

Supplementary Information of the Manuscript

“The deterministic behaviour of earthquake rupture beginning”

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Supplementary Notes 1

Synthetic Displacement Waveforms from the Sato & Hirasawa (1973) Rupture Model

The far-field displacement waveform at a generic receiver located at position $\mathbf{r}$ in a homogeneous, elastic, unbounded, and isotropic medium is given approximately by Aki and Richards (1980):

$$u_c(r, t) = \frac{\mu \mathcal{R}_c}{4\pi \rho c^3 r} \Omega_0 \hat{e}_c,$$

where c is the P- or S-wave velocity, ρ is the density, μ is the rigidity, $\mathcal{R}_c$ is the radiation pattern coefficient, and r is the source-receiver distance. All of these quantities are considered independent of the point ξ on the fault surface (Fraunhofer approximation). The term Ω_0 is defined as:

$$\Omega_0 = \iint_{\Sigma} \Delta \dot{u} \left(\xi, t - \frac{r}{c} \right) d\Sigma, \quad 1$$

where Σ represents the circular fault area and $\Delta \dot{u}$ is the slip-rate function. Additionally, it is assumed that all points on the fault ξ contribute equally in terms of travel time from source to receiver.

Using the slip-rate function proposed by Sato and Hirasawa (1973), the far-field displacement is obtained by computing the time integral of the following expression:

$$\Delta \dot{u}(t, \rho_f) = \begin{cases} \frac{K v_r^2 t}{(v_r t)^2 - \rho_f^2} H\left(t - \frac{\rho_f}{v_r}\right) [1 - H(\rho_f - \rho_0)], & \text{if } 0 < v_r t < \rho_0, \\ 0, & \text{if } v_r t > \rho_0, \end{cases} \quad 2$$

where $K = \frac{24}{7\pi} \frac{\Delta\sigma}{\mu}$, $\Delta\sigma$ is the static stress drop, ρ_f is the distance from the fault center to a point on the fault, ρ_0 is the final radius of the circular fault, v_r is the rupture velocity, and $H(\cdot)$ is the Heaviside step function.

By substituting $\Delta\dot{u}(t - r/c)$ into the surface integral and evaluating it over a circular fault of radius ρ_0 , Sato and Hirasawa (1973) derived the following expression for Ω_0 :

$$\Omega_0 = \begin{cases} 2K v_r \rho_0^2 \left[\frac{\pi}{(1 - k^2)^2} \right] x^2, & \text{if } 0 < x < 1 - k, \\ 2K v_r \rho_0^2 \frac{\pi}{4} \left[\frac{1}{k} - \frac{x^2}{k(1 + k)^2} \right], & \text{if } 1 - k < x < 1 + k, \end{cases} \quad 3$$

with

$$x = \frac{v_r(t - r/c)}{\rho_0}, \quad k = \frac{v_r}{c} \sin\theta,$$

where θ is the angle between the fault normal and the source-receiver ray direction.

Equation (1) is employed to compute theoretical far-field P- and S-displacement waveforms at a set of receivers located on the Earth's surface (Figure S4). The source is modeled as a double-couple fault rupturing according to the circular kinematic model of Sato and Hirasawa (1973), as applied in Lambiase et al. (2024).

This modeling framework is applicable to any double-couple source with known parameters such as magnitude, depth, focal mechanism, rupture velocity, and stress drop. To simulate the effect of anelastic attenuation, the synthetic seismograms are convolved with the constant- Q operator described by Kjartansson (1979).

Supplementary Notes 2

Significant differences with previous works

Significant differences in the processing of data may justify the observed differences in the initial rate of the *P*-wave displacement amplitude with other works (Meier et al. (2016), Meier et al. (2017), Trugman et al. (2019), Odaka et al. (2003)).

The analysis of Meier et al. (2016) mostly concerns few records per magnitude bin and a very limited observation distance (25 km) around the source, thus including possible biases due to the high variability of estimates of magnitude, depth, focal mechanism, directivity, etc., which can significantly affect the *P*-amplitude of a single or very few near source records.

In the work of Trugman *et al.* (2019) the peak displacement measurements are provided with a time step of 0.2 s, which does not allow to properly capture the variations at very short time scales. In our work, we computed the LP_dT curves with a time step of 0.01 s, which allows to see amplitude variations on a very short time scale. This is especially true for small events, for which the largest, initial amplitude variations typically occur on a time scale smaller than 0.1s and the under-sampling with a time-step of 0.2s has the effect of introducing a smaller initial slope ([Text S1 and Fig. S12](#) of the Supporting Information of Colombelli et al. (2020)). Another difference is that Trugman *et al.* (2019) are mixing different events in magnitude bins of 0.5 to compute the curves, while in our analysis, we compute LP_dT curve for single events and do not mix different earthquakes for the curve computation. Furthermore, in their Fig. 3, Trugman *et al.* (2019) showed the time evolution of the curves for different magnitude classes using a unique time and amplitude

scale that compresses all the curves and does not allow to see the detailed behavior and the initial variations of the slope in a very short time range. When zooming in using a short time scale and shifting the curves at the same starting amplitude, the initial variations of the curves appear more evident, as discussed in [Text S1 and Fig. S13](#) of the Supporting Information of Colombelli et al. (2020).

As for Meier *et al.* (2017), they analysed a catalogue of teleseismic STFs of large ($M \geq 7$) subduction zone earthquakes. Because of the signal low-frequency content, the analysed STFs have an intrinsic low time resolution at short periods (smaller than 1-2 sec). Moreover, the STFs were normalized using the centroid time, which is an assumption that requires that STFs have a triangular shape. As done in Meier *et al.* (2016), the authors finally computed the average STFs for a large magnitude bin (7.7–9), for which remarkable differences in the source process can be existent.

Finally, Odaka *et al.* (2003) measured the initial rate of the *P*-wave amplitude and show that this is almost independent of the earthquake magnitude and variable with the recorded epicentral distance. Indeed, they propose the use of the initial rate of the *P*-wave to rapidly estimate the epicentral distance, shortly after the *P*-wave arrival. They used a fitting function of the type $Bt \cdot \exp(-At)$ that depends on two parameters (*A* and *B*), both estimated in a fixed, 3-s time window after the *P*-wave arrival. When discussing the *A* parameter, the authors declare that a positive value of *A* is typical for small earthquakes, indicating that the initial amplitude increases sharply and decays quickly soon after the *P*-wave arrival. On the contrary, when *A* is negative, the initial amplitude increases exponentially with time, and this is a characteristic of large earthquakes, so that they expect that this parameter may be useful for distinguishing large and small earthquakes. As for the other parameter, the authors claim that the *B* value defines the slope of the initial part

of the P waves and can be used to quantitatively characterize the initial rate of the P -wave amplitude. However, given the exponential form of the proposed model, the actual slope of the fitting function is a combination of both A and B. Because of the observed differences in the A parameter for small and large events, a potential scaling with magnitude of the initial slope is not discarded in the Okada *et al.* (2003) model.

Supplementary References

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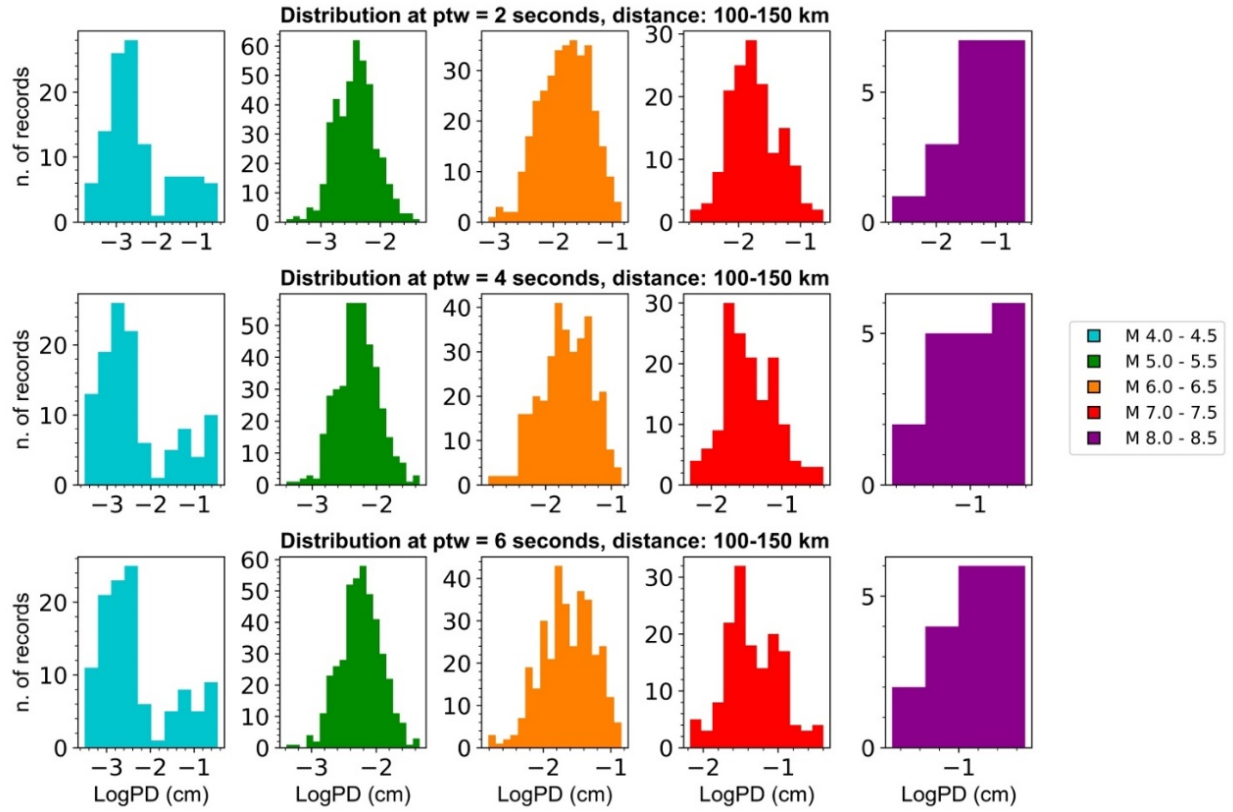


Figure S1: Distribution of Logarithm of P-peak displacement in different P-time windows

(ptw). The figure shows the distribution of P-peak amplitude data in each magnitude bin, to compute, where the mean value and the standard deviation is computed. Histograms show a Gaussian-like shape, at least in the most populated bins. From top to bottom: ptw = 2 seconds; ptw = 4 seconds; ptw = 6 seconds. Distance range is 100 – 150 km, where there is the most completed data availability. Histograms are colored according to the magnitude bin.

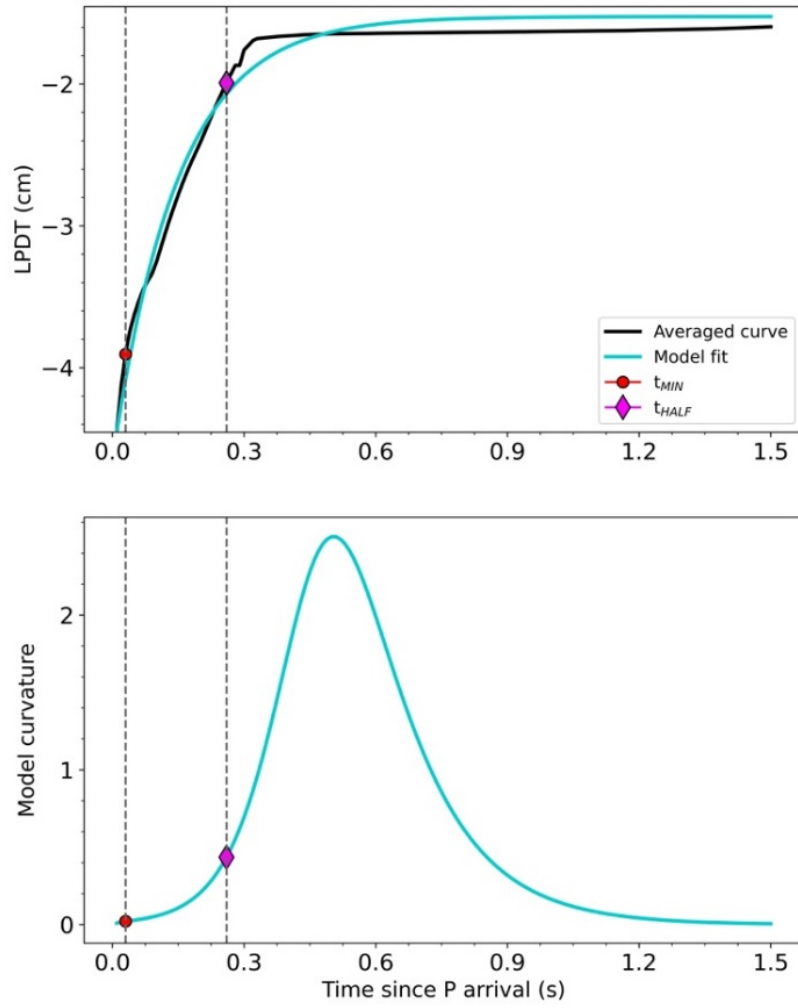


Figure S2: Curvature. Top panel: example of an averaged LPDT curve (black solid line) and model exponential fit (light blue line). Bottom panel: model curvature. Slope on averaged LPDT is evaluated between $t_{MIN} = 0.05$ s and t_{HALF} corresponding to the half of the time at which curvature has its maximum.

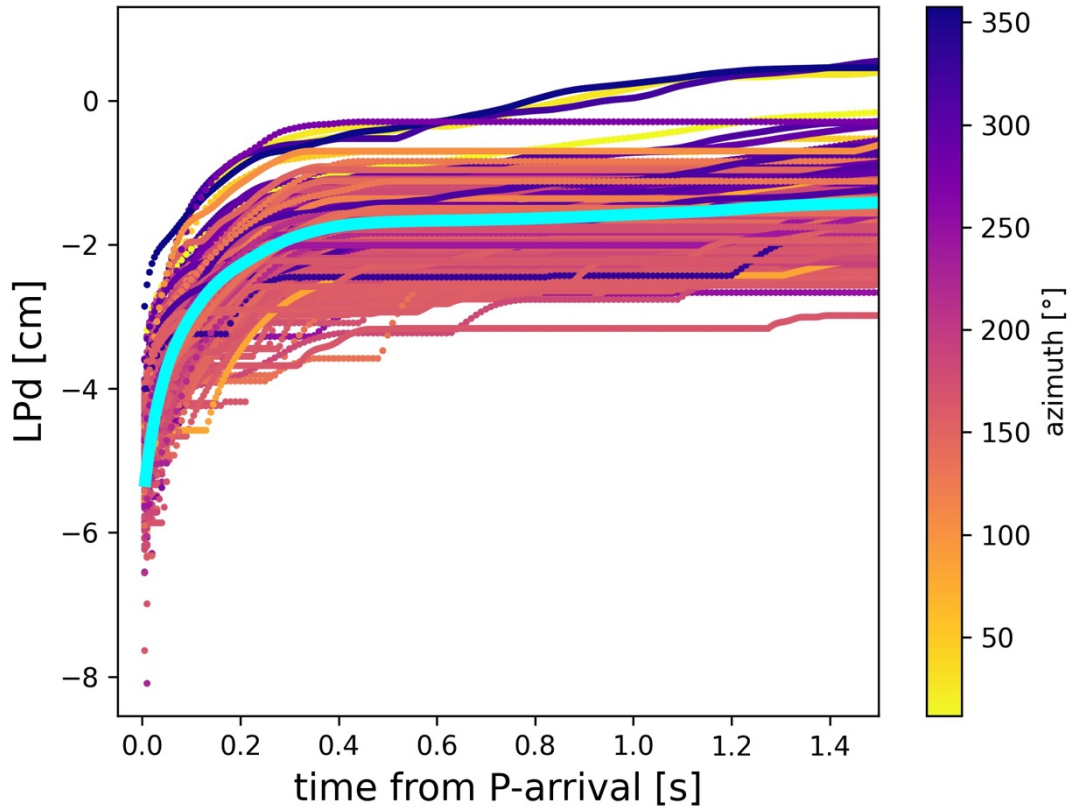


Figure S3: Azimuth average effect on example event 2014-08-24T10:20:44 Mw 6. The solid cyan is the averaged LPDT curve obtained from the single station LPDT curves in colored dotted line. The color bar follows the station azimuth values.

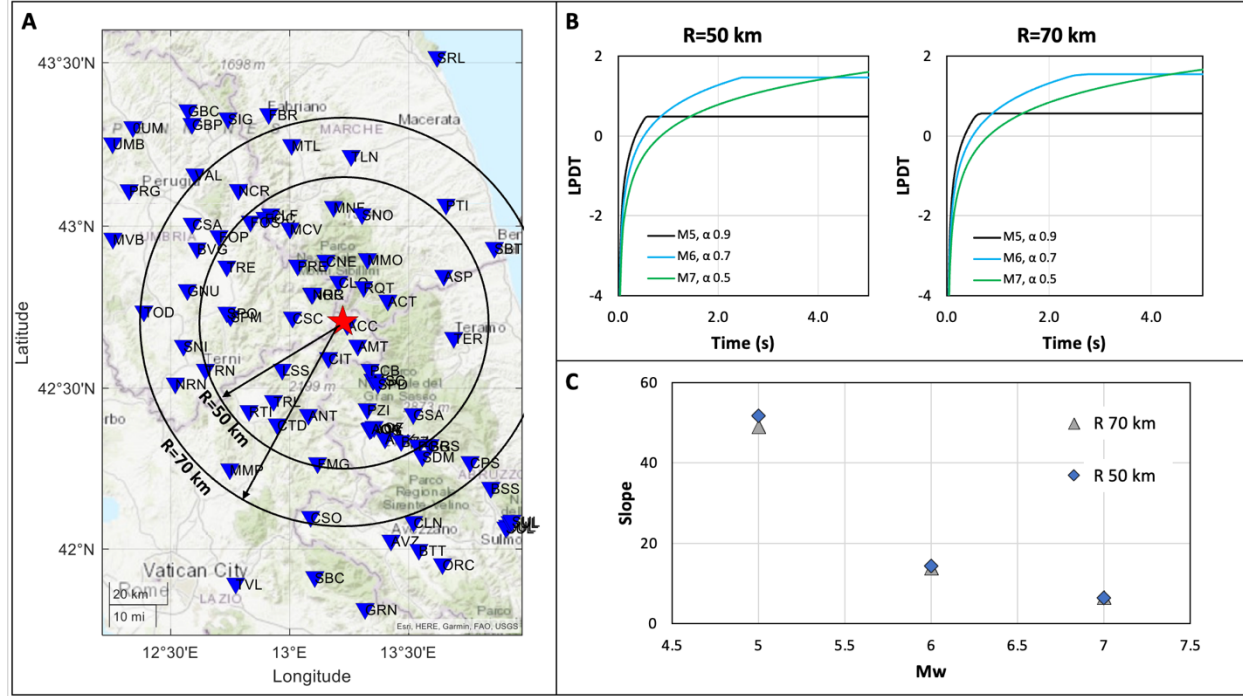


Figure S4. Numerical simulations. The figure displays the LPDT curves simulated at the stations of the network (panel A). The LPDT curves are shown for two different ranges of distance: 50 km and 70 km (panel B). Legend in panel B shows the magnitude and the ratio between rupture and shear wave velocity, here indicated as α , for each simulated LPDT curve. The larger rupture velocity produces faster initial rise of the displacement (higher slope values) for smaller magnitude events. Panel C displays the initial slopes of LPDT curves of panel B versus the moment magnitude. Different symbols and colors are used for the different distance ranges.

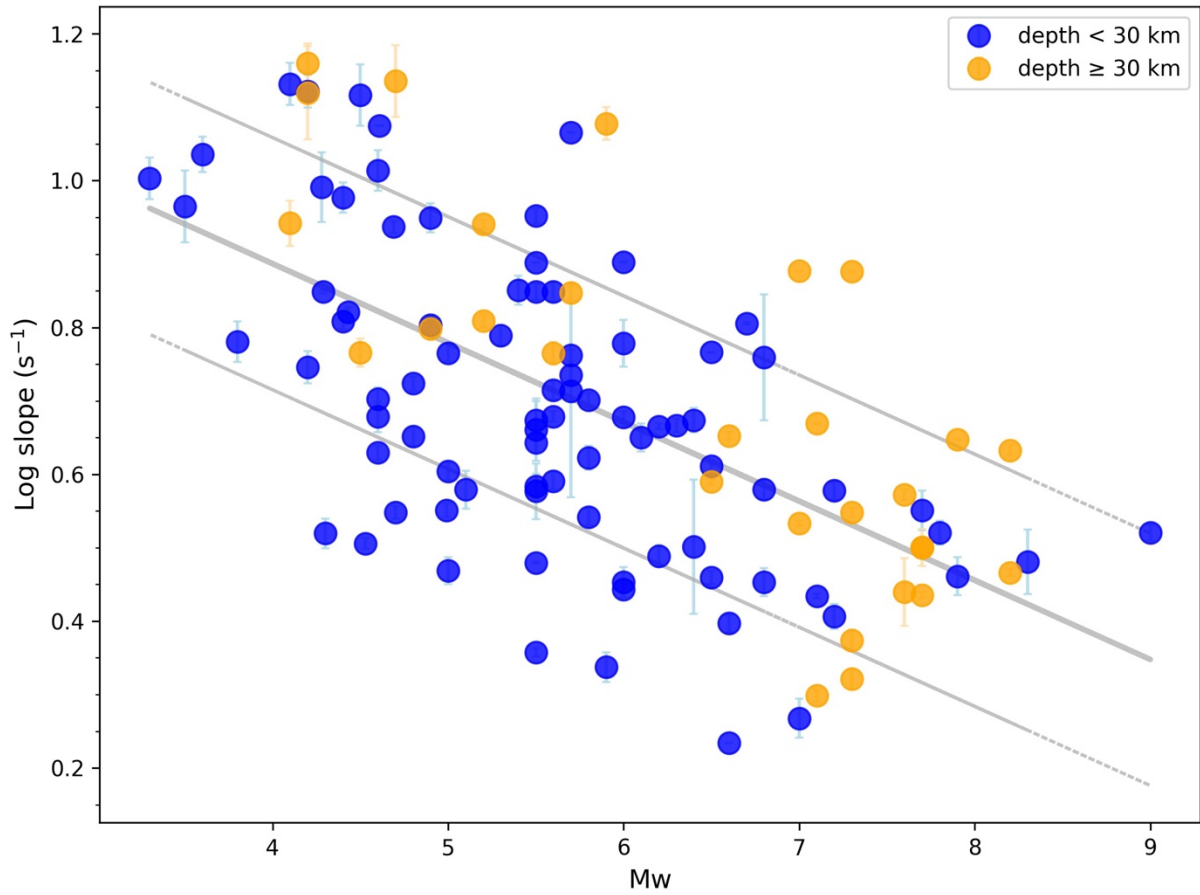


Figure S5. Initial slope of LPDT curves versus magnitude and depth. The figure shows the initial slope of the LPDT curves plotted as a function of magnitude in two different depth classes. Blue points correspond to event depth smaller than 30 km (shallow events) and orange points correspond to event depth higher than 30 km (deeper events). Grey solid and dashed lines are the empirical scaling relationship of initial slope vs magnitude and its standard error respectively.

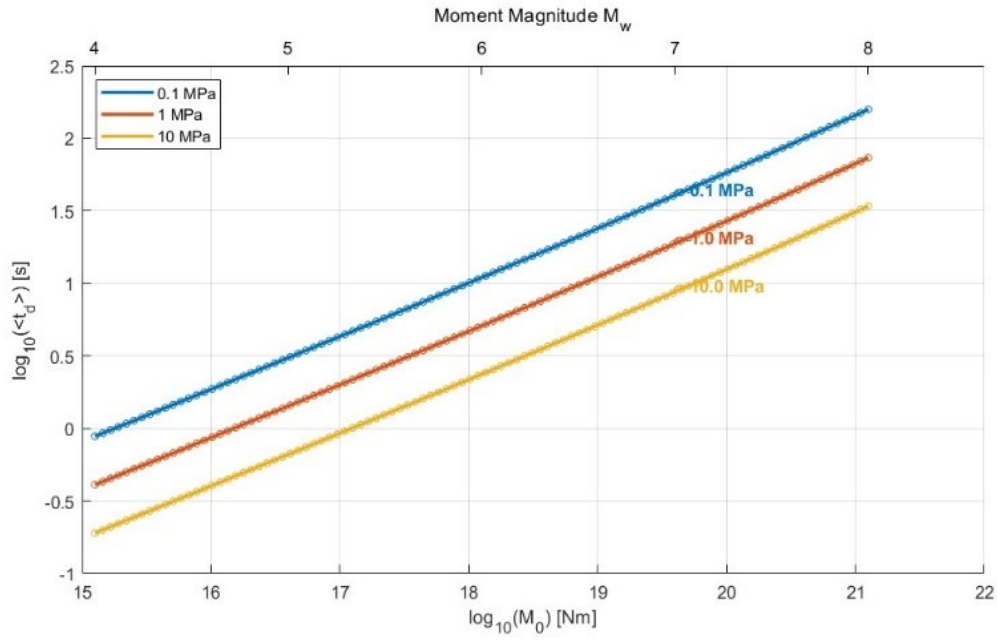


Figure S6: Duration-Moment scaling. The Figure shows the duration-moment scaling produced by a Sato & Hirasawa circular rupture model where a linear decreasing rupture velocity is assigned for an increasing moment magnitude in the range M_w 4-8.

Table S.1: Source parameters of the events used in the paper.

Date	Mw	Lat(°)	Lon(°)	Depth (km)	N. of records
2003-09-26	8	41.781	144.074	42	41
2003-09-26	7.1	41.71	143.691	21	24
2008-05-08	7	36.227	141.607	51	130
2008-06-14	7.2	39.028	140.88	8	161
2008-06-14	4.6	39.09	140.905	13	45
2008-06-14	4.5	39.035	140.903	12	64
2008-06-14	4.3	39.023	140.888	10	60
2008-06-14	3.9	39.057	140.863	10	26
2008-06-14	3.7	39.035	140.893	12	32
2008-06-14	3.5	39.042	140.873	9	18
2008-06-14	4.8	38.995	140.89	10	88
2008-06-16	5.3	38.997	140.84	11	90
2008-06-17	3.2	39.065	140.962	10	16
2010-01-10	6.5	40.652	-124.692	28.737	6
2010-02-04	5.8	40.4123	-124.961	23.048	2
2010-06-15	5.7	32.763	-115.936	9.114	3
2010-03-29	4.3	36.035	139.882	43	121
2010-05-01	4.9	37.558	139.19	9	115
2010-07-21	5.1	34.205	135.693	58	176
2010-10-24	4.4	36.058	139.852	45	138

2011-03-11	9	38.103	142.86	24	26
2011-03-12	6.7	36.985	138.597	8	283
2011-03-23	5.8	37.063	140.77	7	141
2011-04-11	5.9	36.965	140.633	11	201
2011-04-12	6.4	37.052	140.643	15	228
2011-04-13	5.7	36.915	140.707	5	133
2011-06-18	6	37.617	141.82	28	119
2011-07-05	5.5	33.99	135.233	7	124
2011-07-08	5.6	37.097	141.128	55	145
2011-07-25	6.3	37.708	141.627	46	145
2011-08-01	6.2	34.708	138.547	23	214
2011-08-12	6.1	36.968	141.16	52	165
2011-09-21	5.2	36.737	140.577	9	152
2011-10-20	4.4	37.043	140.643	9	104
2011-11-20	5.3	36.71	140.587	9	121
2012-02-13	5.6	41.1432	-123.79	27.358	11
2012-05-20	6.1	44.8955	11.2635	9.5	42
2012-05-29	6	44.8417	11.0657	8.07	91
2012-05-29	5.5	44.8652	10.9795	4.35	83
2012-05-29	5.5	44.866	10.9763	7.2	37
2012-01-28	4.9	35.492	138.978	18	163
2012-01-28	5.4	35.488	138.977	18	231
2012-01-29	4.7	35.537	138.983	21	147

2012-02-19	5.2	36.75	140.588	7	112
2012-03-01	5.3	36.438	140.625	56	183
2012-03-10	5.4	36.717	140.612	7	143
2012-05-18	4.8	36.135	139.84	51	210
2012-05-20	6.5	39.537	143.62	7	18
2012-06-01	5.1	36.027	139.875	44	220
2012-10-25	5.6	38.3	141.9	50	32
2012-10-27	4.5	33.5	133.5	40	104
2013-02-06	7.9	-10.864	165.142	23.8	10
2013-02-06	7	-10.5087	165.817	9.9	2
2013-02-08	7	-10.8933	166.145	22.4	8
2013-02-09	7	1.0345	-77.462	144.2	50
2013-04-06	7	-3.4714	138.474	69.4	11
2013-04-16	7.7	27.9704	62.136	63.1	5
2013-04-19	7.2	46.0722	150.924	109	7
2013-05-23	7.4	-23.0783	-177.213	177.7	8
2013-05-24	5.6	40.1918	-121.06	7.968	6
2013-05-24	8.3	54.815	153.391	607	7
2013-07-07	7.3	-4.0134	153.928	387.1	7
2013-07-15	7.3	-61.0527	-25.2274	19.9	6
2013-08-30	7	51.5001	-175.214	30.2	25
2013-09-24	7.8	26.9109	65.5315	15.5	5
2013-09-25	7	-15.9001	-74.6012	38.2	27

2013-10-12	6.5	35.5277	23.3718	46.8687	4
2013-10-15	7.1	9.8331	124.123	23.2	14
2013-10-25	7.1	37.1457	144.754	14.7	14
2013-11-17	7.8	-60.3783	-46.5876	7.9	6
2014-01-02	6.2	38.1522	20.3912	15	38
2014-01-26	6.2	38.1522	20.3912	15	5
2014-02-01	6.5	14.6682	-58.9272	14.8	9
2014-02-03	6	38.2637	20.3897	5	6
2014-03-10	6.8	40.8287	-125.134	16.441	16
2014-04-01	8.1	-19.6193	-70.7877	17.1	23
2014-04-01	7	-19.962	-71.0177	10.8	1
2014-04-03	7.7	-20.5887	-70.4905	12	25
2014-04-11	7.1	-6.6064	155.033	57.8	7
2014-04-12	7.6	-11.2581	162.139	15.3	7
2014-04-13	7.4	-11.4669	161.96	34.2	8
2014-04-18	7.3	17.3211	-100.994	24.4	21
2014-04-19	7.5	-6.708	154.992	39.8	4
2014-06-23	7.9	51.7028	178.643	102.1	17
2014-08-24	6	38.2152	-122.312	11.12	276
2014-10-14	7.3	12.5893	-88.072	63.9	19
2014-11-01	7.1	-19.8023	-177.833	435.3	11
2014-11-15	7	1.834	126.463	47.8	42
2014-11-22	5.6	45.8977	27.1505	32	11

2015-01-28	5.7	40.3178	-124.607	16.881	6
2015-02-13	7.1	52.5097	-32.0209	16.9	7
2015-02-27	7	-7.358	122.491	559.1	64
2015-03-29	7.5	-4.7758	152.578	41.3	8
2015-04-16	6.2	35.1952	26.8373	22.5896	4
2015-04-25	7.9	28.1302	84.7168	13.4	5
2015-05-05	7.5	-5.5168	151.864	29.6	9
2015-05-07	7	-7.3019	154.555	30.4	11
2015-05-12	7.2	27.8014	86.126	12.3	6
2015-05-22	7	-11.1336	163.594	19.6	15
2015-05-30	7.9	27.8281	140.494	685.5	18
2015-07-27	7	-2.7134	138.543	47.8	23
2015-09-16	8.3	-31.5729	-71.6744	22.44	41
2015-09-16	7	-31.5622	-71.4262	28.41	6
2015-10-20	7.1	-14.8595	167.303	135	13
2015-10-26	7.5	36.5244	70.3676	231	25
2015-11-17	6.5	38.67	20.6	11	3
2015-11-24	7.6	-10.5372	-70.9437	606.21	27
2015-11-24	7.6	-10.0598	-71.0184	620.56	21
2015-12-07	7.2	38.2107	72.7797	22	41
2016-01-24	7.1	59.6204	-153.339	125.6	55
2016-01-30	7.2	54.0057	158.513	163.22	6
2016-03-02	7.8	-4.9521	94.3299	24	13

2016-04-15	7	32.7906	130.754	10	41
2016-04-16	7.8	0.3819	-79.9218	20.59	18
2016-04-28	7	-16.0429	167.379	24	14
2016-07-29	7.7	18.5439	145.541	207.62	3
2016-08-10	5	39.3293	-122.802	14.45	27
2016-08-12	7.2	-22.4778	173.111	16.44	12
2016-08-24	6	42.6983	13.2335	8.1	99
2016-10-26	5.5	42.8747	13.1243	8.1	87
2016-10-26	5.9	42.9087	13.1288	7.5	90
2016-10-30	6.6	42.8322	13.1107	9.2	84
2016-11-24	7	11.9597	-88.8355	10.34	20
2016-12-08	7.8	-10.676	161.33	41	9
2016-12-17	7.9	-4.5049	153.522	94.54	6
2016-12-25	7.6	-43.4053	-73.9403	38	41
2016-12-28	5.6	38.3722	-118.898	10.01	12
2016-12-28	5.7	38.3757	-118.903	7.01	15
2016-12-28	5.5	38.3615	-118.897	2.43	11
2017-01-10	7.3	4.4634	122.575	612.71	33
2017-01-18	5.5	42.531	13.2838	9.6	107
2017-01-22	7.9	-6.2145	155.144	135	6
2017-07-02	6.6	36.9293	27.4139	7	30
2017-07-17	7.7	54.4715	168.815	10.99	18
2017-09-08	8.1	15.0356	-93.9067	56.67	16

2017-09-19	7.1	18.5678	-98.4808	51	28
2017-11-12	7.3	34.9052	45.9563	19	71
2017-11-19	7	-21.3337	168.683	10	14
2018-01-10	7.5	17.4743	-83.5193	10	74
2018-01-14	7.1	-15.7589	-74.7095	39	36
2018-01-23	7.9	56.0464	-149.073	25	234
2018-02-16	7.2	16.3887	-97.9789	25.98	26
2018-02-25	7.5	-6.0529	142.77	24.43	14
2018-08-19	8.2	-18.1125	-178.154	600	11
2018-08-21	7.3	10.7791	-62.907	146.18	42
2018-08-24	7.1	-11.0424	-70.8169	609.48	18
2018-08-29	7.1	-22.0663	170.05	26.68	12
2018-09-06	7.9	-18.4952	179.355	617.87	15
2018-09-28	7.5	-0.1781	119.84	10	39
2018-10-10	7	-5.7078	151.22	45.05	8
2018-10-30	5.7	37.58	20.5457	20.8612	3
2018-11-30	7	61.3464	-149.955	46.7	146
2018-12-05	7.5	-21.9568	169.418	10	11
2018-12-20	7.3	55.0999	164.699	16.56	8
2018-12-29	7	5.8983	126.921	60.21	27
2019-02-22	7.5	-2.199	-77.0231	132.36	9
2019-03-01	7	-14.7016	-70.135	267	20
2019-05-06	7.1	-6.973	146.451	146	9

2019-05-14	7.5	-4.081	152.569	10	4
2019-05-26	8	-5.8132	-75.2775	122.4	9
2019-06-23	5.5	40.2735	-124.3	9.44	24
2019-06-24	7.3	-6.4078	129.169	212	43
2019-07-04	6.4	35.6973	-117.506	14.76	12
2019-07-06	6.8	35.7188	-117.638	3.71	10
2019-07-06	5.5	35.9048	-117.704	6.88	8
2019-07-14	7.3	-0.529	128.093	10	29
2019-11-14	7.1	1.6199	126.414	33	24
2019-11-26	6.44	41.38	19.47	10	4
2020-01-17	4.3	37.5979	20.9084	19.5537	11
2020-01-22	4.4	39.0283	27.8642	13.1127	9
2020-01-25	4.28	39.036	27.8546	12.6161	9
2020-01-28	4.99	39.096	27.8563	12.3432	16
2020-01-28	7.7	19.418	-78.7582	15.18	38
2020-01-30	4.29	35.1327	27.8882	2.9811	2
2020-02-01	4.69	39.1659	20.6065	15.8338	8
2020-02-02	4.61	39.0024	27.8881	14.9947	11
2020-02-02	4.43	39.0939	27.8981	6.542	8
2020-02-06	4.7	39.2022	21.4886	14.3913	13
2020-02-13	7	45.6313	148.929	144	11
2020-02-24	4.3	39.3608	16.241	9.1	17
2020-02-27	4.74	35.169	27.9748	14.5061	1

2020-03-09	5.7	40.3917	-125.094	3.19	14
2020-03-22	4.6	45.8754	15.9717	9.766	6
2020-03-25	7.5	48.9688	157.691	55.39	8
2020-04-15	4.1	40.5397	21.8065	16.6236	1
2020-04-26	4.26	34.521	24.7092	27.1127	1
2020-04-30	4.53	36.9708	28.5566	11.5173	7
2020-05-15	6.4	38.2162	-117.844	13.05	5
2020-06-04	5.5	35.6177	-117.43	12.11	13
2020-06-23	7.4	15.8829	-96.0101	20	17
2020-06-24	5.8	36.447	-117.983	7.31	16
2020-07-17	7	-7.8386	147.775	73	8
2020-07-22	7.8	55.0298	-158.522	28	337
2020-10-03	7	37.91	26.84	10	44
2020-10-19	7.6	54.6093	-159.652	31.08	344
2020-10-30	7	37.9175	26.7901	21	241
2021-01-21	7	5.0054	127.519	80	13
2021-02-10	7.7	-23.0508	171.657	10	11
2021-02-13	7.1	37.7602	141.72	51.89	18
2021-03-04	7.4	-29.6762	-177.842	43	5
2021-03-12	5.6	39.84	22.01	7	3
2021-03-20	7	38.4754	141.633	43	17
2021-05-21	7.3	34.5884	98.2402	10	9
2021-06-05	5.5	33.2422	-116.013	3.8	11

2021-07-08	6	38.5075	-119.5	7.45	13
2021-07-29	8.2	55.3635	-157.888	35	317
2021-08-14	7.2	18.4167	-73.4804	10	47
2021-08-22	7.1	-60.2897	-24.8801	14	5
2021-09-08	7	16.9722	-99.7429	20	9
2021-10-02	7.3	-21.1265	174.896	527	13
2021-11-28	7.5	-4.4528	-76.8109	126	8
2021-12-14	7.3	-7.6046	122.227	15.06	30
2021-12-20	6.2	40.3902	-124.298	27.04	24
2021-12-29	7.3	-7.5465	127.576	164.28	48
2022-03-16	7.3	37.7302	141.595	59.85	19
2022-03-31	7	-22.5855	170.375	10	13
2022-05-26	7.2	-14.8942	-70.1969	252	26
2022-07-27	7	17.5524	120.796	46	17
2022-09-10	7.6	-6.2949	146.503	116	15
2022-09-14	7	-21.1909	170.267	137	13
2022-09-19	7.6	18.4967	-102.982	25.485	18
2022-11-11	7.3	-19.2868	-172.149	37	8
2022-11-12	7	-20.0924	-178.343	586.942	15
2022-11-22	7	-9.809	159.594	14	14
2023-01-08	7	-14.9466	166.879	29	12
2023-01-09	7.6	-7.0642	130.004	105.249	50
2023-01-18	7	2.7357	127.027	28.855	17

2023-02-06	7.8	37.2251	37.0209	10	17
2023-02-06	7.5	38.0235	37.203	10	18
2023-03-16	7	-30.1743	-176.198	10	7
2023-04-02	7	-4.3258	143.159	70	15
2023-04-14	7	-6.0255	112.033	594.028	14
2023-04-24	7.1	-29.9918	-177.811	29	7
2023-04-24	7.1	-0.8026	98.524	34	8
2023-05-10	7.6	-15.6278	-174.492	210	7
2023-05-19	7.7	-23.1903	170.734	32.986	14
2023-05-20	7.1	-23.0483	170.511	25.807	12
2023-06-15	7.2	-22.9936	-177.107	179	10
2023-07-16	7.2	54.3919	-160.761	25	311
2023-08-28	7.1	-6.8051	116.527	500	18