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Zhongwen Zhan et al.
Science 345, 204 (2014);
DOI: 10.1126/science.1252717
EARTHQUAKE DYNAMICS

Supershear rupture in a \( M_w 6.7 \) aftershock of the 2013 Sea of Okhotsk earthquake

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Earthquake rupture speeds exceeding the shear-wave velocity have been reported for several shallow strike-slip events. Whether supershear rupture also can occur in deep earthquakes is unclear, because of their enigmatic faulting mechanism. Using empirical Green’s functions in both regional and teleseismic waveforms, we observed supershear rupture during the 2013 moment magnitude \( (M_w) 6.7 \) deep earthquake beneath the Sea of Okhotsk, an aftershock of the large deep earthquake \( (M_w) 8.3 \). The \( M_w 6.7 \) event ruptured downward along a steeply dipping fault plane at an average speed of 8 kilometers per second, suggesting efficient seismic energy generation. Comparing it to the highly dissipative \( M_w 8.3 \) Bolivia earthquake, the two events represent end members of deep earthquakes in terms of energy partitioning and imply that there is more than one rupture mechanism for deep earthquakes.

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event and the 30 August 1996 $M_w$ 5.5 event) as empirical Green’s functions (EGFs) to calibrate the paths. The $M_w$ 4.3 earthquake’s small moment, similar depth, and probably similar focal mechanism as the $M_w$ 6.7 earthquake (fig. S1) make it an ideal EGF event. Its direct $P$ wave recorded at the PET station displays two distinct arrivals separated by about 2 s (Fig. 2), due to diffraction along the dipping high-velocity slab in the upper mantle (25). Therefore, the apparent 5-s $P$ duration of the $M_w$ 6.7 earthquake at the PET station was partly caused by the structural path effect. We deconvolved the EGF waveform from the $M_w$ 6.7 earthquake $P$ wave to remove the path effect and obtained a more accurate source-time function (STF) (29). Most of the energy then concentrated in the first ~2 s, which we measured as the STF duration at the PET station (Fig. 2; red shading in top STF).

Because teleseismic records of the $M_w$ 4.3 event are noisy, we used the 1996 $M_w$ 5.5 event at somewhat shallower depth (~590 km) with a slightly rotated focal mechanism (Fig. 1) as the teleseismic EGF event. Because we only used teleseismic direct $P$ waves (no absolute amplitude), these small differences in depth and radiation pattern did not significantly affect the accuracy of the EGFs. The $M_w$ 4.3 and 5.5 EGF events had highly similar waveforms at the regional station PET and several quiet teleseismic stations (fig. S2), despite their difference in moment. This suggests that both EGF events can be regarded as delta-function-like point sources and their waveforms are mostly controlled by path effects. We chose teleseismic stations with clean direct $P$ waves from both the $M_w$ 6.7 and the $M_w$ 5.5 earthquakes (Fig. 1 inset) and then deconvolved to estimate STFs and their durations (Fig. 2 and fig. S3). The resulting teleseismic STF durations range from ~0.5 to ~1 s. For both regional and teleseismic stations, relatively simple and compact STFs convolved with the EGFs produce good fits to the direct $P$ and $P$-coda waveforms of the $M_w$ 6.7 earthquake, which suggests effective correction of the path effects. We also attempted to include two more stations, MA2 and YSS, at distances of about 818 and 858 km, respectively (fig. S4). Direct $P$ waves from these stations left the source along approximately horizontal ray paths. However, because of waveform complexities caused by triplications due to the 660-km discontinuity (figs. S4 to S6), we were unable to find an appropriate EGF event to correct for these structural effects.

After removing the path effects with EGFs, we inverted the resulting STF durations for earthquake rupture parameters. The path-corrected STF duration of the PET station (~2.1 s) is still more than two times longer than those of the teleseismic stations (~0.5 to ~1 s), suggesting downward rupture directivity. For three-dimensional unilateral rupture (fig. S7), the STF duration of the $i$-th station $T_i$ can be written as a function of rupture duration $\tau$, horizontal rupture azimuth $\theta_i$, and horizontal and vertical dimensions $L$ and $H_i$, as $T_i = \tau + x_i(\theta_i) L + \eta_i H_i$, where $x_i(\theta_i)$ and $\eta_i$ are the corrections for azimuthal and vertical directivity, respectively. Note that $x_i(\theta_i) = \cos(\theta_i - \alpha)$ is the horizontal directivity parameter for the $i$-th station with azimuth $\theta_i$ and $P$-wave phase velocity $c_p = \frac{\omega}{k_p}$ (18, 29). Here $q_i$ is the takeoff angle for the $i$-th station, and $\alpha$ is the $P$-wave speed. Therefore, the azimuthal variations in STF durations resolve the rupture direction $\theta_i$ and horizontal extent $L$. In the final term, $\eta_i = \frac{r_{ei}}{r_p}$ is the vertical slowness, negative for teleseismic stations (with down-going rays) and positive for regional stations (with up-going rays). This sign

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**Fig. 1. Earthquake and station locations.** The 2013 Okhostk $M_w$ 8.3 mainshock and $M_w$ 6.7 aftershock are displayed as the black and red beachballs, respectively. The two red stars connected with two smaller beachballs represent the EGF events used in this study. Slab contours from the Slab 1.0 model (31) are shown as dashed lines. The inset shows teleseismic and regional stations with four representative $P$ vertical displacement seismograms (green lines).

**Fig. 2. EGF and deconvolution.** The three columns display vertical-component seismograms of the $M_w$ 6.7 earthquake, EGFs, and the deconvolved STFs. To ensure high signal-to-noise ratio and enhance high-frequency energy, we used acceleration seismograms filtered between 0.5 and 1 Hz. Seismograms of the $M_w$ 6.7 event and EGFs are flipped to have the same polarity before deconvolution. The black and red traces in the first column are the data and predictions, respectively. The two numbers beneath station names are distances and azimuths in degrees. In the third column, we show the STF durations defined by the red shading, which includes most of the energy.
Fig. 3. Inversion for earthquake rupture parameters. (A) Misfit as a function of the grid-searched vertical rupture extent $H$ and rupture azimuth $\theta$. The red dot at (11 km, 130°) marks the optimal solution without a substantial tradeoff. The dashed contours show the rupture speeds for all grid-searched solutions at reference speeds of $V_S$, $\sqrt{2} V_S$, and $V_P$. (B) STF durations with and without vertical directivity corrections, assuming the optimal values from (A). The corrected STF durations (blue dots) fall near a straight line with a slope of $L = 4$ km, and zero-crossing duration of $\tau = 1.5$ s (red cross). The green dots show the STF durations without the vertical directivity corrections, in which the PET station has a longer STF duration than all the teleseismic stations.

We used a grid-search method to invert for the rupture parameters ($\tau$, $\theta$, $L$, and $H$). The least-squares misfit of the STF durations, as a function of rupture vertical extent $H$ and rupture azimuth $\theta$, has a well-defined global minimum at $H = 11$ km and $\theta = 130°$ (Fig. 3A). With these optimal values, the STF durations corrected for the downward vertical directivity (Fig. 3B) fall near a straight line with a slope of $L = 4$ km and zero-crossing duration of $\tau = 1.5$ s. With $L = 4$ km and $H = 11$ km, we estimated the rupture dip to be ~70°, coincident with the steeper fault plane's dip of ~69° (~17). Because the rupture direction $\theta = 130°$ is roughly perpendicular to the fault strike (~26°), we conclude that the $M_w$ 6.7 earthquake features a downward mode II rupture on the fault plane dipping steeply to the southeast (Fig. 4A). The rupture propagated $\sqrt{H^2 + H^2}$ or ~12 km in $\tau = 1.5$ s, from which we estimate an average rupture speed of about 8 km/s. This speed is about $\sqrt{2} V_S$, which is substantially higher than the local shear wave speed ($V_S = 5.5$ km/s, based on the Preliminary Reference Earth Model). Contouring the average rupture speeds for all grid-searched rupture parameters (Fig. 3A) shows that within the region with reasonable misfit (inside the dark blue contours), the rupture speed is always higher than $V_S$ and lower than $V_P$. Within 95% confidence limits, the average rupture speed is $8.0 \pm 0.7$ km/s. Anomalously broad teleseismic depth phases ($pP$) also are roughly consistent with the downward rupture model (figs. S8 and S9). However, $pP$ pulse widths exhibit much larger scatter than $P$ pulse widths, and their behavior appears to be heavily influenced by complicated path effects, thus we cannot invert the $pP$ waveforms for rupture parameters with any confidence.

Previously identified extremely high-stress drops (157 MPa to 5.856 GPa) of the $M_w$ 6.7 earthquake and subsequently low radiation efficiency (0.005 < $\eta_R < 0.15$ (~17) depict this event as mechanically distinct from the Okhotsk $M_w$ 8.3 mainshock ($\Delta \sigma \approx 15$ MPa, $\eta_R \approx 0.6$) and more similar to the 1994 $M_w$ 8.3 Bolivia earthquake ($\Delta \sigma \approx 114$ MPa, $\eta_R \leq 0.036$) in a warmer...
slab (Fig. 4B). This complexity suggests strong stress heterogeneity in subducted slabs (17). However, supershear rupture during the $M_w$ 6.7 earthquake brings its stress drop down to 32 MPa and its radiation efficiency to about 1.0 (Fig. 4B), which are much closer to values for the $M_w$ 8.3 Okhotsk mainshock. Therefore, strong stress heterogeneity inside subducted slabs is not required to explain the 2013 Okhotsk mainshock and its $M_w$ 6.7 aftershock. However, the difference in rupture speed (subshear versus supershear) indicates substantial spatial heterogeneity in the fracture strength or fracture energy within the slab.

Compared with shallow supershear events, this deep event has a relatively small rupture dimension and higher static stress drop (by a factor of $\sim$10). Our estimate of high radiation efficiency ($\eta$ = 1.0) during the $M_w$ 6.7 event is also consistent with theoretical predictions of low fracture energy during supershear ruptures (30). This constraint of low fracture energy bears on the question of deep earthquake faulting mechanisms, which is still enigmatic (15, 19). The 1994 Bolivia earthquake involved a large amount of fracture/thermal energy and radiated relatively little energy in seismic waves (16). In terms of energy partitioning, the supershear $M_w$ 6.7 earthquake represents the opposite end member from the Bolivia earthquake, with almost all the available strain energy being radiated as seismic waves. This contrast is consistent with the idea of more than one rupture mechanism for deep earthquakes in slabs with different thermal states (18, 20, 21). The Okhotsk mainshock and aftershock in a cold slab ruptured with the transformational faulting mechanism, whereas the Bolivia earthquake in a warm slab was dominated by shear melting (18).

**REFERENCES AND NOTES**

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28. Materials and methods are available in the supplementary materials.