Supplement Text:

Rupture Complexity of the Mw 8.3 Sea of Okhotsk Earthquake: Rapid Triggering of Complementary Earthquakes?

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1, Path calibration using the aftershock

The calibration is obtained by convolving the mainshock data with the 1D synthetic of the aftershock and then deconvolving with the data of the aftershock. We have applied a 1Hz low-pass filter to the calibrated data because the effect of 3D slab structure in the source region cannot be ignored at higher frequency (>1Hz) (Fig.S1). The mechanism of the aftershock is 29°/68°/-97°/6.7 (strike/dip/rake/Mw) which is obtained by teleseismic P-wave inversion at longer period (>5s), and we assume the source function for the aftershock can be adequately represented as a 1 second trapezoid (Fig. S1).

We assume that the observation (O) at a certain station can be represented as:

$$O_m(t) = S_m(t) * G_{path}(t)$$

and

$$O_a(t) = S_a(t) * G_{path}(t)$$

where subscript "m" denotes the mainshock, "a" denotes the aftershock and "*" means convolution. $G_{path}(t)$ is the path specific Green's function representing the 3D earth structure. $S_a(t)$ is the source function of the aftershock (assumed to be a simple trapezoid) and $S_m(t)$ is the source function of the mainshock, which we are attempting to recover. We assume the only difference between these two records is their source descriptions, so we have:

$$O_m(t) * S_a(t) = O_a(t) * S_m(t)$$

Additionally, we assume that we can model the aftershock using a Green's function computed for a prescribed 1D velocity structure as:

$$O_{aS}(t) = S_a(t) * G_{1D}(t)$$

where $O_{aS}(t)$ is the synthetic aftershock record and $G_{1D}(t)$ is the 1D Green's function. Applying this to the previous equation, we have

$$O_m(t) * O_{aS}(t) = O_a(t) * S_m(t) * G_{1D}(t)$$

Thus, to make a path calibration we convolve $O_m(t)$ with $O_{aS}(t)$ and then deconvolve $O_a(t)$ to construct corrected data to use in the inversions.

$$O^c{}_m(t) = O_m(t) * O_{aS}(t) *^{-1} O_a(t) = S_m(t) * G_{1D}(t)$$

Here, " $*^{-1}$ " represents deconvolution. This process empirically removes 3D path complexities, which are contained in O_a (t), from the observed motions resulting in corrected data $O^c{}_m(t)$ that are represented by $S_m(t) * G_{1D}(t)$. Since this process convolves the aftershock synthetics and then deconvolves the observation of the aftershock, the difference between the mechanisms of the aftershock and the mainshock is also handled. This basic idea has been used effectively in high resolution explosion yield estimation, called waveform intercorrelation [*Lay et al.*, 1984]. An example application of this extra step of data processing is given in Fig. 2. The path calibration technique we used here is similar to the empirical green's function (EGF) method, i.e. [*Ide et al.*, 2011], but with some difference. Our approach can naturally correct the mechanism difference between the mainshock and aftershock due to the convolution of synthetics and then deconvolution of the data of the aftershock. On the other hand, the traditional EGF method requires similar mechanism between the mainshock and aftershock.

2, Finite fault inversion

To generate the kinematic slip models, we adopted the method proposed by [*Ji et al.*, 2002] with the update of Kostrov-like source time function as described in the main text, wherein a finite fault model is constructed from a distribution of sub-patches (small rectangles) that can slip with various slip amplitudes, rakes, rise-times, and delays in rupture onset (rupture velocity). A simulated annealing algorithm is applied to invert these parameters simultaneously in the wavelet domain. Compared with a linear inversion scheme, the non-linear simulated annealing inversion requires much fewer parameters given the same grid spacing. Two animations (A1 and A2) are presented to demonstrate how simulated annealing works in the inversion. As shown in the animations, the inversion started from a model with values of parameters on each sub-fault randomly initiated in the ranges that are allowed, and then as the inversion goes on, these values will change according to inversion criteria and finally converge to a stable and smooth slip model. During the iterations, perturbation of each value goes through the allowed range; it is not very sensitive to the initial random seed.

During the inversion we divided the rectangular fault segment into smaller sub-faults with dimensions of 7.5 km along strike and 7.5 km along dip. We searched for slip amplitude from 0 to 20 m at 1 m intervals, with the duration of rise time for each sub-fault chosen to range from 1 to 10 s at intervals of 1 s, and the rupture velocity varying from 3.5 - 4.5 km/s at intervals of 0.1 km/s. A Laplacian smoothing algorithm is applied to minimize the difference between slip on adjacent sub-faults. We use the fault plane with dip of 10° and strike of 177° after the NEIC W-phase mechanism. The conjugate fault plane with strike of 15° and dip of 80° is easily rejected because the slip on this fault plane cannot fit the waveform with strong directivity observed along the azimuth of 165°, which is 30° off the strike of this steeply dipping fault (Fig.S2).

One of the important parameters in finite fault model is the rupture velocity, which can be used to estimate energy radiation efficiency [*Kanamori et al.*, 1998]. To resolve this parameter, we conducted finite fault inversions with different constant rupture velocities. The inverted slip models and representative waveform fits can be found in Fig.S3 and S4. The waveform misfit vs. rupture velocity plot (Fig.S5) has a minimum value at 4.0km/s. When the rupture speed is less than 4.0km/s, larger misfits on the stations towards the south are observed compared to the case of 4.0km/s due to late arrival of the signals (Fig.S4). The misfit curve becomes gentler when rupture speed is greater than 4.0km/s, mainly because the rupture speed is partly compensated by longer rise times (Fig.S3). These features are very similar to the synthetic tests for rupture velocity presented in Fig.S6 and Fig.S7. Thus, the average rupture speed is estimated to be around 4.0km/s (3.5km to 4.5km/s).

For the unilateral, single source rupture inversion, we obtain the results presented in Fig.S8 with fits given in Fig.S9. Note that allowing the rupture velocity to vary does not resolve the waveform fits to the north (see stations marked in Fig.S9). Imposing a two-stage rupture process solves this problem, essentially allowing the fault to re-rupture with a secondary hypocenter located at the strongest asperity (E2), initiated with a delay of 12s. The waveform fits for this case are given in Fig.S10.

The hypocenter and origin time for E3 were determined by a combination of constraints, examining various possible sub-event move-outs displayed in Fig.S11 and S12. This process involves many trial-and-error models and the resolution of the inversion is established in checkerboard tests. An example of the latter is presented in Fig.S13 using synthetic data demonstrating that multiple patches can be mostly recovered. The results for the real data are presented in Fig.S14 for inversions in velocity and displacement. For the velocity inversion (our preferred solution), we have also included the moment rate functions for the four sub events. To further understand the resolution on timing and location of the second stage rupture (E3), we conducted a few tests using our preferred slip model (Fig.S15). First, we assume 15km (dimension of two subfaults) location offsets of E3 along strike in North and South direction (Fig.S15.E, F). We then shifted the timing of E3 4s later and earlier than the preferred value. The synthetics generated by these perturbed slip models are compared with the data and waveform cross-correlation coefficients (CCs) are plotted in Fig.S15.A-D. Compared with the best waveform fitting (Fig.S16), only the stations in the N-S direction are sensitive to the location offsets. On the other hand, CCs on most of the stations decrease in the time shift cases. The difference of sensitivity can be better observed in waveform comparison on three selected stations are shown in Fig.S15.I,J,G,H. Since the waveform in N-S directions are well fitted in our preferred model, we conclude that our data set and inversion set up have good resolution on both timing and location of E3.

Supplement Figure Caption

Figure S1. Waveform comparison between the GSN observations and synthetics for the M_w6.7 aftershock. (A) Teleseismic station distributions (triangles) for the study of mainshock and aftershock with the red triangles indicating the stations that have significant path calibrations. (B) Vertical component of teleseimic P-waves arranged against azimuth. All the velocity records are filtered between 50s and 1s. (C) 1D synthetics generated with the GCMT source parameters and a trapezoid source time function with duration of 1s. Waveforms are filtered to the same frequency band as in (B). (D) Similar as (B) but filtered to higher frequency bands (50s to 0.5s), note that the phases generated by the slab structure become obvious as indicated by the two small arrows. This waveform complexity is not caused by the finite rupture process of the earthquake since this double arrival is not observed on the other azimuth that is not along the slab as indicated by the larger arrow.

Figure S2. Finite fault inversions on the two conjugate fault planes. The fault plane geometry is obtained from NEIC W-phase moment tensor solution, with one fault plane strikes 177° and dips 10° and another conjugate fault has a strike of 15° and a dip of 80°. The finite fault slip models derived by using these two fault planes are shown in (A) and (B), with selected waveform fits shown in (C) and (D), respectively. The entire waveform fits are summarized in (E) and (F) in terms of waveform cross-correlation coefficients between the data and the synthetics, stations in (C) and (D) are marked by the red rectangles. The slip amplitude is colored and the rupture times are shown as contours. In the waveform fitting plots, the station names are displayed to the most left column, followed by the station azimuth (upper number) and distance (lower number) in degree, the numbers about each trace are the amplitudes in micro-meter per sec. Both data (black) and synthetics (red) are filtered to 3s and longer period. The waveform fits are apparently worse when slip is restricted on the almost vertical fault plane (dip=80°, strike=15°), verifying that the horizontal fault plane (dip=10°, strike=177°) is the fault plane on which the earthquake took place.

Figure S3. Slip models obtained by inverting the real data with constant rupture velocities. Here the velocity waveform data have been calibrated by the M_w6.7 aftershock. The results for rupture speed of 2.0km/s to 6.0km/s are displayed from left to right, with the slip model in the upper panel and the rise time and rupture speed in the lower panel. Note that for the Vr=6.0km/s case, we use a slightly larger fault dimension to ensure there is not much slip on the edge of the model.

Figure S4. Waveform fitting for the rupture speed tests. Representative stations to the south and north, approximately towards and away from the rupture direction, are displayed for the slip models shown in Fig.S3, arranged from left to right according to the rupture speed used in the inversion. The station names are displayed to the most left column, followed by the station azimuth (upper number) and distance (lower number) in degree, the numbers about each trace are the amplitudes in micro-meter per sec.

Figure S5. Waveform misfit vs. rupture speed. Waveform misfits as a function of rupture speed for the inversions displayed in Fig.S3 (left) and Fig.S6 (right). Note the similarities between the synthetic and real data cases.

Figure S6. Synthetic test for the rupture velocity. (A) The upper panel displays the input slip model (5m), the lower panel shows the input rise time (5s) and rupture velocity (4.0km/s), which are used to generate synthetic data. (B) The inverted slip model with rupture velocity fixed to 2.0km/s is shown in the upper panel, the lower panel displays the rise time and the rupture speed (contours of iso-rupture time). The inversions results with other assumed rupture speeds are displayed in c (3.0km/s), d (4.0km/s), e (5.0km/s) and f (6.0km/s).

Figure S7. Waveform fits for the rupture speed synthetic tests. Representative stations to the south and north, approximately towards and away from the rupture direction, are displayed for the synthetic tests shown in Fig.S3, arranged from left to right according to the rupture speed used in the inversion. The station names are displayed to the most left column, followed by the station azimuth (upper number) and distance (lower number) in degree.

Figure S8. Velocity waveform inversion results for single fault plane inversion. Here the data have been calibrated and the rupture speed is allowed to change from 3.5km/s to 4.5km/s with an interval of 0.1km/s. The left panel displays the slip distribution where the red star indicates the hypocenter location and the arrows indicate the slip direction (rake). Rise time (colored) and rupture time (contours) are displayed in the panel on the right.

Figure S9. Velocity waveform fits for the slip model in Fig.S8. The calibrated data waveforms are displayed in black and the synthetics are in red. Station names are displayed at the beginning of each record, followed by the station azimuth (upper number) and distance (lower number) in degree. Stations towards north are highlighted by the two ellipses to indicate the misfits.

Figure S10. Velocity waveform fits for the preferred slip model. Similar waveform fits as in Fig.S9 for our preferred slip model in which backwards rupture is allowed (in Fig. 4). Note the improvement of waveform fits for the stations towards the north and south.

Figure S11. Displacement waveform decomposition analysis. Displacement waveform fits as a function of rupture directivity parameter which is defined as a unilateral rupture towards SSE (azimuth of 165°) with data in black and synthetics in red. The corresponding slip model can be found in Fig.S14. The synthetics in the left column correspond to the entire slip model (slip on S1 and S2). The moment-rate function (moment release as a function of time) is displayed at the top. The middle column shows the synthetics and the moment-rate for slip on S1 and on the right column for S2.

Figure S12. Velocity waveform decomposition analysis. Similar waveform fits as in Fig.S11 for the velocity waveform inversion. The corresponding slip model is shown in Fig. 4.

Figure S13. Synthetic test for multiple dimension asperities. The upper two panels show the input slip model (left) and rise time and rupture speed (right). The inverted results are displayed in the lower two panels with slip model on the left and the rise time (colors) and rupture speed (contours in second) given on the right.

Figure S14. Slip models derived from velocity and displacement inversions. Finite fault models for velocity (upper) and displacement inversions (lower). The slip distributions on fault segments S1 and S2 are displayed in the left. The red star (on S1) and blue star (on S2) indicate the hypocenters of the two stages of the rupture. The rise time and rupture time contours (indicating the rupture speed) are shown on the right. Moment rate functions for the velocity model are shown in the middle, with the contribution of different sub-events (E1, E2, E3 and E4 in the slip distribution plot) marked.

Figure S15. Sensitivity tests for location and timing of second stage rupture (E3). We offset the location of E3 by 15km along the strike in north and south direction (E,F), then we shift the timing of E3 (delay time for the second stage rupture) by 4s later and earlier than the preferred value. Waveform cross-correlation coefficients (CCs) between the data and the synthetics generated from these perturbed slip models are plotted in (A-D), respectively. Three selected stations (circled) for each case are plotted in (I,J,G,H), respectively. Some detail waveforms are marked by the arrows. See Fig.S7 for the detail information in (G-J).

Figure S16. Detail waveform analysis on two selected stations. (A) The station names, azimuth (upper number), and distance in degree (lower number) are indicated at the beginning of each trace. The best fitting single fault synthetic is displayed in red along with the observations in the bottom trace. The upper traces display the improvement by adding S1 and S2. The global fits are improved considerably as given in (B) where waveform cross-correlation coefficients between the velocity data and the single fault synthetics (left) and two fault plane synthetics (right) are displayed.

Animation 1. Inversion process of the M_w8.3 mainshock with the data in velocity. The slip distribution (contoured) for rupture stage S1 (lower) and S2 (upper) are displayed from the beginning of the iteration of simulated annealing inversion. The blue arrows indicate the rake directions; note the color scale changes as the inversion goes on. The waveform misfits are plotted on the top as a function of the number of iteration.

Animation 2. Inversion process of the mainshock with data in displacement.

Reference

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