani
 (on behalf of all co-authors)