Communications Earth & Environment

Supplementary Information for

Immediate foreshock–mainshock arise from a paused model

Xueting Wei[1] and Xiaofei Chen[2,3]

1 School of Earth and Space Science and Technology, Wuhan University, Wuhan, 430072, China.

2 Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen, 518055, China.

3 Guangdong Provincial Key Laboratory of Geophysical High-resolution Imaging Technology, Southern University of Science and Technology, Shenzhen, 518055, China.

Contents of this file

List of Supplementary Items

Introduction

The Supplementary Information includes:

1. event information for representative foreshocks and mainshocks (Supplementary Table S1), relocation results (Supplementary Table S2), and the EGFs and comparison events used in the empirical Green's function analysis (Supplementary Table S3);
2. Source characteristics of earthquake pairs in Japan within a 30 s window (Supplementary Fig. S1);
3. an illustrative foreshock–mainshock pair (Supplementary Fig. S2) and a pair of consecutive events (Supplementary Fig. S3), each with waveforms and velocity spectra;
4. station-by-station waveforms used in the EGF analysis (Supplementary Figs. S4 and S6), and the corresponding spectra and relative source time functions (rSTFs) for representative foreshocks and comparison isolated events at five Hi-net stations (Supplementary Figs. S5 and S7);
5. the model used for dynamic numerical simulations of a paused rupture (Supplementary Fig. S8), the adopted model parameters (Supplementary Table S4), and the source parameters for the two stages representing the foreshock and mainshock (Supplementary Table S5).

Pair ID	Event	Datetime (JST)	Longitude (°E)	Latitude (°N)	Depth (km)	Magnitude (Mw)
(1)	Foreshock	2010-08-06 13:48:33.02	140.7617	39.1995	7.60	2.2
(1)	Mainshock	2010-08-06 13:48:50.10	140.7705	39.2020	7.50	3.4
(2)	Foreshock	2020-12-18 18:09:41.9	139.3047	34.4885	11.07	3.2
(2)	Mainshock	2020-12-18 18:09:56.61	139.3035	34.4880	10.99	5.0
(3)	Foreshock	2020-04-23 15:59:07.93	137.6125	36.2215	5.04	2.0
(3)	Mainshock	2020-04-23 15:59:42.89	137.6462	36.2470	5.52	3.1
(4)	Foreshock	2020-05-19 16:07:10.77	137.6290	36.3028	2.92	2.0
(4)	Mainshock	2020-05-19 16:07:27.69	137.6373	36.2762	3.79	2.8

Supplementary Table S1. Event information for immediate foreshock–mainshock pairs (1–4) from the JMA Unified Hypocenter Catalog.

Pair ID	Event	Datetime (JST)	Longitude (°E)	Latitude (°N)	Depth (km)	Magnitude (Mw)
(1)	Foreshock	2010-08-06 13:48:33.02	140.7620	39.1994	7.499	2.2
(1)	Mainshock	2010-08-06 13:48:50.10	140.7642	39.1994	7.925	3.4
(2)	Foreshock	2020-12-18 18:09:41.9	139.3014	34.4872	11.008	3.2
(2)	Mainshock	2020-12-18 18:09:56.61	139.3012	34.4869	11.056	5.0
(3)	Foreshock	2020-04-23 15:59:07.93	137.6128	36.2184	4.778	2.0
(3)	Mainshock	2020-04-23 15:59:42.89	137.6484	36.2465	5.993	3.1
(4)	Foreshock	2020-05-19 16:07:10.77	137.6288	36.3019	3.726	2.0
(4)	Mainshock	2020-05-19 16:07:27.69	137.6364	36.2727	4.284	2.8

Supplementary Table S2. Event information for immediate foreshock–mainshock pairs (1–4) after hypocentre relocation.

Pair ID	Event	Datetime (JST)	Longitude (°E)	Latitude (°N)	Depth (km)	Magnitude (Mw)
(1)	EGF	2010-08-08 02:56:54.51	140.7604	39.2004	7.566	1.1
(1)	Comparator	2010-08-04 20:15:03.64	140.7656	39.2002	8.278	2.2
(2)	EGF	2020-12-16 00:47:04.75	139.3003	34.4892	11.368	1.9
(2)	Comparator	2020-12-18 19:11:37.17	139.3119	34.4842	10.529	2.9

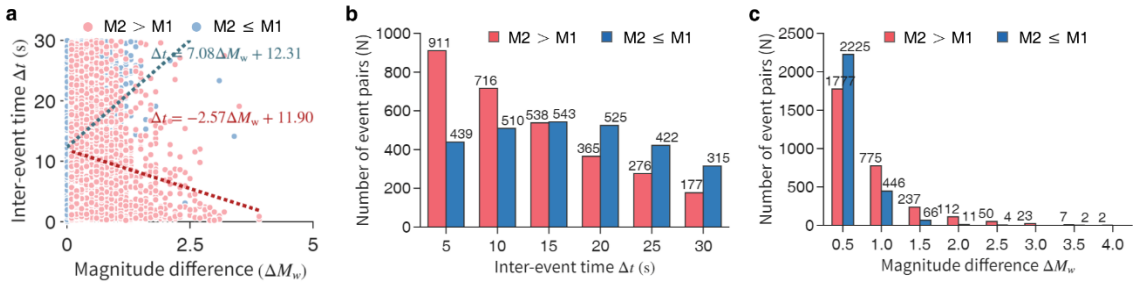
Supplementary Table S3. Event information for the EGF and for isolated earthquakes comparable in magnitude to the immediate foreshock, for pairs (1) and (2).

Definition	Parameter	Value
P-wave velocity	v_{p}	6.000 km/s
S-wave velocity	v_{s}	3.464 km/s
Density	ρ	2670 kg/m^3
Reference friction coefficient	μ_0	0.6
Reference slip rate	V_0	10^{-6} m/s
Initial slip rate	V_{ini}	10^{-9} m/s
Initial shear stress	τ_{ini}	6 MPa
Effective normal stress	$\bar{\sigma}$	10 MPa
Stress perturbation within the nucleation zone	$\Delta\tau_0$	2 MPa
Direct effect coefficient in the velocity-weakening region	a	0.008
Direct effect coefficient in the velocity-strengthening region	a	2.000
Evolution effect coefficient	b	0.080
Characteristic slip distance	L	0.0078 m
Grid size	ds	15 m
Spatial grid size	$N \times N$	160× 160
Nucleation zone radius	R_{a}	300 m
Radius of the velocity-weakening zone	B_{a}	1200 m

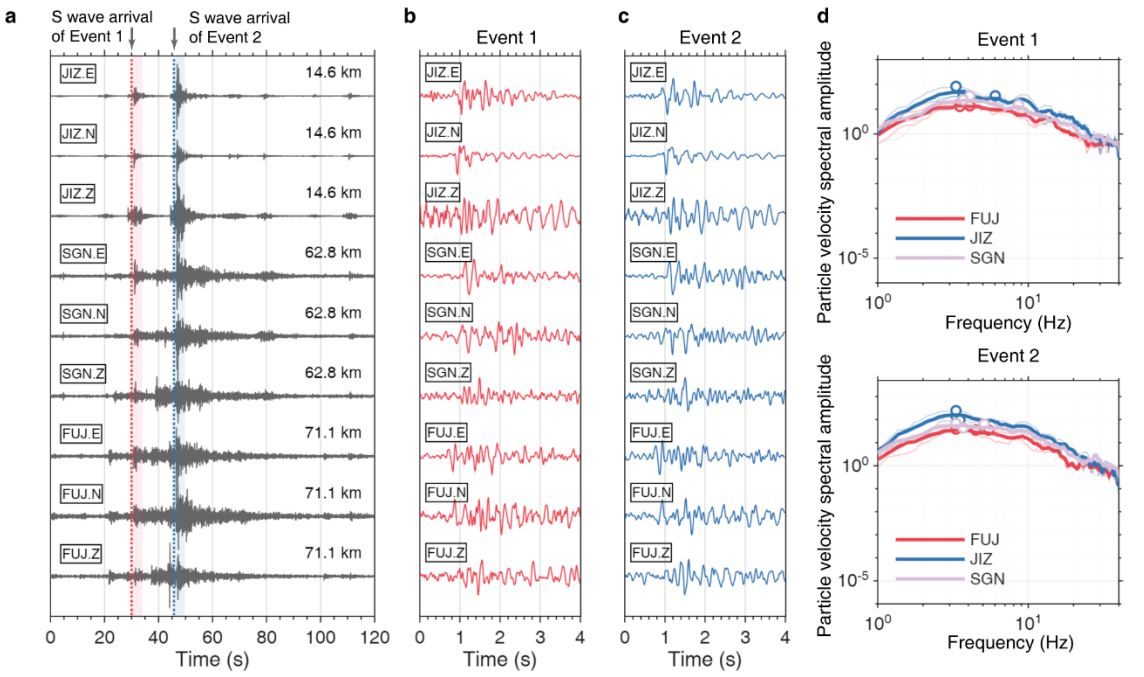
Supplementary Table S4. Numerical values of the computational grid, stress, and constitutive parameters used in the rupture transition simulation.

Source parameter	Unit	Overall	SSAR	Sub-Rayleigh	Rupture pause
Source duration	s	7.92	0.60	1.32	6.00
Stress drop	MPa	7.37	0.76	7.29	0.73
Slip	m	0.21	0.01	0.21	0.01
Slip rate	m/s	0.03	0.01	0.16	0.0024
M_0	N·m	3.03×10^{16}	8.15×10^{13}	2.98×10^{16}	1.84×10^{14}

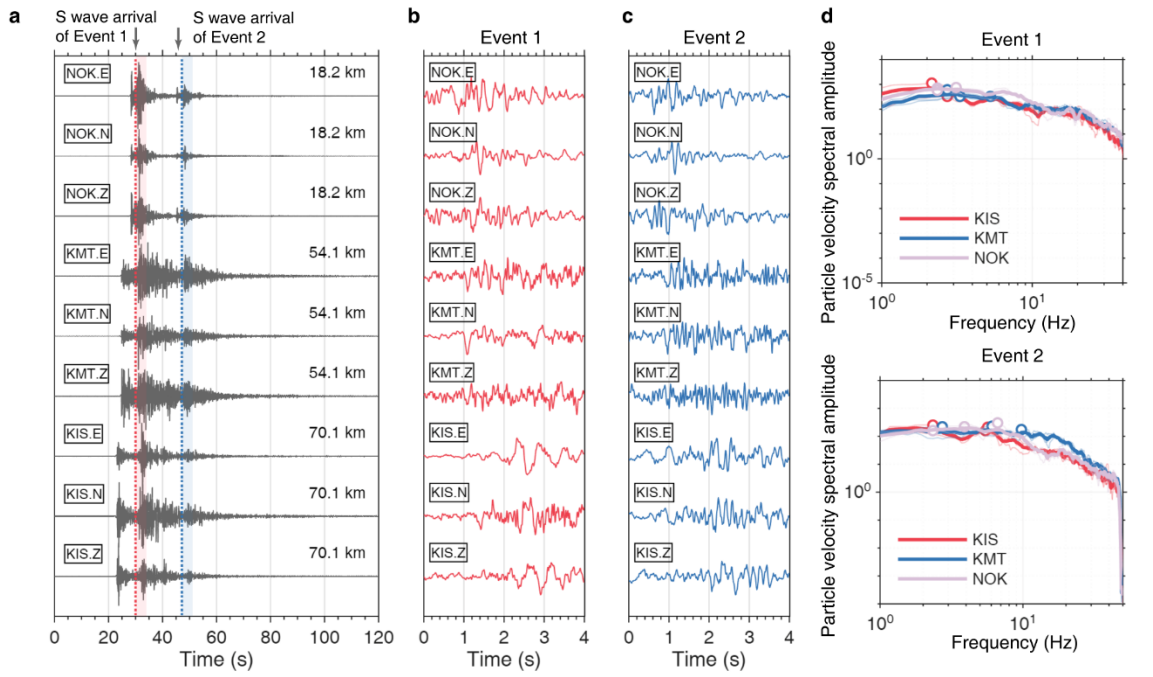
Supplementary Table S5. Summary of source parameters that characterize the transition from slow, self-arresting to sub-Rayleigh rupture, with phase-specific values for the slow self-arresting, pause and sub-Rayleigh stages. Stress drop, slip and slip rate are averaged across the effective rupture area.



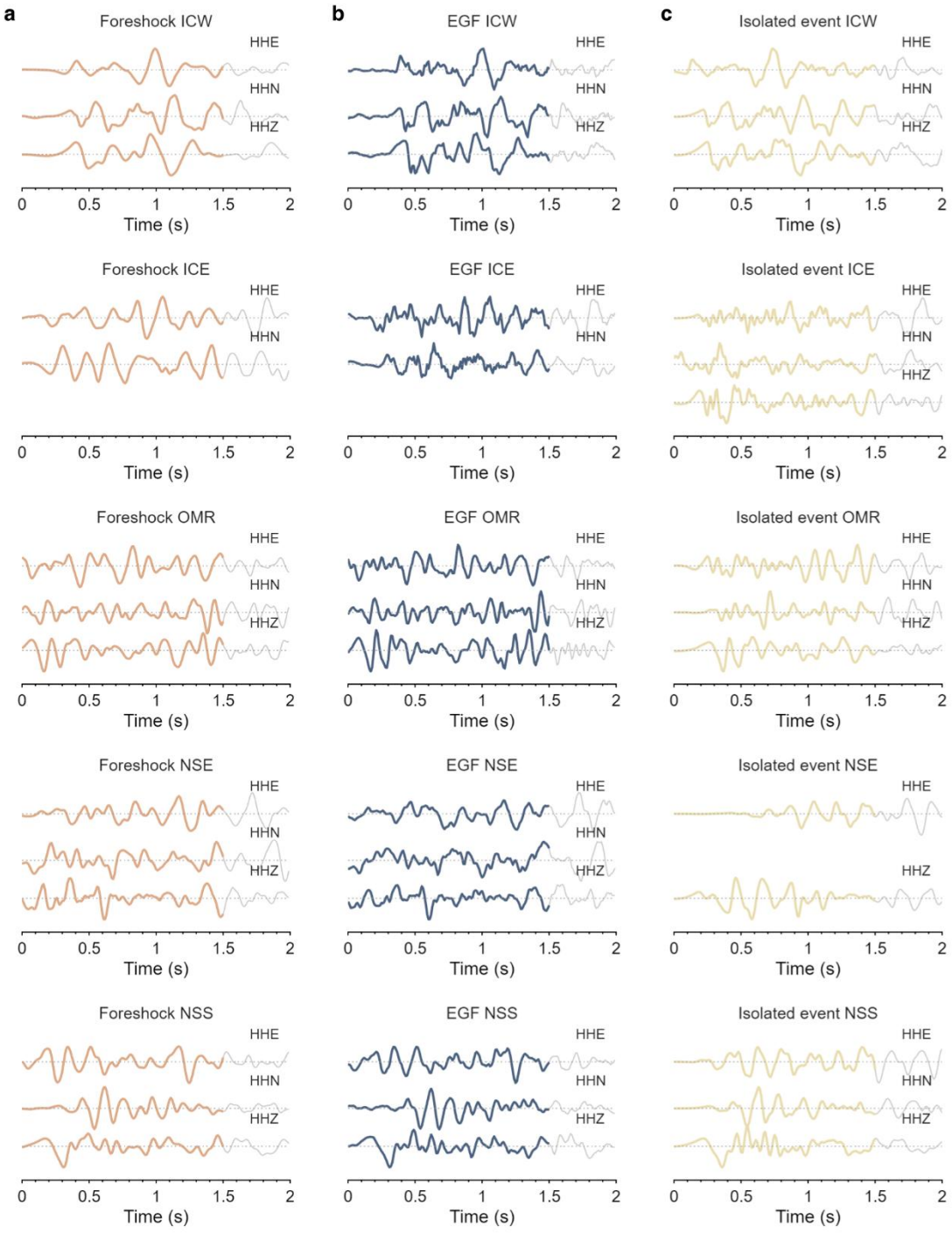
Supplementary Fig. S1. Characteristics of event pairs occurring within 30 s across Japan. **a**, Absolute magnitude difference |M2 − M1| versus inter-event time. Foreshock–mainshock pairs (M2 > M1), red; consecutive pairs (M2 ≤ M1), blue. **b**, Histogram of inter-event times. **c**, Histogram of |M2 − M1|.



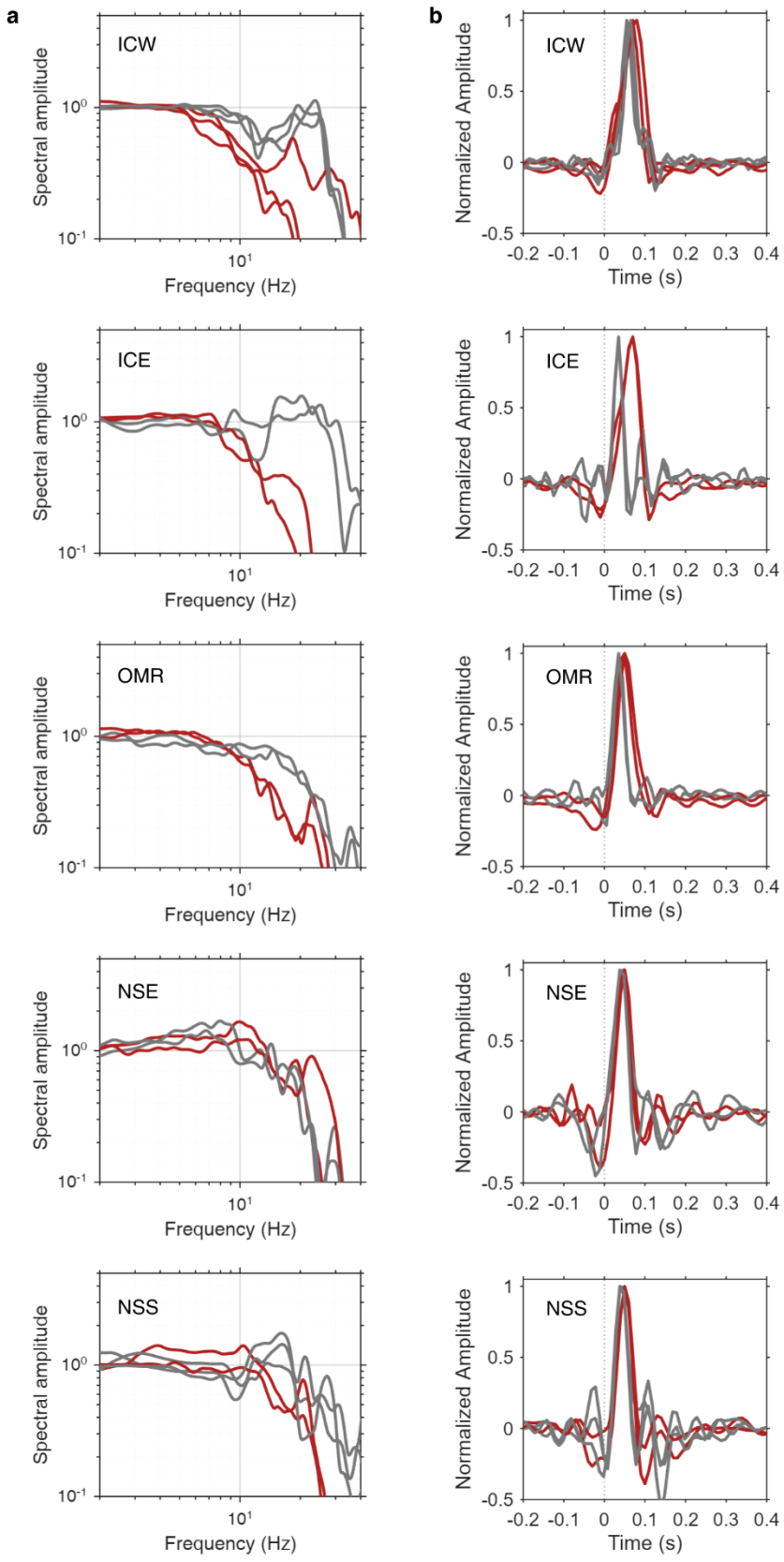
Supplementary Fig. S2. Example waveforms and velocity spectra of a foreshock–mainshock pair. **a**, Example pair: Event 1 (M_w 2.0; 2009-12-18 05:08:19.20 JST; 34.9672°N, 139.1273°E; depth 5.71 km) and Event 2 (M_w 2.7; 2009-12-18 05:08:34.89 JST; 34.9685°N, 139.1277°E; depth 6.01 km), with velocity records at F-net stations JIZ, SGN and FUJ. Waveforms are band-pass filtered to 2–40 Hz. Red dashed lines mark the S arrival of Event 1; blue dashed lines, that of Event 2. **b**, 4 s window starting 0.5 s before the S-wave onset of Event 1 used for spectral analysis. **c**, 4 s window starting 0.5 s before the S-wave onset of Event 2 used for spectral analysis. **d**, Mean velocity spectra across the three stations (three components averaged per station); circles denote apparent corner-frequency picks.



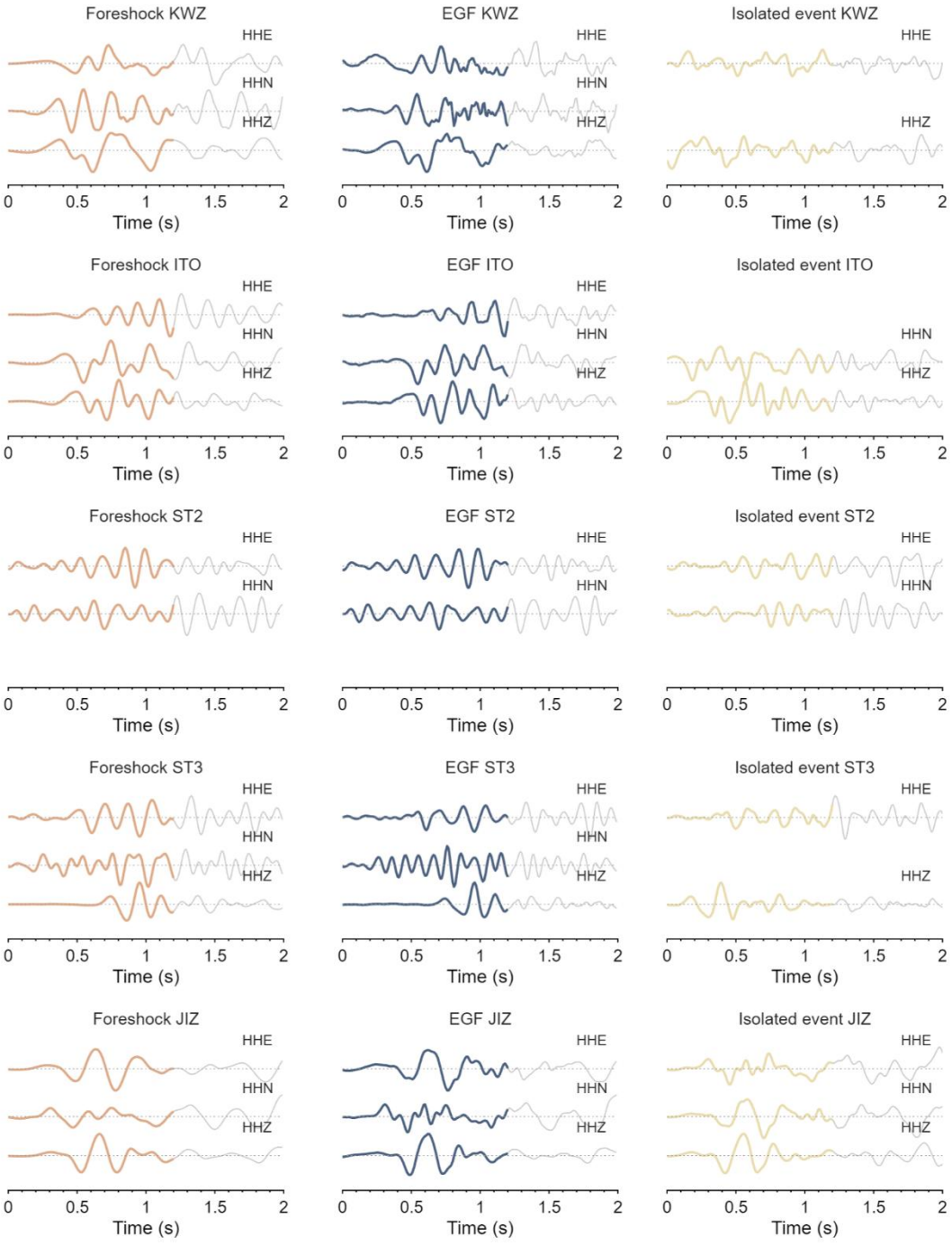
Supplementary Fig. S3. Example waveforms and velocity spectra of a consecutive pair. **a**, Example pair: Event 1 (M_w 3.4; 2013-07-03 09:52:26.77 JST; 34.0902°N, 135.1835°E; depth 5.81 km) and Event 2 (M_w 2.8; 2013-07-03 09:52:43.81 JST; 34.0889°N, 135.1753°E; depth 5.30 km), with velocity records at F-net stations NOK, KMT and KIS. Waveforms are band-pass filtered to 2–40 Hz. Red dashed lines mark the S arrival of Event 1; blue dashed lines, that of Event 2. **b**, 4 s window starting 0.5 s before the S-wave onset of Event 1 used for spectral analysis. **c**, 4 s window starting 0.5 s before the S-wave onset of Event 2 used for spectral analysis. **d**, Mean velocity spectra across the three stations (three components averaged per station); circles denote apparent corner-frequency picks.



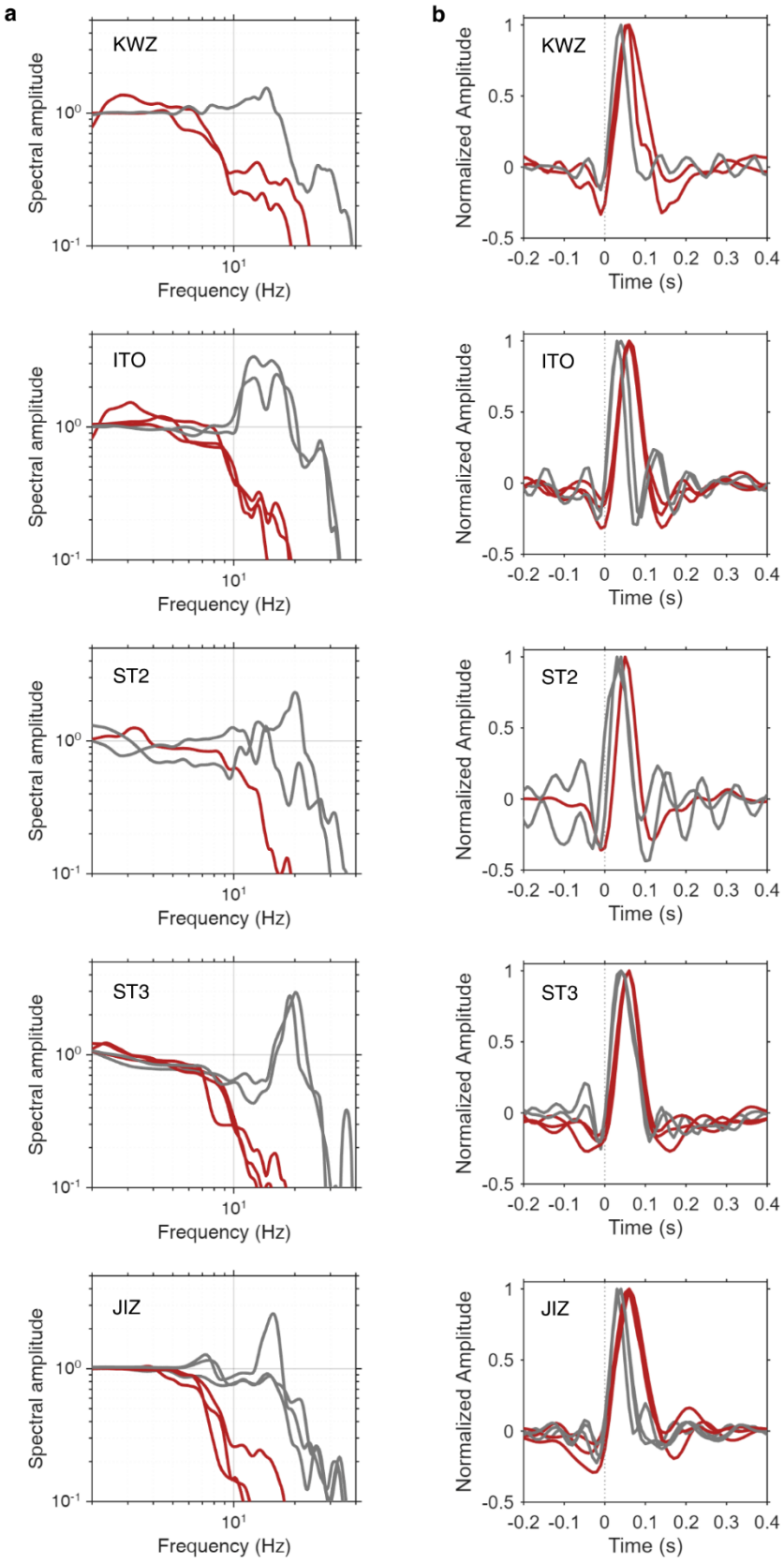
Supplementary Fig. S4. Pair (1): 1.5 s P-wave displacement windows for EGF inversion. All traces are band-pass filtered 2-40 Hz. **a**, foreshock windows at each station (orange); **b**, EGF windows (blue); **c**, equal-magnitude isolated-event windows (yellow).


a
b
ICW
ICE
OMR
NSE
NSS
Spectral amplitude
Frequency (Hz)
Normalized Amplitude
Time (s)

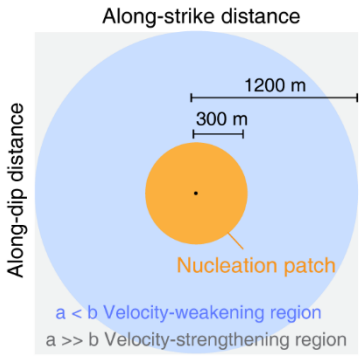
Supplementary Fig. S5. Pair (1): Source spectra **a** and rSTFs **b** at each station for the foreshock and an equal-magnitude isolated event. Red lines indicate the foreshock; grey lines indicate the isolated event.



Supplementary Fig. S6. Pair (2): 1.5 s P-wave displacement windows for EGF inversion. All traces are band-pass filtered 2-40 Hz. **a**, foreshock windows at each station (orange); **b**, EGF windows (blue); **c**, equal-magnitude isolated-event windows (yellow).


a
b
KWZ
ITO
ST2
ST3
JIZ
Spectral amplitude
Frequency (Hz)
Normalized Amplitude
Time (s)

Supplementary Fig. S7. Pair (2): Source spectra **a** and rSTFs **b** at each station for the foreshock and an equal-magnitude isolated event. Red lines indicate the foreshock; grey lines indicate the isolated event.



Supplementary Fig. S8. Model geometry and frictional zoning. A prestressed nucleation patch (yellow) is embedded in a velocity-weakening domain (blue) and surrounded by a velocity-strengthening barrier (grey) that arrests rupture propagation.