

EXCEPTIONAL GROUND MOTION DURING THE SHALLOW M_w 4.9 2019 LE TEIL EARTHQUAKE, FRANCE

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Supplementary Information

Supplementary Methods, Supplementary References, Supplementary Tables S1-S2-S3, Supplementary
Figures S1-S8.

Supplementary Methods

Spectral analysis of seismological data: Bayesian estimation of the model parameters

Using the far-field seismological data, we perform a Bayesian estimation of the model parameters f_c (corner frequency), M_0 (seismic moment) and Q (quality factor). The Bayes theorem expressed as:

$$\rho(m|d) = \frac{f(d|m)\rho(m)}{\int_m f(d|m)\rho(m)dm} \quad (\text{ES1})$$

where $\mathbf{d}$ and $\mathbf{m}$ represent the model and the data space, respectively, $f(\mathbf{d}|\mathbf{m})$ is the likelihood function and $\rho(\mathbf{m})$ is the prior distribution. The model space is sampled using a grid search algorithm, considering the logarithm values for f_c and M_0 and the natural values for Q . The values of $\log_{10}(f_c)$ range between 0.1 and 5Hz with a step of 0.01, the values of $\log_{10}(M_0)$ range between 15.4 and 17.4 with a step =0.02 and the values of Q range between 100 and 1000 with a step of 20. The likelihood function is defined as:

$$f(m|d) = \exp\left(-\sum_i \frac{|\log_{10}(FAS_{obs}(f_i)) - \log_{10}(FAS_{theo}(f_i))|}{\sigma_{FAS}(f_i) + \sigma_n(f_i)}\right) \quad (\text{ES2})$$

where FAS_{obs} and FAS_{theo} represent the observed and theoretical Fourier amplitude spectra. $\sigma_{FAS}(f_i)$ is the distance between the observed FAS and the best theoretical prediction at frequency f_i (*i.e.* Eq. E2 with $\gamma = 1$ and $n=2$, ref. ¹), considering only the frequency range in which the signal-to-noise ratio is above 3. Finally, $\sigma_n(f_i)$ represents the uncertainty on the slope n in Eq. E2. We compute the theoretical models that minimize the L1-norm assuming $n=1.5$ and $n=2.5$ and set $\sigma_n(f_i) = |\log_{10}(FAS_{theo,n=1.5}(f_i)) - \log_{10}(FAS_{theo,n=2.5}(f_i))|/6$.

Displaced rocks analysis

The paucity of strong-motion stations near the 2019 Le Teil earthquake makes it impossible to make instrumental studies of key questions about near-fault strong-motion patterns associated with this extreme shallow event. Observations of displaced rocks allow a qualitative investigation of these problems (*e.g.* ref. ²⁻⁷). The smallest-magnitude event for which the upthrow of rocks is documented is the $M = 6.0$ 1997 Colfiorito, Italy, earthquake (ref. ⁸).

After the Le Teil Mw 4.9 event, displaced rocks were observed during field surveys on several locations all of which located on the SW part on the surface fault trace were numerous limestone outcrops exist (Figure 1, S6). The NE part of the Le Teil surface rupture did not cut through an area with abundant surficial rocks, but we also intensely check for displaced rocks in these NE areas. Accordingly the lack of observed displaced rocks in the NE fault zone is not driven by a lack of possible observations and so it contain information about the shaking levels close to the NE fault zone. The fieldwork began 1 month after the earthquake, with several visits within 2 months. The backcountry area we investigated, in between the Viviers and Le Teil villages (Figure 1), is a rough flat plateau indented by a few small cliffs, less than 10 meters high. The area is covered by many small

to medium-sized rocks, and their displacement, or lack thereof, was easy to determine due to the lack of erosion since the mainshock. We failed to identify precarious rocks, but several small ($1\text{--}3\text{ m}^3$) rockfalls occurred along the same SW branch of the rupture zone (Figure S6.1). All of the displaced rocks (and rockfalls) are located on the hanging wall within less than 0.5 km from the 4.5 km long surface rupture (Figure, 1, 3, S6).

Near the southwestern terminus of the rupture (FR1, Figure S6.2), around 15 flung rocks were observed along a 400 m distance on trails that follow the immediate proximity of the surface earthquake rupture. These rocks were tossed into the air during the earthquake, with freshness of cuts and fractures attesting breakage occurring at the time of impact (Figure 4, Table S2).

A second site, where we observed the largest density of displaced rocks (FR2, Figure 3, S6.3), was found on a flat dolomite limestone outcrop over an area approximately $80 \times 250\text{ m}$. This area of dense freshly fractured rocks, which is fissure rich and relatively stiff, is located at 300 m from the heavily damaged (Rocherenard) hamlet (Figure S6.1). When (around thirty cases) most evidences correspond to flung rocks, (5) some were found displaced a couple of cm from their original position with no evidence that they slid or rolled on the ground (Figure S6.4). For the others cases, rocks were clearly flung into the air and flipped over, landing in between 10-50 cm from their original location (Figure S6.3). The size of chips and broken rocks are of the order of the $0.1\text{--}1\text{ dm}^3$ (0.5 kg), the largest being the displaced rocks. Similarly to (FR1) area, freshness of cuts and fractures geometries allow to reconstruct the initial rock object from the collected fragments (Figure 4, S6). In between FR2 site and Rocherenard hamlet (Figure S6.6, Table S2), we localized evidences of up-thrown rocks on previously piled up stones, probably a long time ago to clear the fields for farming (*e.g.* ref. ⁸).

At a third location, some isolated (3) rocks on a flat section of a dirt road were found displaced from their original position with no evidence that they slid or rolled on the ground (DR1 on Figure S6.1). These rocks had dimensions of tens of centimeters and had moved a few centimeters. A unique case of a fragmented boulder, the largest of our dataset, we observe on soft detritic soil, half of it still embedded within by its socket (FrB, Figure S6.7). For all displaced rocks cases turf between socket and boulder remained without damage (Figure S6). Furthermore fresh broken twigs below the new boulder location evidence the temporality of the displacement (Figure S6.4). Additional evidences from an anthropic displaced object support a low friction (no friction evidence) displacement of 1 m^3 full of water tanks located 400 m southward from FR2 (DT, Figure S6.8). Such a displaced tank moves 3-6 cm Southward, $\text{N}150^\circ\text{--}180^\circ$ (Figure S6.8). In the three locations we analyzed for displaced rocks, many others chips and stones remain un-displaced. Following Khajavi et al. (2012), non-displaced or non-upthrown boulders with similar morphologies and in close proximity to displaced or upthrown boulders are observed at all sites. Simple in-situ experiments told us that a free fall of about 1 m is sufficient to break (some of) these stones. It supports the observed proximity between non-displaced and displaced rocks is controlled by the heterogeneity of the threshold for rock failure, for similar

impact velocity (e.g. Bouchon et al. 2000). We also tested we did not observed elsewhere, including far apart from the fault trace, any freshly fractured rocks or displaced rocks.

All the observations support the density of upthrown rocks and the location of displaced rocks overlap with the above-gravity peak values of simulated ground motions (Figure 3). It supports strong ground motion to be of the order of the gravity during Le Teil earthquake.

Supplementary References

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Supplementary Table S1: 1D velocity model

Depth (m)	P-wave velocity (m/s)	S-wave velocity (m/s)
0	3366	2047
628	5995	3645
1197	1967	1200
1416	3831	2291
2026	3908	2314
2194	5819	3457
5956	5951	3616

Supplementary Table S2: Displaced rocks data

Site	Local slope	(L) Rock size[*], (T) thickness	Mvt type-evidence	N. Obs.	Comments
FR1	<5°	L 10-30 cm T 3-5 cm	Flip and fragmented – color and reconstructed fragments, former imprint	15	Elongated parallelepiped stones on flat terrains or trails (Figure S6.2)
FR2a	<5°	L 5-30 cm T 1- 5 cm	Flip, fragmented and flaked – color and reconstructed fragments, former imprint	30	- Elongated parallelepiped stones; - Flat and thin flaked chips All located on a small plateau (Figure S6.3)
FR2a	<5°	L 20 -30 cm T 5- 10 cm	Displaced rocks (3-5cm slip), soil imprint	5	Bulky rocks All located on a small plateau (Figure S6.4)
FR2b	<5°	L 20-30 cm T 10-15 cm	Flip, fragmented – color and reconstructed fragments	10	Blocky stones, up-thrown rocks on previously piled up stones (Figure S6.5)
DR1	<10°	L 20 -30 cm T 5- 10 cm	Displaced rocks (few cm slip), soil imprint	3	Blocky stones; across gentle slope slide, along a dirt track (Figure S6.6)
FrB	20°	L 40 cm T 30 cm	Fragmented – color and reconstructed fragments	1	The largest observed broken boulder, half of it still embedded within it socket. (Figure S6.7)
DT	<5°	Cubic water Tank	Displaced object (3-6 cm N150°-180° slip)	1	1x1x1 m full of water plastic tank (Figure S6.8)

^{*}L is the largest rock dimension; Sites correspond to Figures S6.1

Supplementary Table S3: Data of funeral slab displacements observed in cemetery C1. The slabs back onto headstones, so that their motion is blocked in a 180°-wide azimuth range (column 4, see also Figure S7).

Slab label	Slab displacement (cm)	Azimuth of displacement (°)	Range of azimuths in which slab movement is blocked (°)	Observation of slab rotation (° clockwise if any)	Type of interface*
1	1.5	150	[-110 – 70]	No	2
2	3	160	[-110 – 70]	No	1
3	3	160	[-110 – 70]	No	1
4	3.5	-	[-110 – 70]	No	-
5	2	160	[-110 – 70]	No	2
6	4	158	[-110 - 70]	No	2
7	7	162	[-110 - 70]	No	1
8	3.5	118	[-110 - 70]	No	2
9	10	125	[-110 – 70]	No	1
10	4.5	150	[-110 – 70]	No	2
11	3.5	130	[-110 – 70]	No	3
12	3.5	130	[-110 – 70]	No	3
13	1	80	[-110 – 70]	No	1
14	3	145	[-110 – 70]	~10°	1
15	7	129	[-110 – 70]	No	1
16	2	160	[-110 - 70]	No	2
	6	127	[-110 - 70]	~2°	2
	5	160	[-110 - 70]	No	2
	6.8	168	[-110 - 70]	~1°	2
17	4.9	125	[-115 - 65]	No	1
	2.9	129	[-115 - 65]	No	1
18	6.9	133	[-118 - 62]	No	2
	7.3	130	[-118 - 62]	No	2
19	9.6	125	[-118 - 62]	No	2
	7.1	113	[-118 - 62]	No	2
20	1.9	118	[-120 - 60]	No	3
	5.6	126	[-120 - 60]	~1°	3
	6.6	134	[-120 - 60]	No	3
21	4.5	135	[-120 - 60]	No	2
	6.7	123	[-120 - 60]	No	2
22	12.3	140	[-120 - 60]	~2°	2
23	9	147	[-80 – 100]	No	1
24	9	-	[-80 – 100]	~5°	1
25	4	190	[-70 - 110]	No	2
26	3.6	50	[65 – 245]	~1°	2
27	3.5	40	[70 – 250]	No	1
28	1	70	[70 – 250]	~5°	2
29	1.2	65	[70 – 250]	No	2
30	3	60	[70 – 250]	No	1
31	2	65	[70 - 250]	~1°	4
32	1.7	50	[70 - 250]	No	4
33	1	70	[70 - 250]	No	2
34	3	70	[70 - 250]	No	2
35	1.5	62	[120 – 300]	No	1
36	4.3	82	[120 – 300]	~10°	1
37	4	78	[120 – 300]	No	1
38	6.7	38	[60 – 330]	No	2
39	2	318	[70 - 250]	No	2
40	2.5	350	[70 - 250]	No	1
41	3	338	[70 - 250]	~2°	3
42	7.5	-	[70 - 250]	17°	2
43	5.5	337	[70 - 250]	No	1
44	1	70	[70 – 250]	No	-
45	6	138	[170 – 350]	No	1
46	8	140	[170 – 350]	No	1
47	3.5	140	[-90 – 90]	No	1
48	3	134	Not blocked	No	1

* 1: polished granite over smooth granite (except for 33: concrete over smooth granite), 2: rough granite over concrete, 3: rough concrete over rough concrete, 4: smooth granite over smooth granite.

Supplementary Figures

Figure S1: (a) Map of the seismological stations used for the source analysis. (b) Estimation of seismic moment M_0 and corner frequency F_{cP} from the displacement spectra of the recorded P-waves (in the frequency range where the signal-to-noise ratio is above 3), by fitting the source model described in Eq 2 and Eq 3 (Methods). The gray area represents the 68% confidence interval. (c) Bayesian estimation of M_0 , F_{cP} and Q_P (P-wave quality factor). Left: 2D-posterior distribution of F_{cP} and M_0 . Right: 2D-posterior distribution of Q_P and F_{cP} .

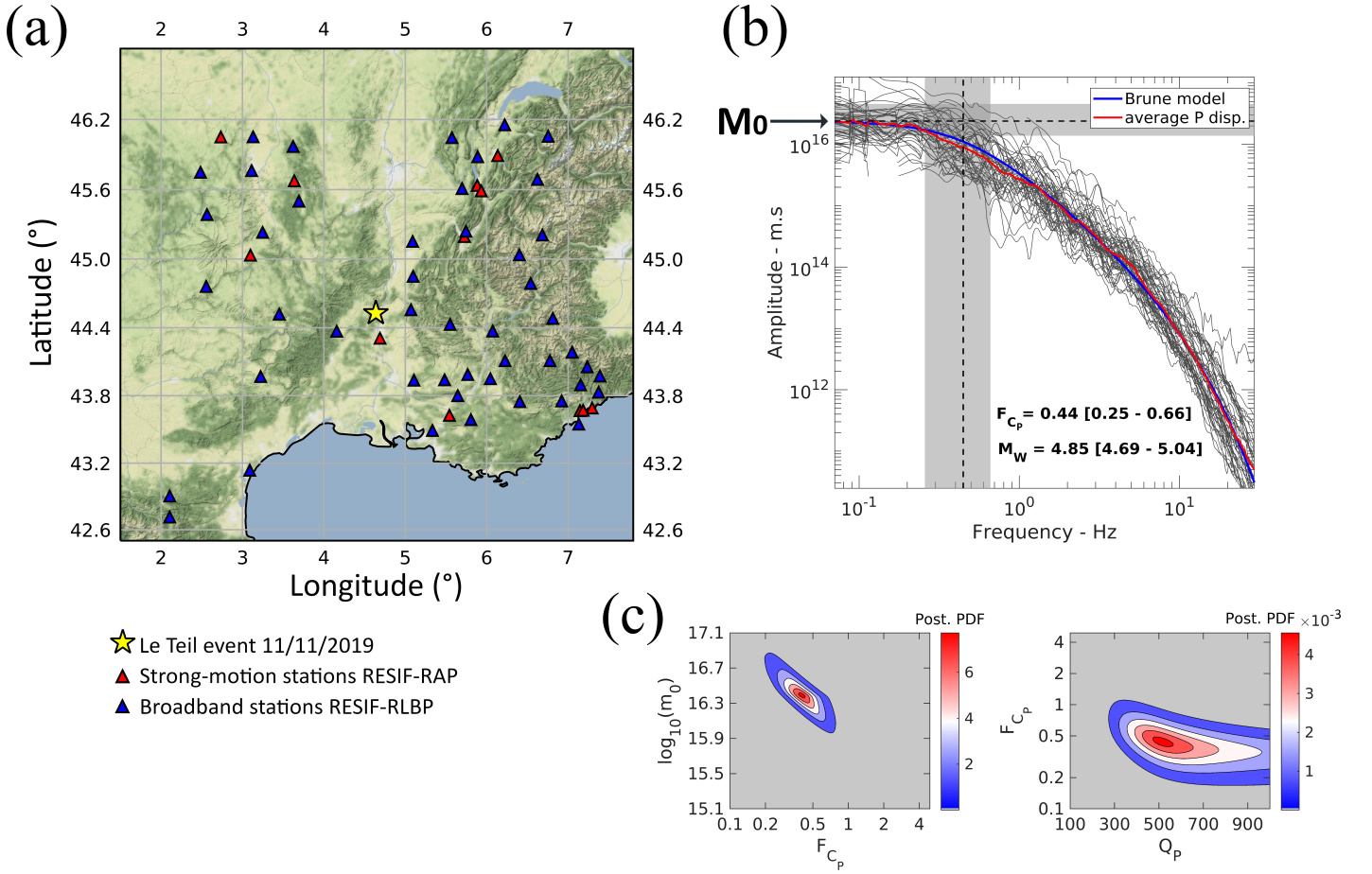


Figure S2: Azimuthal dependency of the corner frequency. Observations are represented by the gray squares (error bars give the median plus or minus standard deviation), while the colored curves are obtained from a line source theoretical model considering a bilateral rupture (left) or a unilateral rupture (right). α is the ratio between the shear-wave and the rupture velocity. i is the takeoff angle.

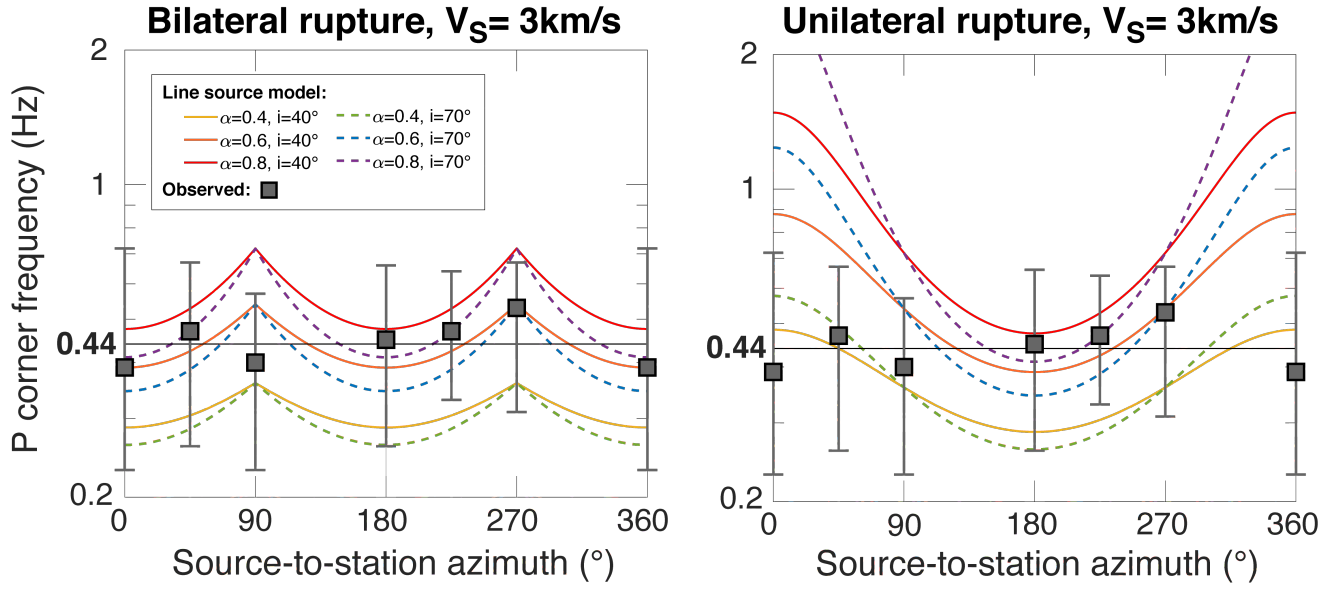


Figure S3: (a) Three realizations of kinematic rupture models (randomly chosen over 2000 realizations), representing the rupture propagation on the fault. f_c is the corner frequency, V_R is the rupture velocity and the rise-time is the local slip duration. The star denotes the hypocenter, the white countourlines represent the rupture front (every 0.25 s), and the color scale indicates final slip (top) or peak slip velocity (bottom). (b) Median profile of the obtained surface slip, and comparison with field observations from Ritz et al. (2020). The dashed line represents the median plus or minus standard deviation (computed over 2000 realizations of rupture models). (c) Example of source time functions (or moment rate functions), including the three rupture models shown in (a). (d) Left: Source spectra (amplitude Fourier spectra of the source time function) for the 2000 realizations of rupture models (gray lines). The black line represents the average and the red line is the best fitting Brune (1970) source model; (right): distribution of the rupture duration (duration of the source time function). The average value of 2 s matches the value inferred from the far-field seismological observations.

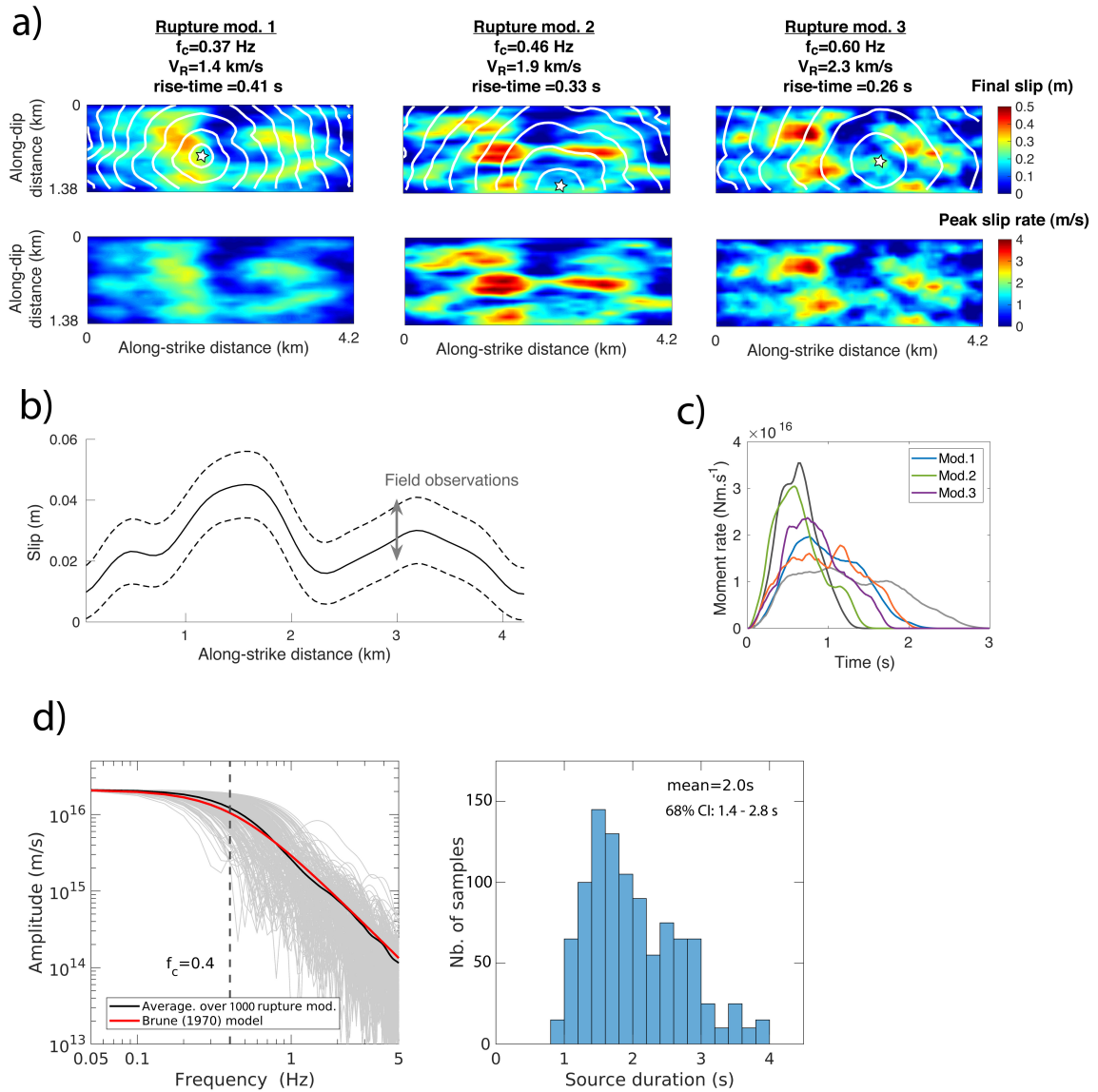


Figure S4: Top: simulated median values of the Peak Ground Velocity (PGV) between 0 and 5 Hz on the array of virtual stations. The inter-stations distance is 500 m. Bottom: PGV variability, computed over 2000 rupture realizations, expressed in terms of the standard deviation of the log10 values. The dashed rectangle represents the surface rupture projection. The thick black polygon line is the area where displaced rocks are observed.

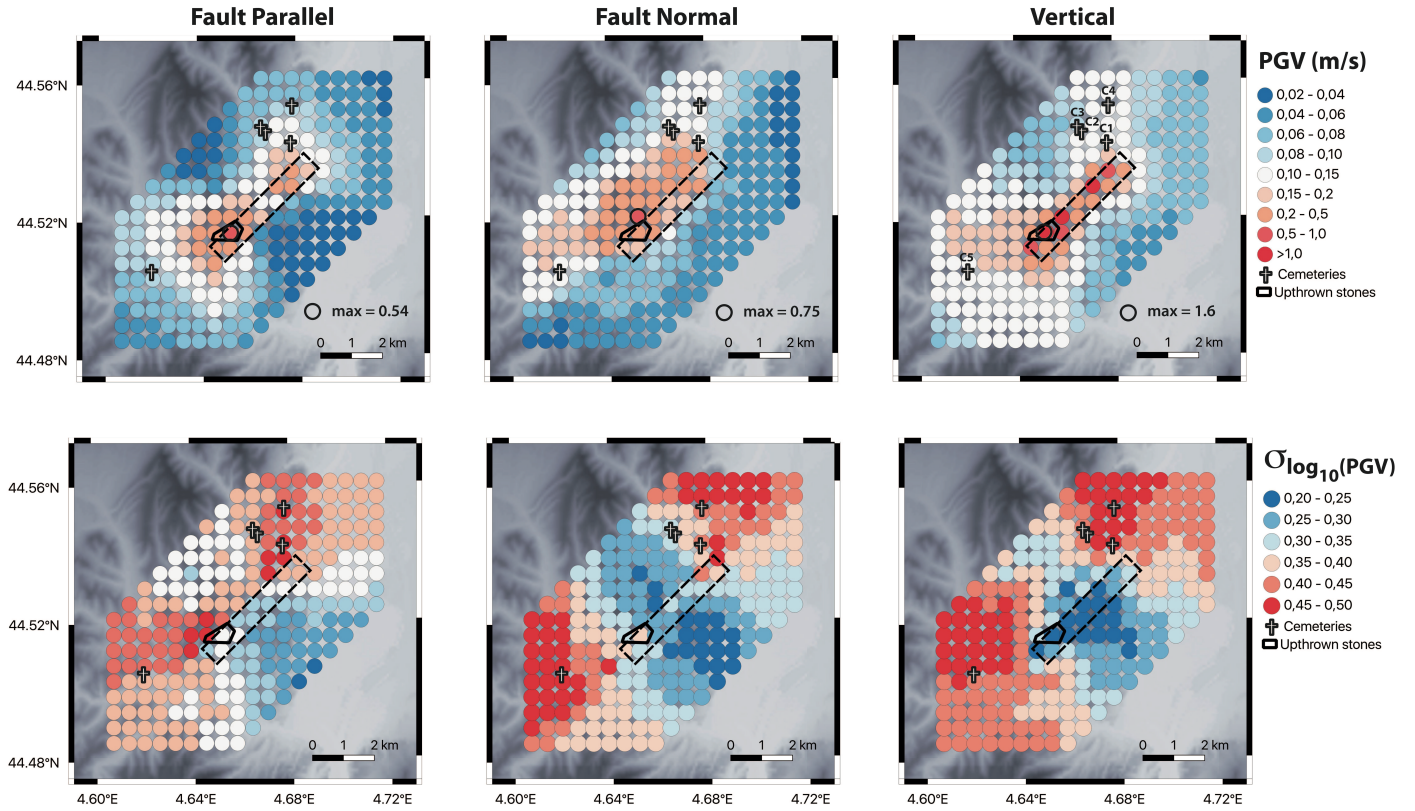


Figure S5. Extracted Rayleigh (a) and Love (b) wave phase velocities and (c) signed ellipticity angle of Rayleigh waves as a function of frequency with their uncertainty (black dots with error bars indicated the median plus or minus standard deviation). Gray curves indicate dispersion data (phase velocities, signed ellipticity angle) forward modeled from velocity profiles indicated in (d). (d) Ensemble of inverted V_P and V_S profiles (gray curves) that explain dispersion data within their uncertainty bounds. Best misfit profiles are indicated in black. This analysis has been performed using 6 days of seismic ambient noise recorded at 19 temporary broadband stations, shown in Figure 1a.

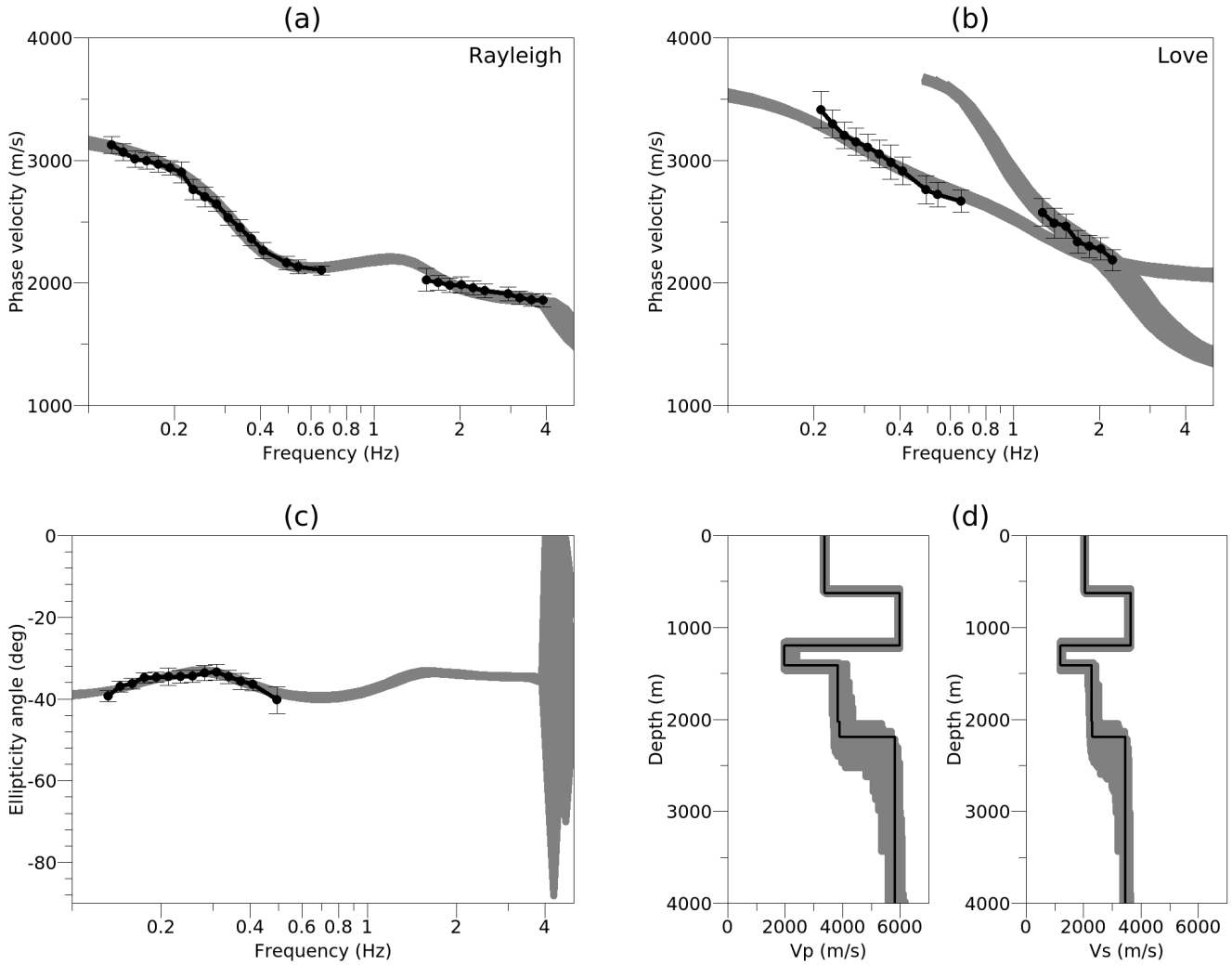


Figure S6: Displaced rocks. The locations of these rocks are defined on Figure (S6.1). The Figures (S6.2-S6.8) describe the types and evidences of movement for the displaced rocks we report.



Figure S6.1.: Synthesis map of observed displaced rocks. Blue square, evidence for flung broken rocks. Blue triangles, displaced rocks. Blue circle, (FrB) is the largest, isolated, fractured boulder. Red triangle, (DT) displaced water tank. Arrows are earthquake triggered rockfalls. Red dotted line is the surface fault rupture (adapted from Cornou et al. (2020)). FR1, FR2ab, DR1 refer to observation site as described below. All these site correspond to the polygon area on Figures 1-2. (Maps Data: Google, ©2019 CNES / Astrium, Maxar Technologies).



Figure S6.2a: FR1, flipped rock; the white face denotes flip; initial soil imprint is identified, on the right side.



Figure S6.2b: FR1, broken flung rocks. The two fragments match each other.



Figure S6.2c: FR1, broken flung rocks. (left) as observed; (right) fragment reconstruction.



Figure S6.3a : FR2a site, overview of local landscape: (upper left), local landscape looking NE ; the white arrow is a rare large boulder we observe locally; (upper right) looking SW; (bottom) zoom on the large (50x60x40 cm) boulder the arrow points onto. It stays undisturbed, located in the vicinity (30m) from displaced rocks cases of figure (3b). Red compass and (upthrown) broken stones at the bottom of upper figures relate to figure (3b) for references.



Figure S6.3b. FR2, Slabs of rock flung into the air and flipped over. (left) as observed ; (right) fragment reconstruction.



Figure S6.3c: FR2a chips flip: (left) observation, (right) reconstruction from fragments.



Figure S6.3d.: FR2a, Bulky broken stones: (left) observation, (right) reconstruction from fragments and color tones.



Figure S6.3e.: FR2, bulky broken stones : (left) observation, (right) reconstruction from fragments and color tone



Figure S6.4a.: FR2a site, displaced boulder (downward on the figure).



Figure S6.4b.: FR2a site, flung rock (right direction on the figure) with initial imprint location.



Figure S6.4c. FR2a site, flung rock (leftward on the figure) with initial imprint location. Note the broken twig on the bottom left on the current rock location.



Figure S6.5.: FR2b site, up-thrown rocks, on previously piled up stones. (left) observed white stones faces; (right) reconstructed position with grey face up for the bottom boulder.



Figure S6.6.: DR1site, 2 displaced boulders (downward displacement on the figure).



Figure S6.7.: FrB site, the largest broken boulder : (top) observed fragment locations ; (middle-bottom) reconstructed boulder fragments. Half of the boulder is broken and ejected. The others 2 fragments remain inside the soil socket.



Figure S6.8.: DT, displaced water-tank site. Three displaced water tanks (1 ton each). (top left) full view of one tank; (top right and bottom) zoom on the distance in between former tank location (ageing tank imprint on the concrete-stone) and the post earthquake location that points on a 5 cm displacement without friction evidence.

Figure S7: Representation of the funeral slab displacement vectors of Table S3, observed in cemetery C1. The colored areas represent the azimuth ranges in which the slab motions are blocked by the headstones. The different colors represent the type of interface, as reported in Table S3.

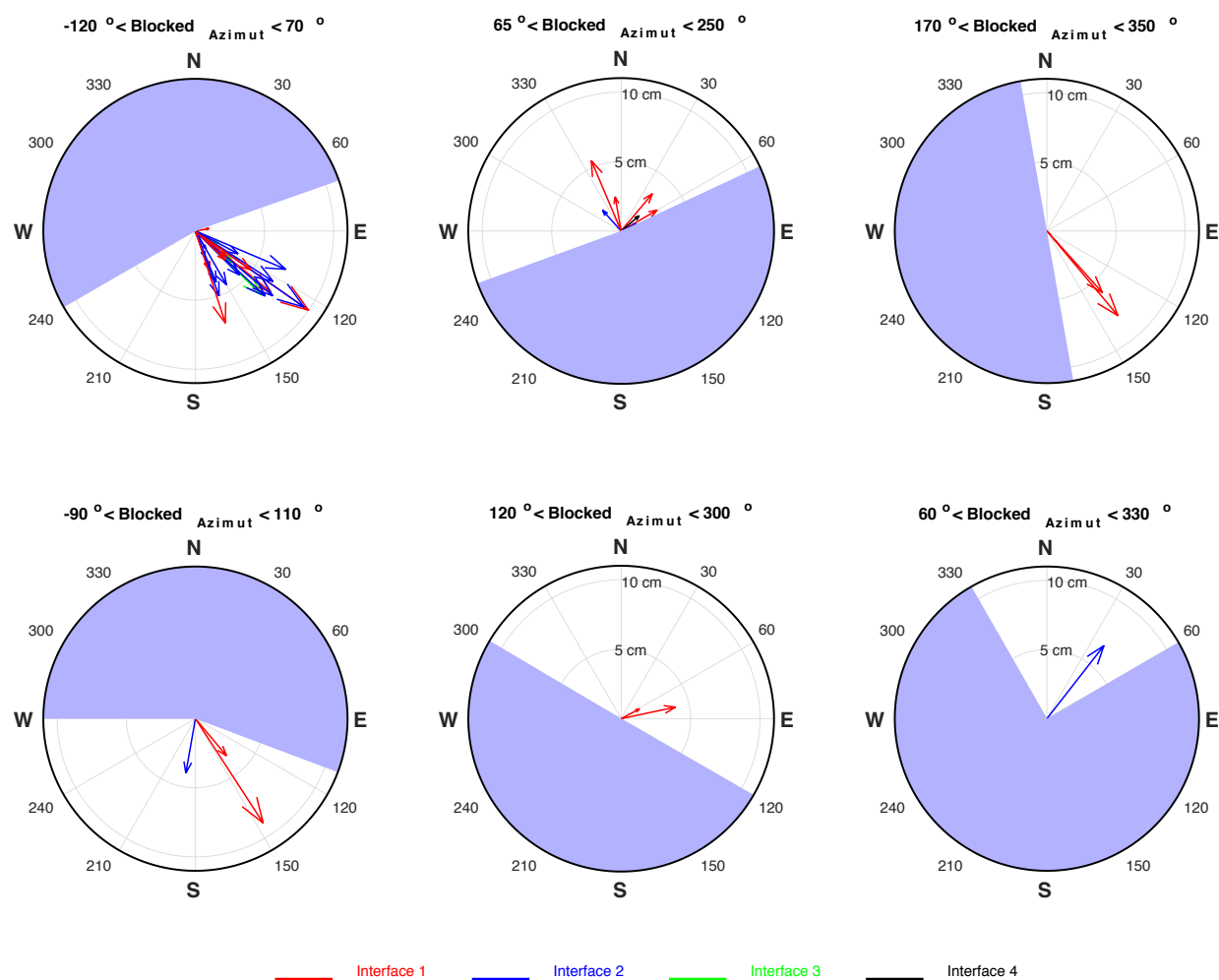
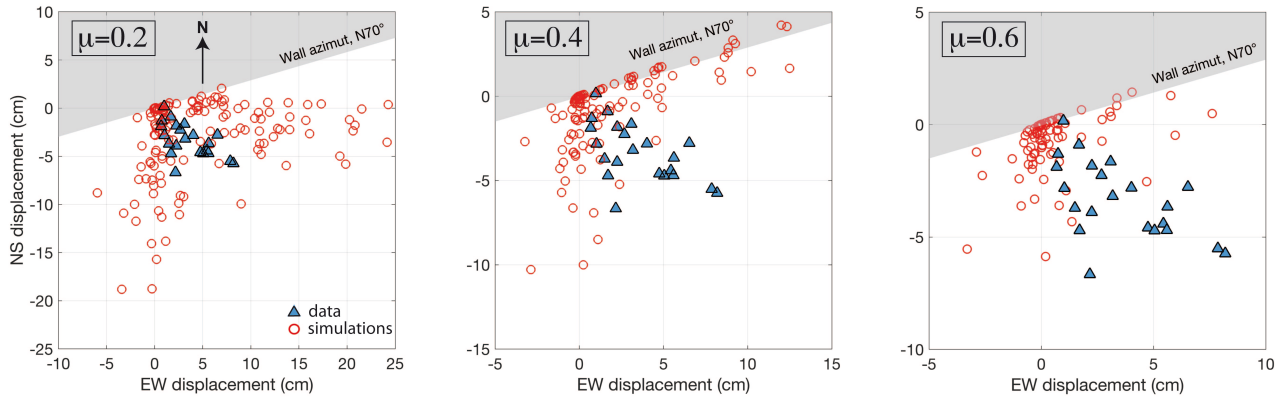


Figure S8: (a) Comparison between observed and simulated funeral slab displacement in the EW-NS plane for different values of the friction coefficient μ . The gray area represents the directions in which the slab motion is prevented by the headstones. The dataset (blue triangles) includes only slabs that have not experienced rotation during the ground shaking. For a better visualization, the modeled slab displacements are only shown for the first 250 ground motion simulations (red circles). (b) Comparison between modeled slab displacements for slab motion blocked by the headstone toward SE or NE, for different values of the friction coefficient μ . As for (a), only 250 simulations are displayed.

a) Comparison between observed and simulated slab displacement



b) Comparison between simulated slab displacement for slab motion blocked toward SE ("move NW") or NW ("move SE")

