Supplementary information of “The 2013 Okhotsk Deep-Focus Earthquake: Rupture Beyond the Metastable Olivine Wedge and Thermally-Controlled Rise Time near the Edge of a Slab”

Back Projection of the Okhotsk earthquake on the vertical plane

To test the candidate geometry of a vertical fault, we perform the BP analysis on the vertical plane with a strike of 12 degree (from GCMT). The BP result (Fig. S5) is not in favor of a vertical plane since the 300 km dimension is excessively large compared with the aftershock distribution (Fig. 1). One possible concern is that the large apparent dimension is the result of the BP artifact instead of the effect of the testing geometry. We perform the BP of the M6.8 earthquake, to understand the possible BP artifact on a vertical fault plane. We find that the “swimming” effect only happens in the coda and moves downward (i.e. towards to the direction of the array along its average ray path). In the vertical BP of the mainshock, we do find the expected downward going artifact in the coda (after 30s). However, within the duration of the mainshock BP (first 30s), the apparent rupture dimension already exceeds 300 km and moves upward, which is clearly not a BP artifact but the biased projection due to the incorrect vertical fault geometry. We therefore rule out the vertical plane for the possible fault geometry of the mainshock.

Synthetic tests of P and pP phases on horizontal, SE dipping and slab-parallel planes

As outlined in the main text, we discriminate between a single horizontal plane and a slab-parallel plane by comparing the BPs of P and pP phases on the two planes. For the P
phase, we use the most reliable BP results in the band of 0.5 to 2 Hz. For the pP phase, we use the frequency band of 0.25 to 1 Hz due to lower coherency.

The horizontal plane BP for all phases and arrays are consistent. The BPs of the P phase of the NA and EU arrays are very consistent across the whole rupture (Figure 1). The P and pP of the NA array are consistent for the SSE rupture segment (Figure 1). The pP result missed the NE rupture because the beginning of the pP data is contaminated by the coda of the direct P phase.

The SE-dipping plane for all phases and arrays are inconsistent. While the BPs of the P phase of the NA array shows that the southern rupture propagates in the SE direction, the BPs of the P phase of the EU array and pP phase of the NA array show it propagating towards almost southward (Figure S2-left). The SE-dipping plane is therefore ruled out.

We cannot compare the slab-parallel plane BP of all combinations of phases and arrays. Only the P phase of the NA data has sufficient resolution. The P phase of the EU array and pP phase of the NA array have take-off vectors sub-parallel to the slab interface (as defined by Slab 1.0), which causes a large spatial uncertainty. The pP of the EU array is affected by the large coda of the direct P phase and has very low coherency.

Alternatively, for the P phase of the NA array we can assess if the slab-parallel BP and the horizontal BP are compatible, i.e. if their spatial differences in map view are only due to the fact that BP maps a source onto the piercing point of the seismic ray (possibly extrapolated) through the assumed plane. This validation can be done through synthetic
tests: we consider the BP of a certain phase on a certain plane as an “input source”, generate synthetic array waveforms and back-project the synthetic data of a different phase on a different plane to get a set of “output sources”. We then compare this output source to the corresponding BP of the real data. Only if the input source is on the true fault plane its synthetic output sources can be consistent with all the observations. The inconsistent plane can be ruled out. The possible phase and plane combinations for the NA array are the P phase on the slab-parallel plane (P Slab), P phase on the horizontal plane (P Horizontal) and pP phase on the horizontal plane (pP Horizontal). Since the location of the southern rupture of the pP and P phases on the horizontal plane is consistent, we construct from them a single input source. We therefore have P Slab, P (pP) Horizontal as possible inputs and P Slab, P Horizontal and pP Horizontal as possible outputs. We tested the six combinations of input and output (Table S1, figure S3). The four tests using the same phases as the input and output are expected to be self-consistent (left and middle columns of Fig. S3). The critical tests that discriminate the different fault planes are those using different phases as input and output (Right column of Fig. S3). We found that the real and synthetic BP solutions are consistent except for the BP with P Slab as input and pP Horizontal as output (Top-right of Fig. S3), which yields a long SSW-oriented rupture segment inconsistent with the observed short SSE rupture of pP phase of the NA array result on a horizontal plane (Figure S2-left). We also perform similar synthetic tests for the SE dipping plane (Figure S10). We find inconsistency of BP with P on SE dipping plane as input and pP Horizontal as output, which also rules out the SE dipping plane. In summary, while the horizontal plane solution is compatible with all the synthetic tests, the slab-parallel plane solution is inconsistent with the pP phase
observations. We therefore consider that the horizontal plane is the only hypothesis satisfying all our observations.
Figure S1. Selected stations (pink triangles) used for P back-projections from the North American network (NA) and European network (EU) and a coherent subset (green triangles) of NA Array stations for pP BP.
Figure S2. Inconsistency of the BPs of different phases on SE dipping plane (left) and on the slab plane (right).
Figure S3. Synthetic tests of pP and P on a sub-horizontal and en echelon (slab-parallel) plane, for the NA array. The six panels show all combinations of the input and output rupture geometry for the synthetic tests. The circles are the recovered BP locations of the synthetics color-coded by time. The black asterisks are the input rupture models, the red squares are BP locations of the real data on the same plane as the synthetic output. Variable amplitudes of 1, 1.5 and 1.25 are assigned to the three clusters of sources from north to south based on the observed BP power. The most useful tests that use combinations of different plane and phases in the input and output are in the right columns (red box); The circles and red squares are generally consistent in all the tests except the top-right panel.
**Figure S4.** Aftershocks and background seismicity in the source region. Color circles are the primary (filled) and secondary (empty) peaks of a reference BP result (P phase, NA array, 0.5-2 Hz, single sub-horizontal plane). The asterisks are the hypocenter solutions from different agencies. The NEIC hypocenter (at a depth of 610 km) is 40 km shallower than the slab model, presumably due to uncertainties of both the hypocenter location and the slab model. We use the NEIC1 hypocenter in our main analysis. The colored small triangles are the background PDE seismicity. The large triangles with gray edges are the aftershocks also from the IDC catalog. The dashed contours are from the Slab 1.0 model. The seismicity and slab model are color-coded by the depth (color scale on the right, in km).
Figure S5. BP results of P phase of the NA array on a single vertical plane with a strike of 12 degree (from GCMT). The circles are the recovered BP locations color-coded by time and sized by power.
Figure S6. Spatiotemporal distribution of seismic radiation sources of the M7 class earthquakes imaged by back-projection of the direct P phase recordings of the North America network. The color circles indicate the locations of the BP peaks with their size scaled by beamforming power and their color indicating timing relative to the hypocentral time (color bar on the right). The red asterisks denote the hypocenters. The black curves are contours of the Slab 1.0 model with a depth interval of 20 km. The top panel shows the M7.3 earthquake processed in the frequency band of 1-2 Hz with a sliding window length of 3 s and time increment of 0.5 s. The bottom panel shows the M7.7 earthquake processed in the band of 0.5-2 Hz with window length of 5 s and time increment of 1 s.
Figure S7. Results of 3D joint BP of the direct P phase and depth phase recorded by the NA network shown in map-view (left) and N-S cross-section (right). Individual BP is first performed for each phase in 3D, i.e. without assuming a fault surface. The log of the MUSIC pseudo-spectra are then added to obtain the joint BP image. The color circles indicate the locations of the BP peaks, with size scaled by beamforming power and color indicating timing relative to the hypocentral time (color bar on the right). The red asterisks denote the hypocenter. The blue curves are contours of the Slab 1.0 model with a depth interval of 20 km. The joint BP result is dominated by the direct P phase, modulated by the trade off along the ray path in the NE-SW direction. The pP phase has a minor contribution due to smaller signal to noise ratio. The spatiotemporal distribution of the joint 3D BP results in map-view is grossly consistent with that of the BP on the single sub-horizontal plane. In the cross-section view, the SSE rupture is 30 km deeper than NE rupture.
Figure S8. Rupture speed estimation based on the BP results of NA 0.5-2 Hz. (Left) HF radiators grouped in (1) northern and (2) southern clusters (gray ellipses). (Right) HF radiators as a function of rupture time and distance along the major axis of the grey ellipses. Rupture speed is estimated for individual clusters. For the southern rupture the estimate accounts for an apparent ~10 s delay of the rupture onset (assuming it starts from the same hypocenter as the northern rupture). The average rupture speeds for the northern and southern segments are 3.4 km/s and 4.0 km/s, respectively.
**Figure S9.** Snapshots of the 3D BP. The three columns show the BP images of P, pP, and joint phases at 0 s, 10 s, 20 s relative to the origin time. The dark red surfaces show the -10 dB (P and Joint) and -5 dB (pP) isosurface of the MUSIC pseudo-spectrum (with maximum at 0 dB). The color contours on the side of the boxes are the 2d cross-sections of the 3d images. The red dot is the location of the maxima. The black dot is the hypocenter. The black contour lines indicate the slab 1.0 model. These snapshots show elongated array response function along the ray-path direction. The P and pP phases contribute to uneven resolutions. In particular, the pP phase has a lower resolution than the P phase because only a subset of coherent stations of the USArray can be used for the pP phase. Therefore, the joint BP is dominated by the P phase with trade-off along its ray path.
Figure S10. Synthetic tests of pP and P on a sub-horizontal and SE dipping plane, for the NA array. The six panels show all combinations of the input and output rupture geometry for the synthetic tests. The circles are the recovered BP locations of the synthetics color-coded by time. The black asterisks are the input rupture models; the red squares are BP locations of the real data on the same plane as the synthetic output. Variable amplitudes of 1, 1.5 and 1.25 are assigned for the three clusters of input sources from north to south based on the observed BP power. The most useful tests that use combinations of different plane and phases in the input and output are in the right columns (red box); the circles and red squares are generally consistent in all the tests except the top-right panel.
Figure S11. BP results of M6.8 aftershock of P phase of the NA array on a single vertical plane with a strike of 12 degree (from GCMT). The circles are the recovered BP locations color-coded by time and sized by power.
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<th>Input\Output</th>
<th>P Slab</th>
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<th>pP Horizontal</th>
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<td>Expected</td>
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<td>P/pP Horizontal</td>
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**Table S1.** Summary of the synthetic tests of all possible combinations of planes and phases. The test is marked as “Expected” if the spatial pattern of the output BP source is consistent with that of the BP of the corresponding real data, “Unexpected” otherwise.