Kinematic rupture model of the February 6th 2023 Mw7.8 Turkey earthquake from a large set of near-source strong motion records combined by GNSS offsets reveals intermittent supershear rupture

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Key points

1. **We infer the kinematic slip history of the 2023 M7.8 Turkey earthquake from unprecedentedly-dense near-fault strong motion data**

2. **We identify several portions of the East Anatolian Fault where the rupture is transiently supershear**

3. **We associate transitions to supershear speed with regions of reduced fault slip, which could relate to failure of local rupture barriers**

Abstract

The 2023 M7.8 SE Turkey earthquake was recorded by an unprecedentedly large set of strong motion stations very close to its rupture, opening the opportunity to observe the rupture process of a large earthquake with fine resolution. Here, the kinematics of the earthquake source is inferred by finite source inversion based on strong motion records and coseismic offsets from permanent GNSS stations. The strong motion records at stations NAR and 4615, which are closest to the splay fault where the rupture initiated and which were previously interpreted as containing the signature of supershear rupture speeds, are successfully modeled here by a sub-shear rupture propagating unilaterally to the NE. Once the rupture on the splay fault reaches the East Anatolian Fault (EAF), it propagates on the EAF bilaterally, extending about 120 km NE and 180 km SW. To

the South, the depth extent of the rupture decreases as it passes a bend of the EAF. While the rupture velocity remains globally sub-shear along the EAF, we identify several portions of the fault where the rupture is transiently supershear. The transitions to supershear speed coincide with regions of reduced fault slip, which suggests supershear bursts generated by failure of local rupture barriers. Towards the SW termination, the rupture encircles an asperity before its failure, which is a feature that has been observed only on rare occasions. This unprecedented detail of the inversion was facilitated by the proximity to the fault and the exceptional density of the accelerometric network in the area.

Introduction

The February 6, 2023 (01H17 UTC) earthquake of moment magnitude (Mw) 7.8 in SE Turkey (Pazarcık, Kahramanmaraş, Türkiye) involved three major fault segments well differentiated by location and orientation (e.g. Melgar et al., 2023). The rupture started on a fault branch that splays off from the East Anatolian Fault (EAF) and runs adjacent to the city of Narli where strong motion stations 4615 and NAR are located **(Figure 1**). This splay fault is sometimes referred to as the Narli Fault, however Melgar et al. (2023) referred to it as the Nurdağı-Pazarcık Fault; it will be called hereafter the splay fault (SPF). The rupture later propagated on two segments of the EAF.

In principle the time-dependent earthquake rupture process can be constrained by seismological data, but in practice such efforts are often limited by the scarcity of near-source recordings. Our objective here is to take advantage of the existence of numerous strong motion stations in the immediate vicinity of the ruptured fault segments to determine with fine resolution the characteristics of the rupture in space and time. GNSS static coseismic offsets are also used to

60 further constrain the spatial distribution of slip. Previous studies (USGS 2023; Melgar et al. 2023)
61 have highlighted the general characteristics of the earthquake by combining different types of
62 data, but using only a limited number of strong motion stations (< 15). So far, the potential for
63 source inversion enabled by the dense strong motion network installed in the area by the Turkish
64 Disaster and Emergency Management Authority (AFAD) has only been partially exploited. In
65 particular, the signals from two stations very close to the splay fault (NAR and 4615) were
66 proposed to contain evidence for supershear rupture on this branch of the rupture (Rosakis et al.,
67 2023), but these signals have not yet been modeled by source inversion studies. Moreover, earlier
68 studies of this earthquake reported sub-shear speeds on the EAF. Here, exploiting the complete
69 dataset we gain further insights into the evolution of rupture speed during this earthquake.

70 In this study we model a large set of 31 strong motion stations, including the closest ones to the
71 rupture segments, plus the available horizontal coseismic offsets from 20 GNSS stations. These
72 data are inverted jointly to constrain the parameters of a kinematic source model of the Mw 7.8
73 earthquake. Our inversion results provide a view of the rupture process, including the spatial
74 variability of rupture speed, with an unprecedented level of resolution.

75

76 **Strong motion data**

77 A very dense set of near-field strong motion records (3 components: NS, EW and vertical) from
78 the Turkish National Strong Motion Network have been made publicly available by the Disaster
79 and Emergency Management Authority (AFAD) through the Turkish Accelometric Database and
80 Analysis System (TADAS). We selected 31 stations covering the entire rupture zone, including

stations located very close to the ruptured segments (**Figure 1**). Signal processing includes removal of the pre-event mean amplitude, double integration to displacement, and bandpass filtering. The low frequency cutoff varies between 0.005 and 0.06 Hz, depending on the amount of long-period noise observed after the double integration. The high-frequency cutoff is set to 0.3 Hz, corresponding to the highest frequency at which we judge waveforms can be modeled adequately using a simple velocity model for wave propagation. Synthetic seismograms are computed by the wavenumber integration method of Bouchon (1981) adopting a 1D velocity model (**Table S1** in the electronic supplement to this article) derived from the regional velocity model determined by Güvercin et al. (2022). On the fault segment located in the immediate vicinity of the NAR and 4615 stations (segment 1bis, see model description in Section "Kinematic model, inversion method, and constraints on rupture parameters"), we computed synthetic waveforms using exact expressions for the displacement field at the surface of a uniform elastic half-space (Johnson, 1974), including near-field waves, as implemented in Legrand (1995).

GNSS data

Coseismic static offsets obtained from GNSS time series were made available by the Nevada Geodetic Laboratory for stations from the CORS (Continuous Operating Reference Stations) network, calculated with final orbits from the NASA Jet Propulsion Laboratory (JPL) on 26 February 2023. We selected the horizontal offsets at 20 stations closest to the rupture zone (**Figure 1**). We calculated synthetic static displacements using the formulation of Savage (1981) for dislocations in an elastic half-space

Kinematic model, inversion method, and constraints on rupture parameters

We define the kinematic model and conduct the finite source inversion following a similar approach to that used by Delouis et al. (2002) to model the 1999 Izmit (Mw 7.6) earthquake. The rupture is represented by rectangular fault segments, subdivided into small dislocation surfaces (subfaults) to model static surface displacements, and represented by a point source at their center to model seismic waveforms. The model and subfault dimensions are provided in **Table 1** and their surface projection is shown in **Figure 1**.

The local source time function associated with each point source is represented as the sum of three isosceles triangular moment rate functions, mutually overlapping, each with a total duration of 4 s. Two bounding rupture velocities, called Vrmin and Vrmax, limit the rupture onset times along the fault by enforcing the constraint $V_{rmin} \leq dist\_subfault / onset\_time \leq V_{rmax}$. Here we define dist_subfault as the distance along the fault segments between the subfault center and the rupture initiation point. The latter is set as the hypocenter for segments 1 and 1bis, and as the junction between SPF and EAF for segments 2 and 3 **(Figure 1**). This constraint has the following physical meaning: at any given location along the faults, the average rupture slowness (defined as the rupture slowness spatially averaged over horizontal along-fault distance between the rupture initiation point and the given location) is constrained to lie between $1/V_{rmax}$ and $1/V_{rmin}$. Within the constrained range, the rupture onset times are allowed to vary freely, thus the rupture speeds at any point of the fault (called hereafter the local rupture speed) can lie beyond the Vrmin - Vrmax range (see **Figure S1** for an illustration, in the electronic supplement to this article).

The inverted parameters are, for each subfault, the rupture onset time, the amplitudes of the triangular functions, and the rake angle. The inversion itself is carried out with a simulated annealing algorithm. The cost function to be minimized is a weighted sum of the normalized RMS (root mean square) misfit functions for each dataset, plus a seismic moment minimization function and a smoothing function.

The strong motion stations are located much closer to the rupture than the GNSS stations (**Figure 1a**), thus they are more sensitive to fine details of the rupture and more difficult to model. Consequently, a lower weight (w=0.4) is assigned to the GNSS data than to the strong motion data (w=1.0). The weights assigned to the seismic moment minimization and smoothing functions are adjusted so as not to incorporate excess seismic moment for little gain in data fit, and to avoid incorporating a level of detail in the model that is poorly constrained by the data.

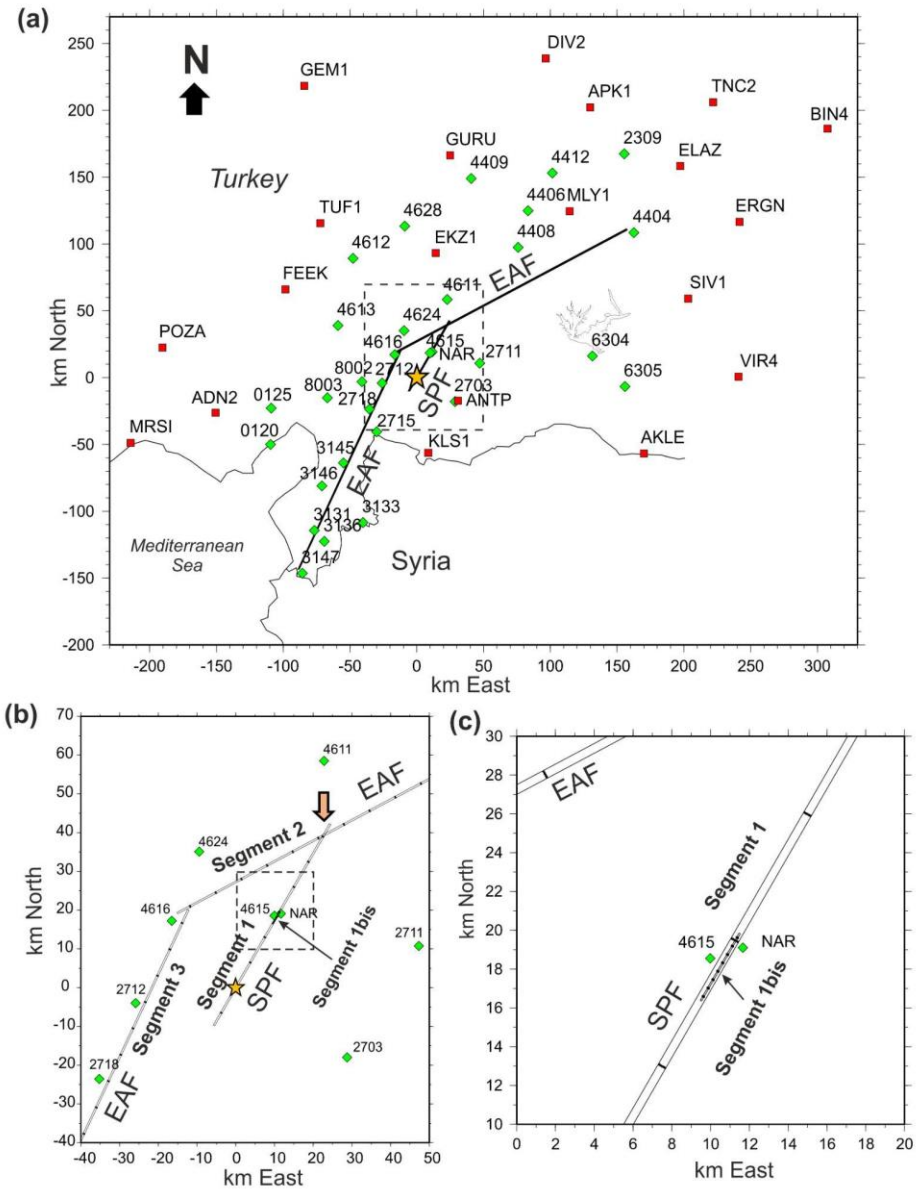


Figure 1. (a) Overview map showing the strong motion (green diamond) and GNSS (red squares) stations used in this study, with corresponding names. Thick black line: surface trace of the fault model. Orange star: epicenter of the mainshock (37.22°N, 37.025°E, this study) at the origin of the coordinates (0,0). The dashed box indicates the zone (b). **(b)** Close-up of the epicentral area. Thin lines with small dots show the fault model with the center of the point sources,

projected on the earth surface. The names of the fault segments are shown. The dashed frame indicates the zone (c). Orange arrow: junction between segment 1-1bis (splay fault) and segment 2 (East Anatolian Fault). **(c)** Close-up of the area where the fault model passes between the strong motion stations 4615 and NAR and where a finely discretized fault segment 1bis is used. SPF: splay fault; EAF: East Anatolian Fault.

The hypocenter has been located by many agencies, systematically more than 15-20 km south of the EAF (e.g. AFAD, KOERI, USGS). As in Melgar et al. (2023), we consider that the hypocenter occurred on a NNE-SSW fault branch, a splay fault (SPF, **Figure 1**) with respect to the EAF. Using P arrival times and a few S arrival times at the nearby strong motion stations, we located the epicenter of the main shock at 37.22°N and 37.025°E, with an estimated uncertainty of less than 5 km, using the GRIDSIMLoc nonlinear approach (Delouis et al., 2022). However, the hypocenter depth, ranging from 3 to 20 km, is not well constrained by the arrival times. We used this epicenter to define the rupture initiation point in our kinematic slip model, and tested different hypocenter depths based on the discretization of our rupture model. Finally, the best results were obtained with a hypocenter depth of 12.5 km, but the inversion results are not very sensitive to variations of this parameter within +/- 5 km.

The rupture model includes three fault segments, corresponding to the minimum degree of complexity to represent to first order the rupture geometry constrained by satellite imagery, aftershock distribution and field observations (e.g. map from the USGS Turkey Earthquake

Emergency Response (Reitmann et al., 2023), and the compilation of documentation on the Kahramanmaraş Supersite science web page, see Data and resources). Segment 1 corresponds to the NNE-SSW trending splay fault hosting the hypocenter. Segments 2 and 3 correspond to the NE-SW segment (striking N62) and NNE-SSW segment (striking N25) of the EAF, respectively (**Figure 1** and **Table 1**). On all segments, we allow the rake to vary by +/- 45° around the central value of 0 corresponding to a dominant left-lateral strike-slip motion (**Table 1**). In initial inversions, we allowed the dip of fault segments to vary between 80 and 90 degrees, to the NW or SE, but we observed no real impact on the data modeling. Since the data do not appear to be very sensitive to the choice of dip when it is close to vertical, we set it at 89° to the SE for all segments.

Preliminary constraints on rupture speeds

Two accelerometer stations were the focus of special attention, as their positioning is of primary importance to constrain the initial phase of the rupture on the SPF. These are stations 4615 and NAR, the closest ones to the epicenter. Between these two stations, separated by only 1.8 km, surface breaks have been identified, with displacements of the order of 2.6 to 2.8 m (**Figure S2** in the electronic supplement to this article). This is strong evidence that these stations are located on opposite sides of the ruptured splay fault.

A major pulse, clearly visible on the velocity seismograms and marked by a maximum displacement of 210 cm southward at station 4615 and 90 cm northward at station NAR, starts about 4.8 s after the first arrival of the P-wave at these two stations (**Figure S3** in the electronic

supplement to this article). We interpret this part of the signal as being produced by the left-lateral surface faulting between the two stations. The rupture, located less than one kilometer from the stations, moves 4615 southward and NAR northward. The reversal of the direction of displacement and the magnitude of the displacement observed at these two stations so close to each other appears to be the direct signature of a local fault offset of at least 3 m (2.1 + 0.9 m), in agreement with the surface observations (**Figure S2** in the electronic supplement to this article).

Modeling the first 15 seconds of the signal following the P-wave onset at stations 4615 and NAR required special effort. We found it necessary to incorporate a finely discretized portion of the fault between the two stations, denoted as segment 1bis (**Table 1** and **Figure 1b-c**). The synthetic seismograms generated by segment 1bis for stations 4615 and NAR were calculated using the exact analytical solution for a homogeneous half-space of Johnson (1974), which is more accurate for very small source-station distances than the numerical approach by wavenumber integration (Bouchon 1981). The homogeneous velocity model assumed has P-wave velocity of 4.90 km/s and S-wave velocity of 2.83 km/s.

Rosakis et al. (2023) made observations suggesting that a transition from subshear to supershear rupture velocity (Vr) occurred on SPF between stations 4615 and NAR. To examine the rupture velocity on the splay fault, we performed a series of inversions where Vr on segments 1 and 1bis is fixed to a constant value varying from 2.0 to 5.0 km/s. **Figure 2a** shows the variation of RMS fit of all 31 stations on the one hand, and of the two stations 4615 and NAR on the other hand, as a function of the fixed Vr value. The effect of the choice of Vr on the modeling of the north component of 4615 and NAR is illustrated in **Figure 2b**. Best results are obtained for constant Vr

in the range 2.8 to 3.0 km/s, with already good results for Vr=2.5 km/s. This indicates that, to model displacement waveforms in the frequency band used here, it is not necessary for Vr to transition from sub-shear to supershear. We will come back to this point in the discussion. In our final inversion, we relax the constraint of a constant Vr on the splay fault by allowing the average Vr to vary between Vrmin = 2.5 km/s and Vrmax = 3.3 km/s.

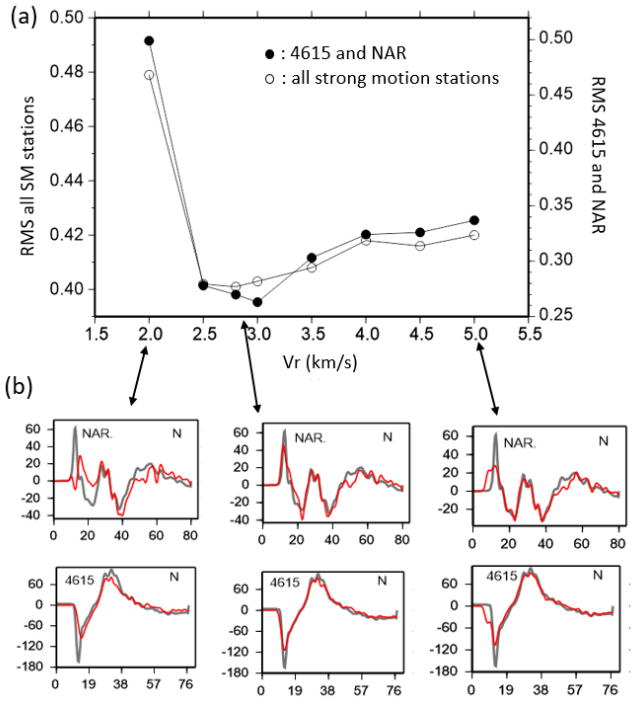


Figure 2. Exploration of the rupture velocity (Vr) on segments 1 and 1bis. **(a)** RMS waveform misfit value for all strong motion stations (SM) and for 4615 and NAR only as a function of fixed constant Vr values. **(b)** North component waveform fit for NAR and 4615 stations for constant Vr values of 2.0, 2.8 and 5.0 km/s. Waveforms are in

displacement and bandpass filtered between 0.01 and 0.3 Hz. Only the north components of NAR and 4615, being the most sensitive to Vr and the most difficult to model, are shown but the inversion is performed with the three components N, E and Z of all strong motion stations.

During initial inversions, we observed that slip on segments 1 and 1bis (SPF) could reach 6 m, in disagreement with independent evidence of surface offsets of no more than 3 m along this fault section (**Figure S2** in the electronic supplement to this article). Although it cannot be ruled out that slip at depth may exceed slip at the surface, we noted that the fit of the data was not significantly improved when the maximum slip on these segments increased from 4 to 6 m. In the final inversion the slip on segments 1 and 1bis is limited to 4 m.

A delay is imposed to the initiation of the rupture on segment 2 to force the rupture on the EAF to start after the rupture along the SPF has reached the junction with the EAF (**Figure 1b**). We tested delay values (relative to the hypocenter origin time) ranging from 10 to 18 s and retained the value of 14 s which gives the best fit of the data.

Regarding the EAF (segments 2 and 3), optimum results are obtained by using Vrmin = 2.0 km/s and Vrmax = 4.0 km/s. Expanding the range Vrmin - Vrmax beyond these limits does not produce a significant improvement in data fit. On segments 2 and 3, the distance considered to constrain Vr is the distance along the fault relative to the SPF-EAF junction (**Figure 1b**), with a time origin corresponding to the start time on segment 2, i.e. 14 s after rupture initiation on segment 1. The maximum allowed slip on the EAF was explored between 5 and 12 m. The improvement in the fit

of the data becomes small for a maximum slip greater than 7 to 8 m, and slip was limited to 8 m in the final inversion. However, the maximum slip on the EAF is not constrained with an uncertainty better than +/- 1 to 2 m.

Segment	Strike (°)	Dip (°)	Central rake (°)	L (km)	W (km)	Δl (km)	Δw (km)	Vrmin (km/s)	Vrmax (km/s)
1	30	89	0	60	25	7.5	5.0	2.5	3.3
1bis	30	89	0	4	5	0.5	1	2.5	3.3
2	62	89	0	195	25	7.5	5.0	2.0	4.0
3	25	89	0	180	25	7.5	5.0	2.0	4.0

Table1. Fixed parameters for the fault segments of the kinematic rupture model. L: length; W: width; Δl and Δw subfault length and width. Vrmin and Vrmax: bounding rupture velocities. The top of all segments is located at the free surface.

Final slip model and rupture timing

We present here the final slip model resulting from the joint inversion of the strong motion and GNSS static data. The spatial distribution of slip is shown in **Figure 3**. The spatial and temporal distribution of the slip is presented on **Figures 4, 5, 6**, **and 7** separately for the SPF (segments 1 and 1bis) and for the EAF (segments 2 and 3).

On the SPF, the rupture is unilateral to the NNE. The total slip is limited at the hypocenter and south of it. Beyond about 15-20 km NE from the epicenter, slip is mainly localized near the surface, between stations 4615 and NAR, and at the end of the SPF at its junction with the EAF. From the junction on, the rupture propagates bilaterally on the EAF, for about 120 km to the NE and 180 km to the SW. On segment 2 slip reaches 20-25 km depth, whereas on segment 3 it is shallower,

localized above 10 km depth. Along the whole rupture, the maximum slip is found close to the surface. It reaches our maximum allowed value of 8 m on both segments of the EAF.

On the EAF, slip at the junction with the splay fault is small, but it may be partially compensated by slip at the NNE termination of the splay fault. The slip observed at the NE end of segment 2 is likely an artifact, possibly related to a geometric complexity of the rupture not taken into account in the model.

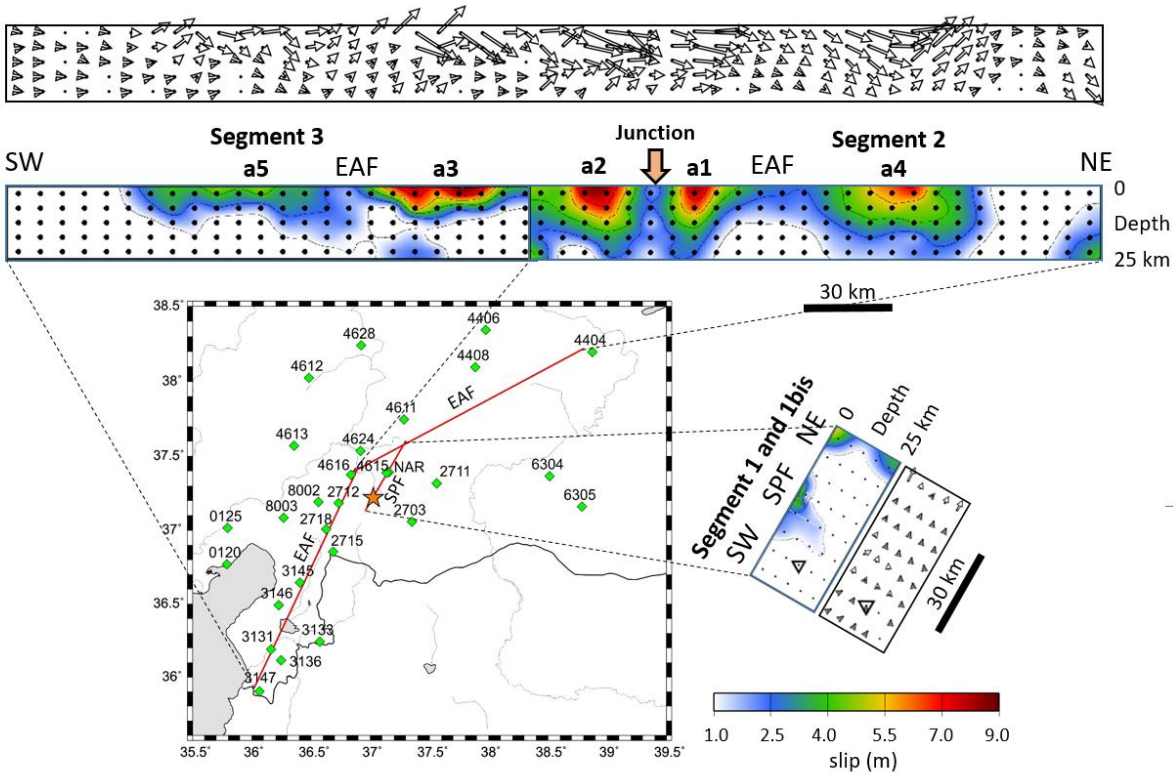


Figure 3. Slip distribution from the joint inversion of strong motion and GNSS data on the three segments of the kinematic model, and relation with the map view. SPF: splay fault; EAF East Anatolian Fault. On the map, the epicenter, the surface trace of the rupture model, and the strong motion stations are represented by the orange star, the red lines and the green

diamonds respectively. The hypocenter on segment 1-1bis (SPF) is marked by the open triangle. The junction between the splay fault (SPF, segment 1) and Segment 2 of the EAF is marked by the orange arrow. a1 to a5: labels for the main slip areas along the EAF. The slip direction is indicated by the open arrows scaled with slip amplitude.

On the SPF, the rupture propagates horizontally at a near constant rupture velocity of 2.5 to 2.6 km/s (**Figure 4a**). In the time interval between 12 and 20 s, the rupture front is faint and difficult to follow on the slip velocity snapshots (**Figure 6a**) and little slip is accumulated (**Figure 6b**). After 20 s, larger slip emerges near the junction with the EAF.

Along the EAF, the average rupture velocity calculated from the junction with the splay fault remains below 3 km/s along segment 2 and close to 3 km/s over most of segment 3. (**Figure 4b**). However, we identify notable local deviations from this average trend.

To analyze the inversion results, we estimate the local rupture speed and acceleration (horizontal apparent values) by tracking the onset of slip on the sub-faults (**Figure 5**). We determine the apparent rupture acceleration, as a function of along-strike distance, that minimizes the difference between the observed position of the rupture front and the double integral of the rupture acceleration, with a mild smoothness constraint on the acceleration. The resulting acceleration is integrated once to obtain the rupture speed along the fault.

Initially and up to a distance of about 30 km from the junction, rupture propagates both to the NE and to the SW at a relatively low speed, between 2 and 2.5 km/s, generating two main slip areas we denote as a1 and a2 (**Figures 4b, 5, and 7**). Then, we observe a pattern common to both rupture directions: after running through a low slip section (gray areas on **Figure 5**), rupture speed increases when entering into the next high slip area (a3, a4, a5), reaching locally a value of 4 km/s or more, maintained over a distance of 20 to 30 km (red F markers on **Figure 5c**, and on **Figure 7a**). This pattern involves multiple transitions from sub-shear to supershear rupture speed along the EAF at the scale of a few tens of kilometers.

As an independent verification of the rupture trajectory along Segment 3, we inspected the strong motion waveforms of selected receivers closest to the fault (**Figure S4 in the electronic supplement to this article**). The three-component waveforms were bandpass filtered from 1 to 5 Hz, after which we computed the amplitude of motion as $A=\sqrt{(N^2+E^2+Z^2)}$ for components N, E, and Z. The passage of the rupture was clearly visible as a strong pulse in the amplitude time series, the timing of which was manually picked. To acknowledge uncertainty in the onset time due to the emergent onset, an onset time range was selected; this time range is indicated in **Figure 4b**, and verifies the rupture trajectory inferred by source inversion. Notably, the manual picks confirm the existence of brief supershear phases along Segment 3.

The lateral progression of the rupture generally takes place first at or near the surface (**Figures 6 and 7**). There is one notable exception: around the main slip area a5 on segment 3, the snapshots at 56 s of slip velocity and cumulative slip (**Figure 7a and b**, green U mark) show that rupture propagates first at 10-12 km depth, leaving unbroken the shallowest portion of the fault. This shallow part slips a few seconds later (see the next snapshot at 59 s). Such a delayed rupture of

an asperity after it has been surrounded by slip has been described by Zhang et al. (2012) for the 2008 Mw 7.9 Wenchuan earthquake in China, and by Meng et al (2018) for the 2015 Mw 8.3 Illapel earthquake in Chile, though here it is observed at a smaller scale.

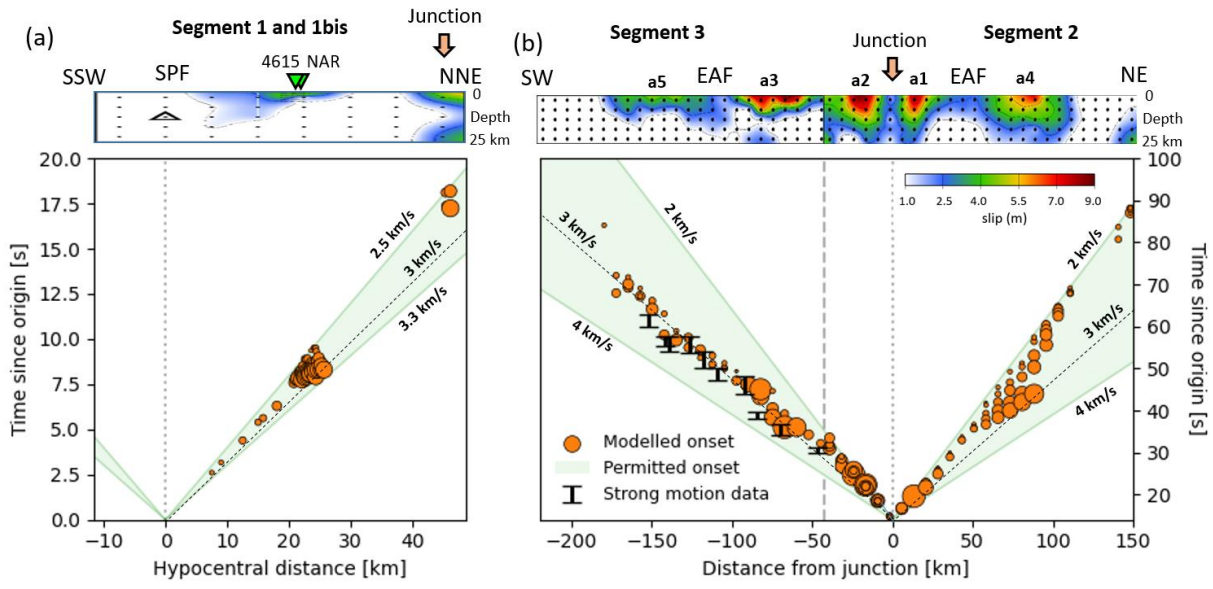


Figure 4. Time-distance plots of slip for segments 1 and 1bis **(a)** and for segments 2 and 3 **(b)** from the joint inversion of strong motion and GNSS data**.** SPF: splay fault; EAF: East Anatolian Fault; orange dots: subfault timing at a function of distance, with size proportional to slip (larger than 1 m). Green shaded area: allowed domain for average rupture speed. Oblique black line: average rupture speed 3 km/s. Lines of average rupture speed start from the hypocenter in **(a)** and from the junction between the splay fault (segment 1) and the EAF (segment 2) in **(b)**. The slip distribution along strike and dip is shown above the graphs. On top of **(a)**, the position along strike of strong motion stations 4615 and NAR is indicated, and on

top of **(b)**, the junction with the splay fault is indicated by the orange arrow. a1 to a5: labels for the main slip areas along the EAF.

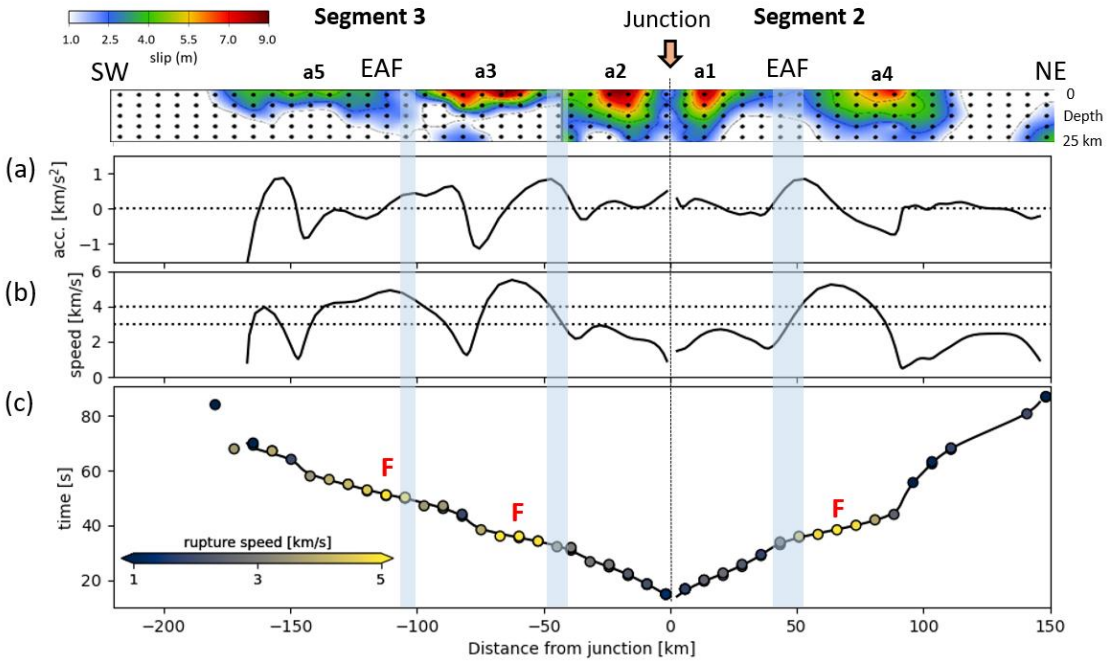
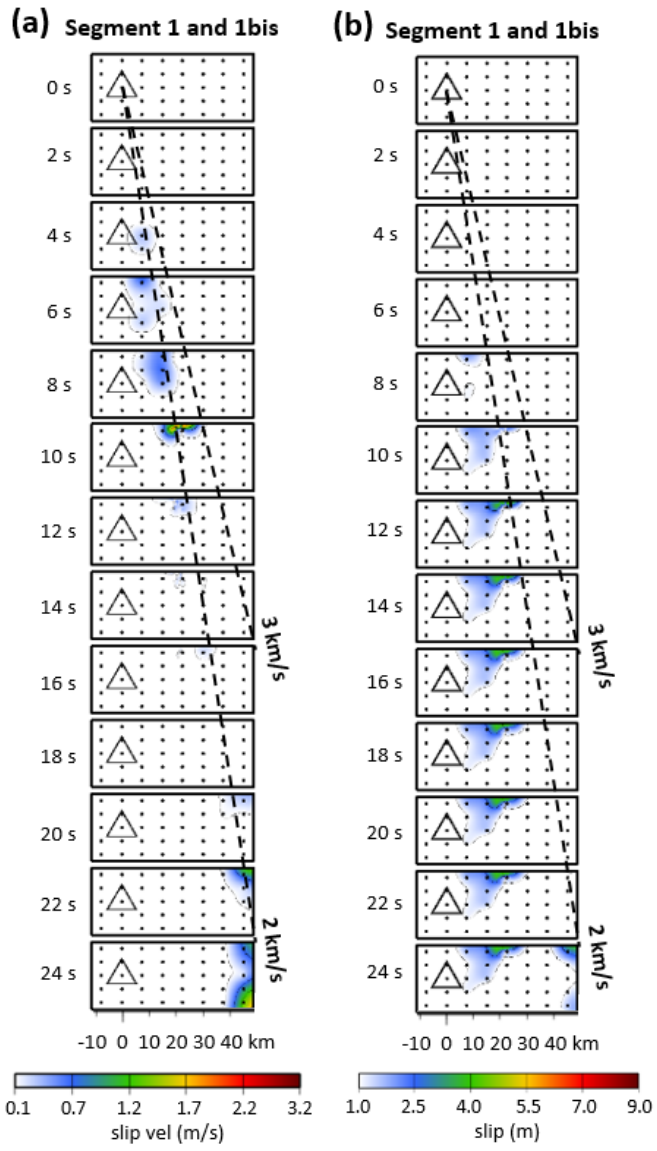


Figure 5. Estimation of rupture speed as a function of distance from the junction along the EAF (Segment 2 and 3). **(a)** Inverted rupture acceleration. **(b)** Local rupture speed (integral of acceleration). **(c)** Black curve: rupture onset time (related to the second integral of acceleration). The markers represent the observed onset times colored according to the estimated local rupture speed. Compared to Fig. 4b, only the subfaults whose time is less than 1 s from the rupture front at a given horizontal position are included in the inversion and panel c. The shaded regions indicate the locations of low slip. F (fast) markers in red point to areas of high local speed, reaching supershear. Slip map on top with the same labels as in previous Figures.



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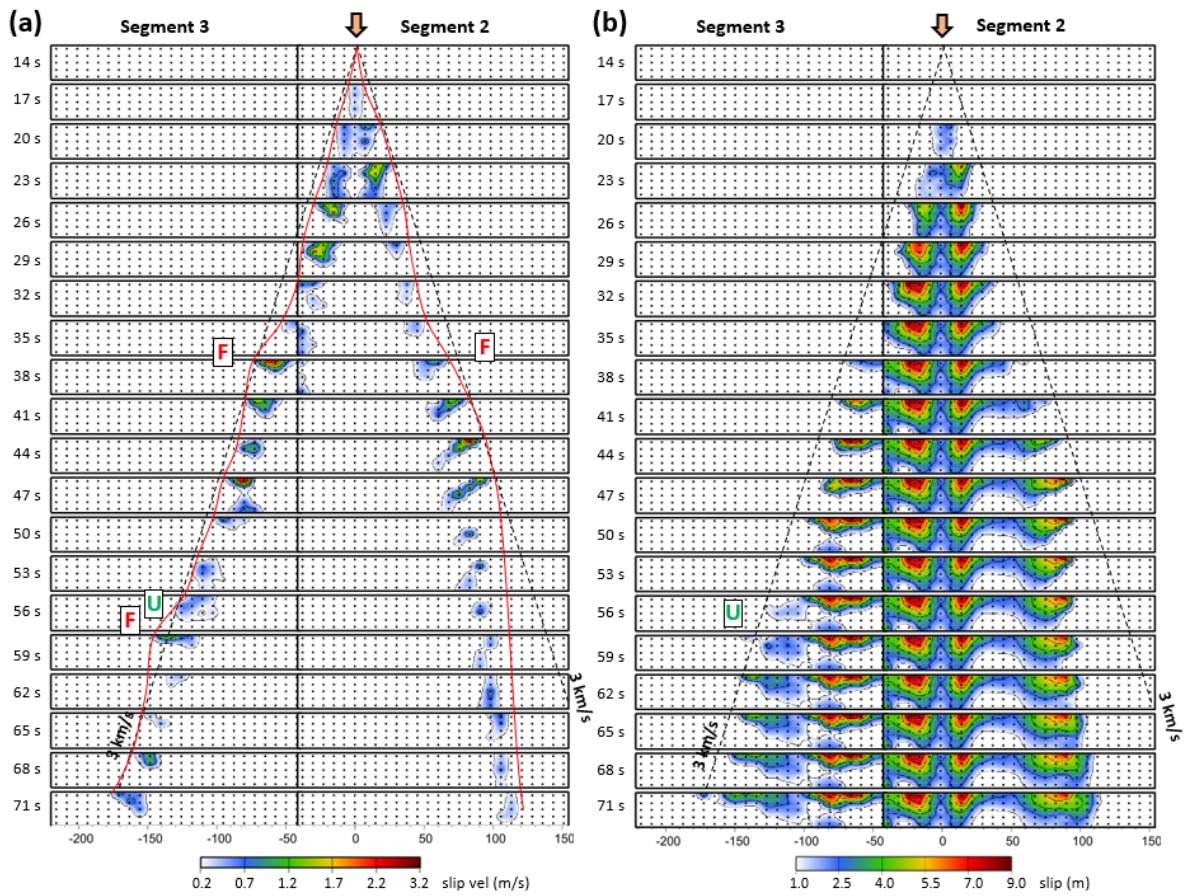
340 **Figure 6.** Snapshots of the space-time evolution of the rupture on
341 segments 1 and 1bis (splay fault) from the joint inversion of strong
342 motion and GNSS data. **(a)** slip velocity at each time step, **(b)** cumulative
343 slip. Time steps are indicated on the left side. Open triangle: hypocenter.
344 Oblique dashed black lines: reference slopes corresponding to average
345 rupture velocities (Vr) 2 and 3 km/s, starting from the hypocenter.



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347 **Figure 7.** Snapshots of the space-time evolution of the rupture on segments
348 3 and 4 (EAF) from the joint inversion of strong motion and GNSS data. **(a)**
349 slip velocity at each time step, **(b)** cumulative slip. Time steps are indicated
350 on the left side. Oblique dashed black lines: reference slope corresponding
351 to average rupture velocity (Vr) 3 km/s, starting from the junction with the
352 splay fault (orange arrow). The red curve in **(a)** tracks the rupture front with
353 its variations. Boxes labeled F (fast) in red point to areas of increased local
354 Vr, reaching supershear, related to the F markers in **Figure 5c.** Box labeled U
355 (underneath) in green indicates where the slip is moving below the near-
356 surface area that will slip about 4 m in the following seconds.

The overall source time function is shown in **Figure 8a**, together with those corresponding to the NE-ward part of the rupture **(Figure 8b)** and to the SW-ward part of the rupture **(Figure 8c)**. The total duration of the rupture is about 80 s, with the NE and SW parts contributing simultaneously between 15 to 72s. The initial pulse on **Figure 8a** (0 – 15 s) is due solely to the splay fault. The overall moment magnitude Mw is 7.83. The moment magnitudes of the NE part, the SW part, and the splay fault are 7.58, 7.64, and 6.98, respectively.

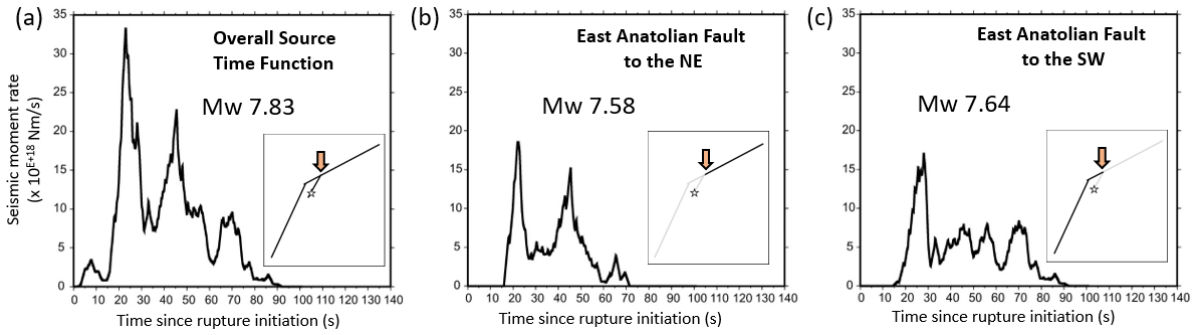

Figure 8. (a) Overall source time function (all rupture segments). **(b**) Source time function for the part of the East Anatolian Fault rupturing to the North-East from the junction with the splay fault. **(c)** Source time function for the part of the East Anatolian Fault rupturing to the South-West from the junction with the splay fault. The corresponding moment magnitude Mw is indicated in each case, and the rupture segments involved are shown with heavy black lines in the inner frame. Orange arrow: junction. Open star: epicenter. From the joint inversion of strong motion and GNSS data.

374 The data fitting of the strong motion records integrated to displacement is shown on **Figure 9**,

375 and that of the horizontal GNSS offsets on **Figure 10**.

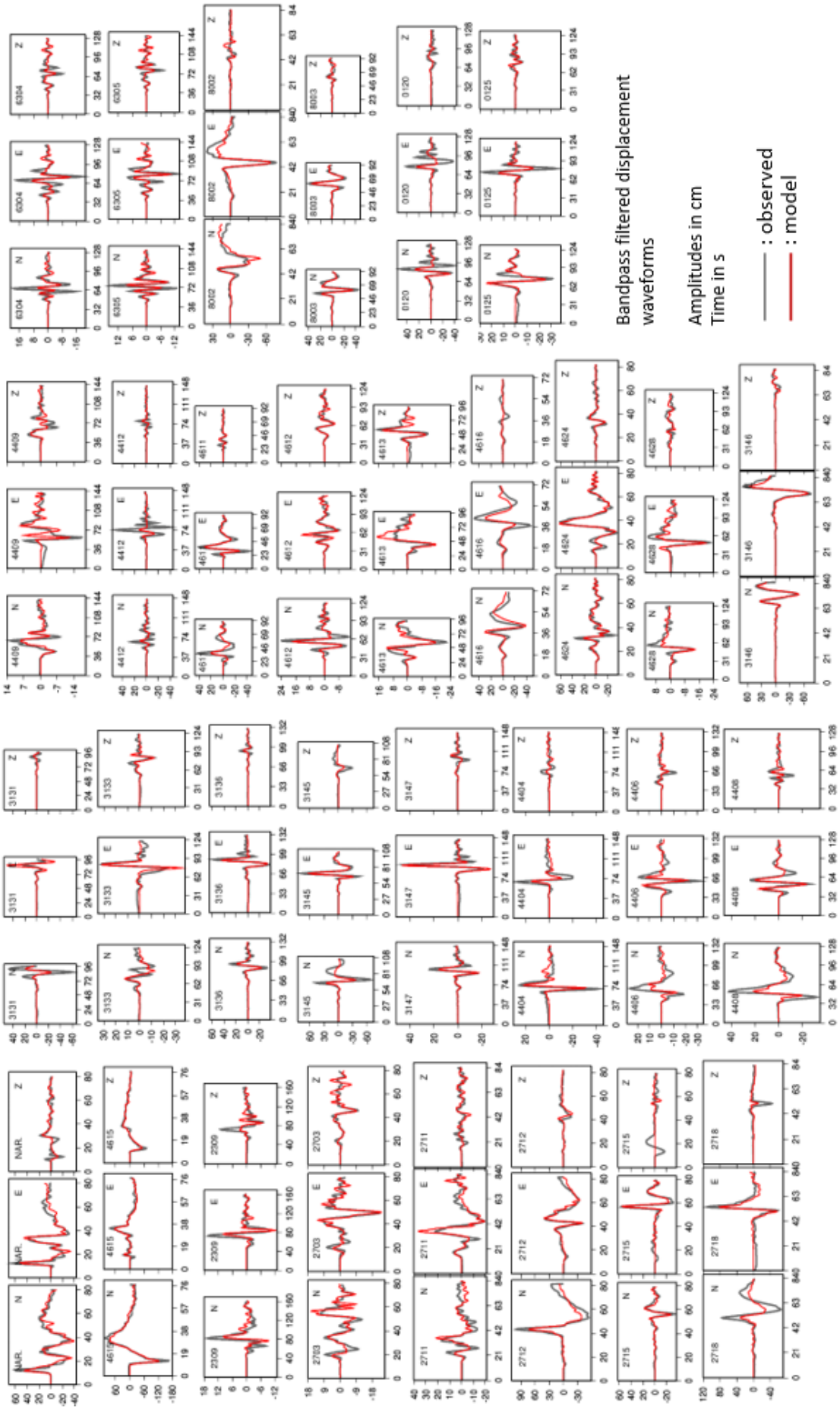
Bandpass filtered displacement
waveforms
Amplitudes in cm
Time in s
: observed
: model

Figure 9. Waveform fitting by joint inversion of strong motion and GNSS data. N, E, Z: north, east, vertical (up) components respectively. All displacement waveforms bandpass filtered.

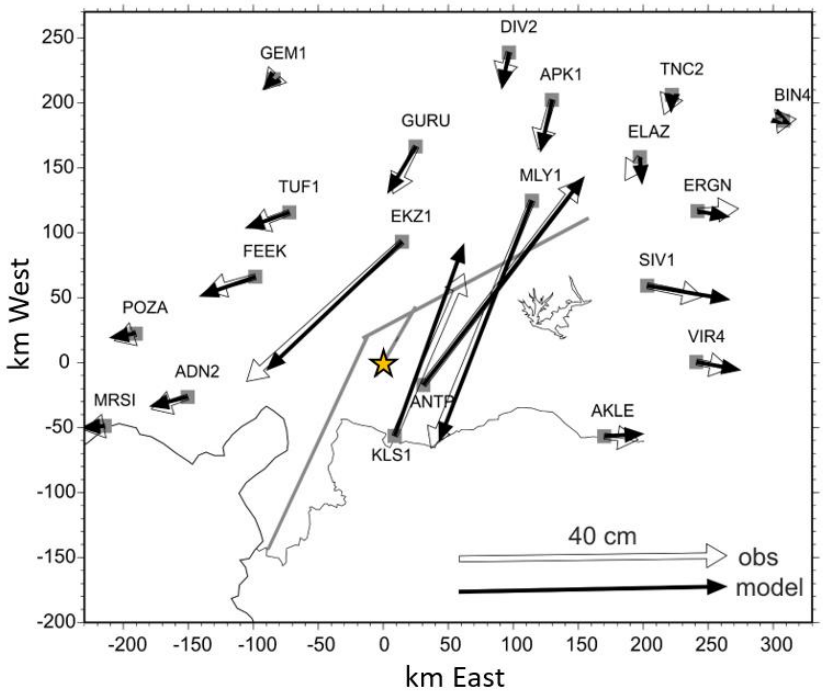

Figure 10. Horizontal GNSS offsets fitting by joint inversion of strong motion and GNSS data. Orange star: epicenter. Heavy gray lines: trace of fault model. Obs: observed.

Discussion

Rupture velocity along the splay fault

Rosakis et al. (2023) analyzed the records of strong motion stations NAR and 4615, integrated to velocity and rotated to fault parallel (FP) and fault normal (FN) components with respect to the splay fault assuming a strike of N22°. According to their analysis, based on theoretical and laboratory experiments, the observed ratio FP/FN of 1.2 at station NAR is the signature of a supershear rupture (FP/FN > 1). They further found that station 4615 is located at the transition from sub-shear to supershear rupture.

Here, we find that ground displacement waveforms in the frequency band 0.01 to 0.3 Hz at stations 4615 and NAR can be modeled correctly with a constant sub-shear rupture velocity on the splay fault, as low as 2.5 km/s (**Figure 2a**). The question then arises whether the supershear signature is present only on velocity signals, possibly only on unfiltered ones. In a first step, we verified that the FP component of NAR is effectively larger than its FN component in velocity, both on the unfiltered and on the 0.01 to 1 Hz bandpass filtered signals (**Figure S5** in the electronic supplement to this article). This is illustrated for two possible azimuths of the splay fault, N22° and N30°. In a second step, we verified that it is possible to model the velocity signals of both stations NAR and 4615 without a transition to supershear (**Figure S6** in the electronic supplement to this article). The modeling is done in the frequency band 0.01 to 1 Hz by finely discretizing the rupture segment corresponding to the splay fault, but limiting its spatial dimensions to the minimum necessary to model the first 15 s of signal, which include the main pulse associated with the suspected supershear Mach front identified by Rosakis et al. (2023). The amplitude of the main velocity pulse is correctly matched using a constant rupture velocity of 2.8 km/s all along the splay fault, both on the N and E components and on the FP and FN components (**Figure S6** in the electronic supplement to this article). We conclude that the criterion FP/FN > 1 is not

necessarily the signature of a supershear rupture, and that the main pulse observed in the initial part of the records of stations NAR and 4615 can be explained by left-lateral shallow faulting propagating at sub-shear velocity between the two stations.

The failure of the FP/FN criterion could be caused by a level of complexity of the rupture that has not been accounted for in the underlying theoretical models and laboratory experiments. Indeed, on the SPF the slip emerges at the surface at a substantial distance NE of the epicenter. This pattern is reminiscent of the Mw 6.0 2014 South Napa, California earthquake, in which the rupture propagated within a narrow corridor upward and obliquely from the hypocenter (Premus et al., 2022). In contrast, the FP/FN criterion to distinguish sub-shear and supershear ruptures arises from theoretical and experimental models with relatively more simple rupture front geometries (Aagaard and Heaton, 2004; Dunham and Arhuleta, 2004; Bizzarri et al., 2010; Mello et al., 2016).

Resolution of the kinematic model

We carried out a synthetic test to assess the resolution of the kinematic inversion. We designed a synthetic kinematic model with variable slip and variable rupture velocity as shown in **Figure S7-left** (slip distribution) and **Figure S8** (gray dots, rupture timing) in the electronic supplement to this article. Based on this model, we generated synthetic displacement waveforms and static offsets at the same strong motion and GNSS stations as for the real data. Amplitudes of the synthetic data were randomly modified by a factor 1.1 or 0.9 at each station (10% change). These modified synthetic data were inverted using exactly the same rupture parameterization and algorithm than our real data inversion. However, we used a slightly modified 1D velocity model

to compute the Green's function (model of **Table S1** to generate the synthetic data, model of **Table S2** for the inversion), to avoid unrealistically perfect conditions. Overall, the main features of the synthetic model are retrieved. Nevertheless, there is some spreading of slip zones and poorer timing resolution of moderate amplitude slip patches on the NE propagating portion of the rupture, which can be related to the smaller number of stations and their relatively greater distance from the rupture on this part of the source. We also observe an overestimation of the subfault onset time at the NE termination of the splay fault. It can be assumed that the same effects occur with the real data.

Rupture transition from the splay fault to the East Anatolian Fault

In our final model, rupture starts on the EAF at 14 s after the earthquake onset, before the development of slip at the termination of the splay fault between 17 and 24 s (**Figure 4a and 6a**). This suggests that rupture on the EAF was triggered before the end of rupture on the splay fault. However, we have shown that a constant rupture speed of 3 km/s, or even a little faster, on the splay fault produces an equally low RMS misfit of the data (**Figure 2**). At 3 km/s, the rupture arrives at the junction with the EAF approximately 14 s after origin time, leading to a continuous rupture from the splay fault to the EAF. We acknowledge an uncertainty of a few seconds on the timing of the end of the rupture of the splay fault, as observed in the synthetic test. This uncertainty could possibly be linked to a trade-off with the slip on the EAF at the junction, which in turn may be due to the absence of strong motion stations very close to the junction.

Necessity of local rupture speed variations

To further evaluate whether rupture velocity variations along the EAF are indeed required by the data, we performed an additional test in which a constant velocity of 3 km/s is imposed on segments 2 and 3. The negative impact of this constant velocity assumption on waveform modeling is clear at stations near the SW-ward rupture along segment 3 (**Figure S9** in the electronic supplement to this article). The effect is less clear at stations around the NE-ward rupture along segment 2. We conclude that variations in Vr are well-constrained by the data, especially for the SW branch of the rupture, which is the best resolved part of the source owing to the presence of several stations in close proximity.

Comparison with other kinematic models

Two kinematic models obtained by inversions of multiple data, including strong motion records, have been published previously. These are the USGS finite fault model and that of Melgar et al. (2023). The data used are not the same, although they partially overlap with each other and with ours. While our study relies primarily on the dense network of strong motion instruments, the two previous studies use a smaller subset of strong motion records and combine other data types such as HR-cGNSS time series (which are not very close to the rupture), teleseismic data and InSAR data. Note that Melgar et al. (2023) model both the Mw 7.8 and 7.6 earthquakes that occurred on the same day in SE Turkey, which are covered by the same InSAR data.

Our kinematic model has in common several major features with the above mentioned models: the initiation on the splay fault with moderate slip, followed by bilateral propagation on the EAF, a more superficial rupture on the south-westernmost segment of the rupture, a maximum slip of the order of 8 to 9 m on the EAF. We confirm that the average rupture velocity along the EAF did

not exceed about 3.2 km/s, as stated by Melgar et al. (2023). However, by modeling more strong motion records, particularly the NAR and 4615 stations near the splay fault that were not incorporated in previous studies, as well as other stations along the EAF, we find remarkable features of rupture propagation that have not been fully addressed before, in particular the existence of several portions where the rupture front propagates at supershear speeds along the EAF.

Transient supershear speeds

The spatial fluctuations of local rupture speed are among the earthquake source properties that are most difficult to constrain robustly, often due to scarcity of near-fault seismological data. Transient supershear rupture was recently reported for the 2021 Mw 7.3 Madoi, China earthquake using teleseismic back-projection analysis (Cheng et al., 2023), a technique that was essential to reveal the steady supershear propagation of the 2018 Mw 7.5 Palu, Indonesia earthquake (Bao et al., 2019). While systematic studies of global earthquakes show that teleseismic back-projection can constrain well their average rupture speeds (Bao et al., 2022), spatial fluctuations of rupture speed at scales of 10 km or less are best resolved with local strong motion observations, as done in our present study.

Our source inversion results regarding rupture speed challenge simple models of dynamic rupture. Theoretical models of steady ruptures with large aspect ratio (rupture length much larger than rupture width), including supershear ruptures (Weng and Ampuero, 2020), predict a correlation between final slip and rupture speed. We do not find such a correlation in our inversion results (**Figure 5**). This implies that the exceptional dataset available for the 2023 Mw

7.8 Turkey earthquake warrants further extensions of current theories, which so far assume simple rupture fronts or depth-averaged rupture properties (Weng and Ampuero, 2019). The intermittent supershear bursts found here might result from 3D rupture patterns that cannot be captured by 2.5D models. A possible scenario, proposed in dynamic rupture models by Dunham et al (2003) and Page et al (2005), is a rupture front that reaches the edge of an asperity, goes around it, then breaks it and generates a burst of rupture acceleration to supershear. The fine-scale details of such a pattern may not be resolvable by kinematic source inversion, even though its coarser effect on rupture speed is, and may warrant elucidation by dynamic source inversions (e.g. Premus et al, 2022).

Conclusions

Taking advantage of the exceptional strong motion dataset made available by the Turkish Disaster and Emergency Management Authority (AFAD), which had been used less comprehensively by previous studies, and to a lesser extent of GNSS static data, we determine the rupture characteristics of the February 6, 2023 Mw 7.8 earthquake in southeast Turkey.

We explore in detail the rupture properties required to model the seismograms recorded by two stations, NAR and 4615, located very close to the splay fault on which the earthquake started. We show that supershear rupture speed is not required on the splay fault. Indeed, these seismograms can be correctly modeled, in displacement and in velocity, by a sub-shear rupture passing between the two stations with about 4 m of slip at or near the surface.

About 14 s after rupture initiation, the rupture on the splay fault reached the East Anatolian Fault (EAF). It then propagated bilaterally along the EAF, extending about 120 km NE and 180 km SW. The depth extent of the rupture decreases as it passes the bend of the EAF to the SW. The highest slip values are located near the surface on each rupture segment, with a maximum of 8 m +/- 2 m along the EAF.

The along-strike averaged rupture velocity remains below about 3.3 km/s, but locally, when entering strong slip zones after crossing weak slip zones, the rupture velocity becomes supershear for a few tens of kilometers. This pattern of rupture deceleration and acceleration is observed at three different locations along the EAF, thanks to the exceptionally dense near-fault recordings available.

Lateral progression of the rupture generally begins at or near the surface before propagating at depth, with a notable exception in the south-westernmost part of the rupture where a slip patch at the surface breaks after the rupture has surrounded it at larger depth.

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Data and resources

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Some figures were partly made using the Generic Mapping Tools (GMT) package by Wessel et al. (2019) (https://www.generic-mapping-tools.org/) (last accessed on April 17, 2023).

Seismic data processing was partly done using the Seismic Analysis Code (SAC) package by Goldstein et al. (2003) and Goldstein and Snoke (2005) (http://ds.iris.edu/ds/nodes/dmc/software/downloads/sac/102-0/ (last accessed on April 12, 2023).

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