

Compressive sensing of frequency-dependent seismic radiation from subduction zone megathrust ruptures

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Megathrust earthquakes rupture a broad zone of the subducting plate interface in both along-strike and along-dip directions. The along-dip rupture characteristics of megathrust events, e.g., their slip and energy radiation distribution, reflect depth-varying frictional properties of the slab interface. Here, we report high-resolution frequency-dependent seismic radiation of the four largest megathrust earthquakes in the past 10 y using a compressive-sensing (sparse source recovery) technique, resolving generally low-frequency radiation closer to the trench at shallower depths and high-frequency radiation farther from the trench at greater depths. Together with coseismic slip models and early aftershock locations, our results suggest depth-varying frictional properties at the subducting plate interfaces. The shallower portion of the slab interface (above ~15 km) is frictionally stable or conditionally stable and is the source region for tsunami earthquakes with large coseismic slip, deficient high-frequency radiation, and few early aftershocks. The slab interface at intermediate depths (~15–35 km) is the main unstable seismogenic zone for the nucleation of megathrust quakes, typically with large coseismic slip, abundant early aftershocks, and intermediate- to high-frequency radiation. The deeper portion of the slab interface (~35–45 km) is seismically unstable, however with small coseismic slip, dominant high-frequency radiation, and relatively fewer aftershocks.

subduction zone earthquake | coseismic radiation and slip | aftershock distribution | depth-varying friction

Most great earthquakes [moment magnitude (M_w) >8.0] occur at the shallow plate interface between the subducting and overriding plates in subduction zones (1). Variations in the geometrical and physical properties of subducting interfaces and differences in composition and ambient tectonic environments of subduction zones (2, 3) lead to substantial variability in the rupture processes of megathrust earthquakes (1, 4, 5). The along-strike variations in rupture of these events are probably caused by variations in the distribution of asperities on the fault plane (1), as manifested by heterogeneous slip and rupture velocity on the fault planes in seismic and/or geodetic slip inversions (6–10) and complex patterns of high-frequency (HF) seismic radiation from waveform backprojection (11–19). The along-dip (or depth-dependent) rupture of megathrust earthquakes is typically harder to resolve seismically compared with along-strike rupture variations, because these giant events generally rupture further in the along-strike direction (6–10). However, depth-dependent frictional properties and stability regimes of subducting plate interfaces (20) imply along-dip variations of rupture behavior should occur. It is well known that shallower earthquakes in subduction zones, in particular tsunami earthquakes, have significantly longer source durations and depleted short-period energy (5, 21, 22). This is consistent with slower rupture propagation of tsunami earthquakes caused by soft low-rigidity sediments on the shallow plate interface (5, 22) and possibly the increase of dynamic pore pressure in the shallow up-dip region (23).

However, a detailed picture of depth-varying rupture processes of megathrust events (see Fig. 1 for a summary) was not well established until recently, from extensive seismological investigations of the 2011 M_w 9.0 Tohoku earthquake in Japan. This

earthquake exhibits apparent along-dip variations in rupture properties, with major slip occurring in the up-dip region closer to the trench as seen in finite-fault slip inversions (9, 10, 15), whereas HF radiation dominates in the down-dip region closer to the Japan coast as imaged using waveform backprojection (10, 14–18). Similarly, apparent along-dip rupture differences were observed for several other large megathrust events by comparing the slip distribution with HF radiation observations (4, 15). Because waveform backprojection usually uses velocity seismograms (i.e., proportional to the slip acceleration in the source region), observed backprojection power cannot be directly related to finite-fault slip models. Recently, comparisons between time-domain backprojection power at various frequency bands for the Tohoku earthquake (14, 16, 17) and the 2010 Maule earthquake in Chile (19) have also revealed frequency-dependent along-dip energy radiation, with higher-frequency radiation at deeper depths. However, due to poor spatial resolution of waveform backprojection at lower frequencies (17), there are large uncertainties in this type of comparison and the resulting inferences on the details of along-dip rupture characteristics.

We use compressive sensing (CS) (24–28) and seismic array data (Figs. S1 and S2) to systematically analyze the along-dip energy radiation at 0.06–0.6 Hz from the four largest megathrust earthquakes in the past 10 y (see *Materials and Methods*), i.e., the 2011 M_w 9.0 Tohoku earthquake in Japan, the 2010 M_w 8.8 Maule earthquake in Chile, the 2005 M_w 8.6 Sumatra earthquake, and the 2004 M_w 9.2 Sumatra earthquake. CS is a sparse-source inversion method with higher resolution than the conventional beamforming approach (29) or superresolution beamforming methods [e.g., multiple signal classification (MUSIC); refs. 30 and 31] in resolving two or multiple sources, in particular for transient earthquake signals. We compare the frequency-dependent energy radiation to the spatial distribution of major coseismic slip and the early aftershocks to infer the depth-varying frictional properties of subduction zone slab interfaces.

Results

The resulting spatiotemporal distributions of energy radiation at three representative frequencies for the four events (Figs. 2 and 3) show clear along-dip patterns, with low-frequency (LF) energy radiation much closer to the plate boundary near the trench. This feature is even more evident when we compare the along-dip average radiated power at various frequencies (Fig. 4) or over different frequency bands (Fig. 5). Because we use teleseismic data with nearly vertical rays leaving the source region, we do not have

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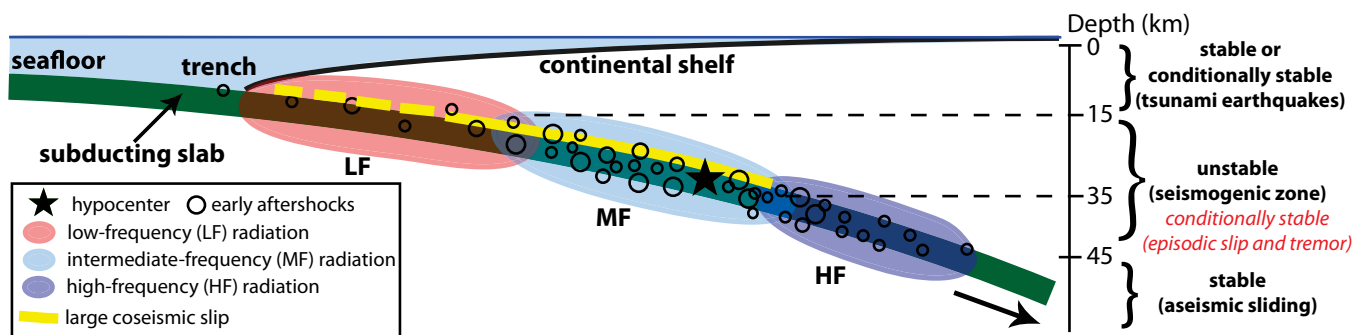


Fig. 1. Seismic observations of subduction zone megathrust earthquakes and frictional stability regimes of the subducting plate interface. The yellow dashed line suggests possible large coseismic slip in the shallow portion of the slab interface in the case of tsunami earthquakes.

depth resolution for the source locations. Here, we assume that the obtained sources (energy bursts) occurred at the subducting slab interface. Therefore, the sources closer to the trench will be shallower than those farther away from the trench. This implies that, during rupture, the LF radiation tends to dominate in the shallow part of the plate interface, whereas the HF radiation dominates at greater depths, although the details of this frequency dependence vary with each of the megathrust earthquakes.

For the Tohoku earthquake, the seismic radiation is dominated in a down-dip region closer to the coast for frequencies above 0.3 Hz (Figs. 2*B* and 4*A*), similar to previous HF back-projection studies (14–18, 31). However, seismic radiation shows

an up-dip pattern closer to the trench for frequencies below 0.16 Hz (Figs. 2*D*, 4*A*, and 5*A*). This apparent along-dip shift of energy radiation is also evident in previous studies (14, 16, 17, 24), although detailed features may vary due to differences in methods or frequency bands. For the Maule earthquake, the general rupture behavior seen in the HF radiation at 0.48 Hz (Fig. 2*F*) is similar to that of previous backprojection studies (13, 17, 19). There is no clear migration pattern of seismic radiation above 0.1 Hz (Figs. 4*B* and 5*B*). However, at the low frequency of 0.08 Hz (Fig. 2*H*), the seismic radiation is much closer to the trench and there is little down-dip energy radiation, consistent with recent backprojection results (19). For the 2005 Sumatra

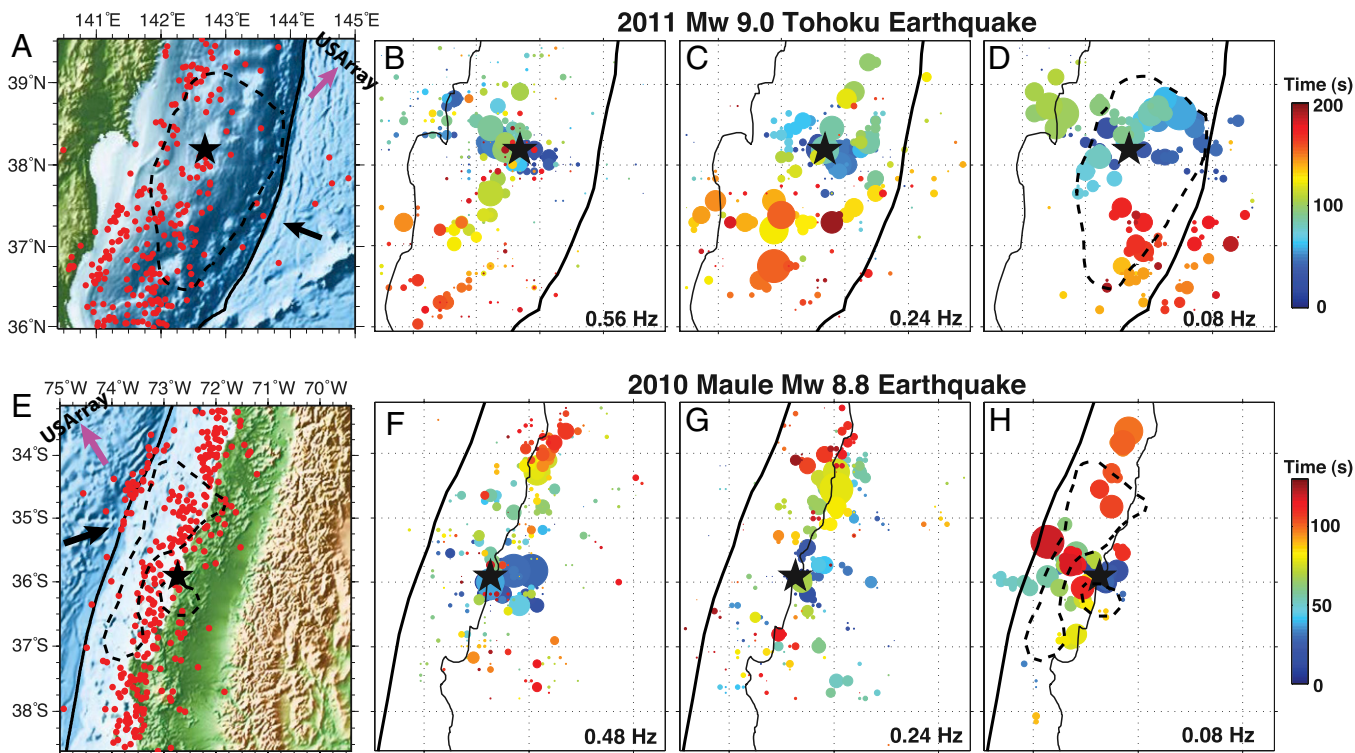


Fig. 2. (A) Locations of the hypocenter (star, location from ref. 32) and early aftershocks (red dots), and (B–D) the spatiotemporal distribution of the recovered sources (large energy bursts, color dots) during the main shock of the 2011 Mw 9.0 Tohoku earthquake at three frequencies. The early aftershocks are those with magnitudes above 4.5 (from the catalogue of the National Research Institute for Earth Science and Disaster Prevention of Japan) within the first 48 h. The relative plate motion direction (black arrow) and direction to the seismic array (magenta arrow) are shown. The color and area of each dot show the source time (right color bar) and relative power at that frequency. The power is relative to the maximum power of all recovered sources in all time windows at that frequency. The plate interface is shown as the thick black line. E–H are similar to A–D but for the 2010 Mw 8.8 Maule earthquake with the hypocenter and aftershock locations from the US Geological Survey catalog. The black dashed line in A, D, E, and H shows the region of large coseismic slip (4). For both earthquakes, we used stations in the United States (mostly from USArray), which are closer to the trench than the down-dip region.

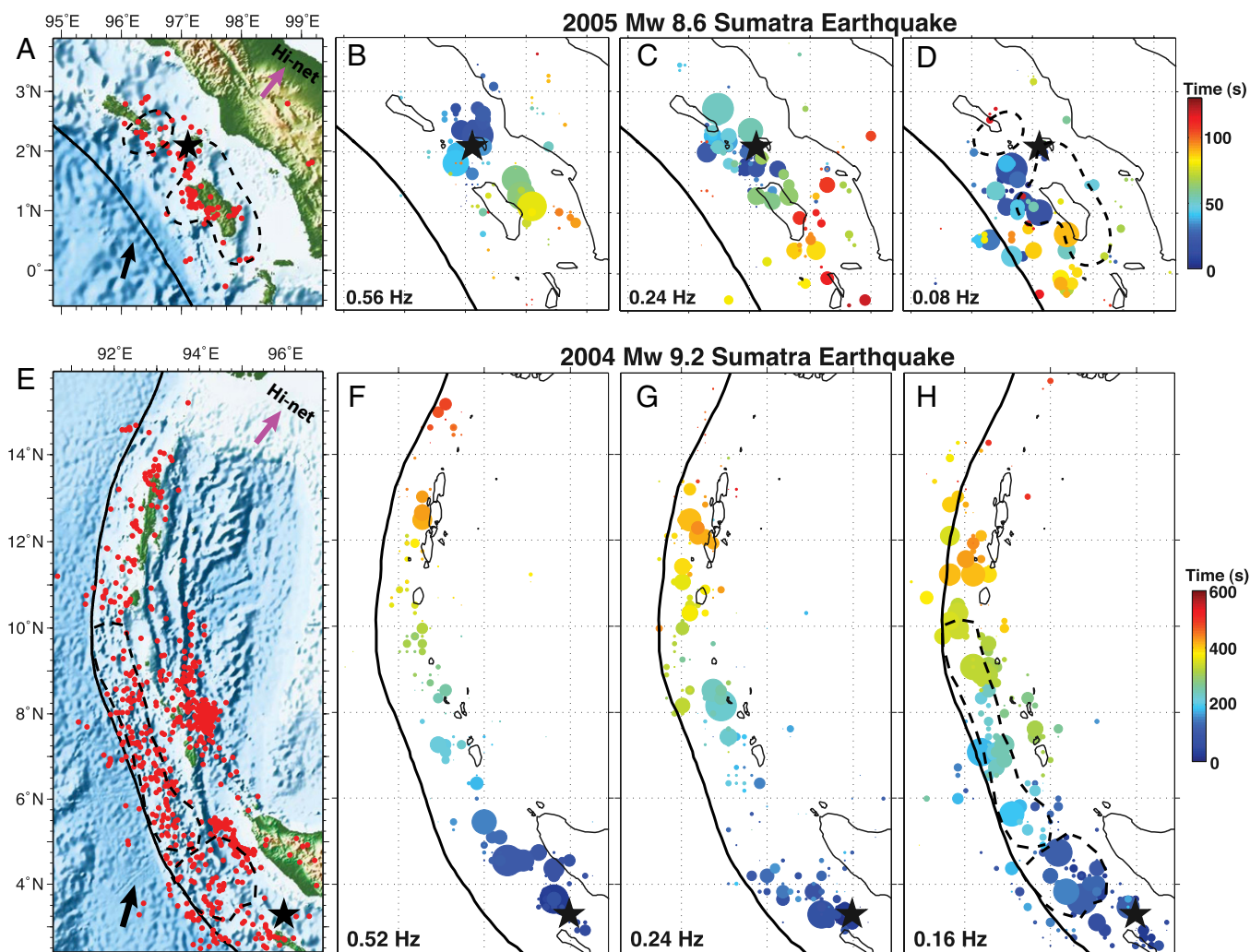


Fig. 3. Similar to Fig. 2 but for the 2005 Mw 8.6 Sumatra earthquake (A–D) and 2004 Mw 9.2 Sumatra earthquake (E–H). For both earthquakes, we used stations from the Hi-net array in Japan, which are closer to the down-dip region than the trench.

earthquake, the imaged HF radiation (Fig. 3B) is similar in location to that seen previously using backprojection (12). The mainshock radiation shows clear along-dip frequency-dependent characteristics (Figs. 3B–D, 4C, and 5C) with LF radiation systematically shallower (closer to the trench) than HF radiation. For the 2004 Sumatra event, the northward rupture is evident from the spatiotemporal distribution of energy radiation (Fig. 3F–H), consistent with previous backprojection results (11). The frequency- and depth-dependent seismic radiation of this event is obvious at intermediate to lower frequencies below 0.3 Hz (Figs. 4D and 5D). Above 0.3 Hz, the overall peak energy radiation mostly occurs at a similar distance to the trench (Fig. 4D).

Discussion and Summary

The systematic frequency/depth-varying seismic radiation pattern is not likely an imaging or depth-phase (18) artifact because the four events are analyzed using two different source-array geometries (Figs. 2A and E, and 3A and E), and backprojection of a number of moderate magnitude aftershocks has suggested no systematic bias that could cause HF energy to occur down-dip (4, 19). Therefore, the along-dip frequency-dependent seismic radiation characteristics for these earthquakes are real and imply variations of rupture processes and related changes in physical properties at the plate interface.

Not only does the seismic radiation of these megathrust earthquakes exhibit frequency/depth-varying properties, the coseismic slip and the distribution of early aftershocks also show some depth-varying features. The coseismic slip is not significant in the down-dip region for the Tohoku, Maule, and 2004 Sumatra earthquakes, where intermediate- to high-frequency radiation dominates. For the 2005 Sumatra earthquake, perhaps due to its smaller magnitude (Mw ~8.6), the large slip region correlates more with intermediate- to low-frequency radiation (Figs. 3C and D and 5C). The major coseismic slip mainly occurred in the up-dip region or around the hypocenter depths (Figs. 2A and E, 3A and E, and 5), in particular for the Tohoku earthquake and the 2004 Sumatra earthquake, for which large slip patches probably extend all of the way up-dip close to the trench (6, 9, 33). The large slip area corresponds well to the region where the intermediate- to low-frequency seismic radiation occurs (Figs. 2D and H, 3D and H, and 5). This implies that these megathrust earthquakes rupture more slowly and continuously in a large area in the up-dip region to generate LF seismic radiation along the shallower portion of the subduction plate interface. The slower rupture speed and prolonged rupture duration in the up-dip region are probably caused by the low rigidity of the fault material, e.g., subducted sediments (22, 34), and the increase of dynamic pore fluid pressure (5, 23). For the 2010 Maule and 2005 Sumatra earthquakes,

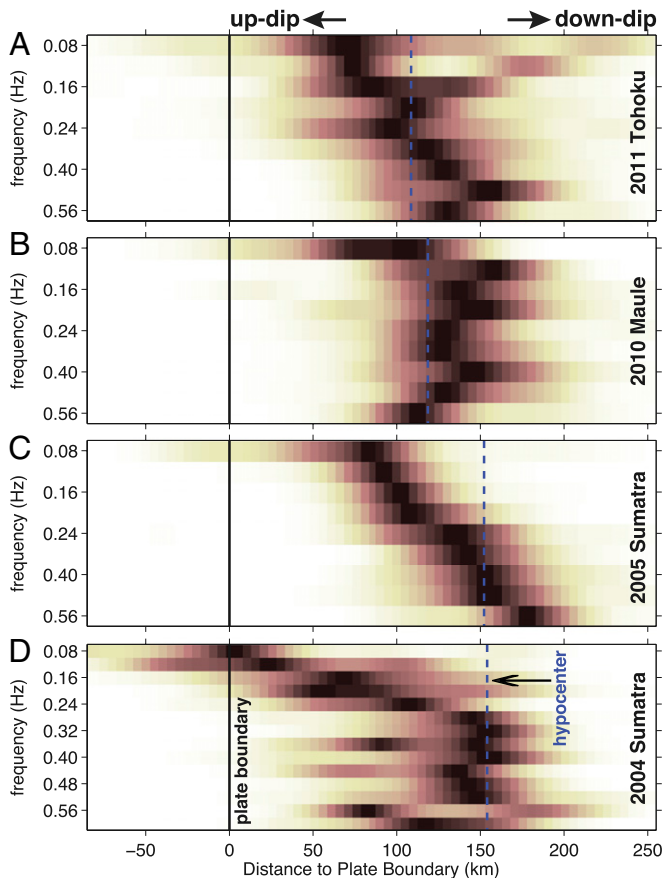


Fig. 4. Comparison of the along-dip average radiated power (normalized to 1 for each frequency) at all studied frequencies between 0.06 and 0.6 Hz for the four events. The frequencies shown on the y-axis are the central frequencies of study with the bandwidths given in *Materials and Methods*. The solid black line at $x = 0$ gives the position of the plate boundary and the dashed blue line shows the hypocenter position.

the observed tsunami heights are much smaller, only a few meters as reported. However, both the 2011 Tohoku and 2004 Sumatra earthquakes caused big tsunamis, up to 20–30 m high as observed in nearby coastal regions, which strongly correlates with very large coseismic slip and dominant LF radiation at very shallow slab interfaces close to the trench for these two events.

For the Tohoku, Maule, and 2005 Sumatra earthquakes, there is a systematic lack of early aftershocks in the shallow up-dip region (e.g., above 15 km) and the early aftershock rate is also very low deeper than 35 km (Figs. 5A–C), although the depth range of aftershocks for each event appears different. For the Tohoku earthquake, the along-dip distribution of early aftershocks correlates well with that of the HF radiation (Fig. 5A). The lack of early aftershocks and the existence of large slip in the shallower up-dip region suggest the accumulated strain during the interseismic period may have been largely released during the mainshock. For the 2004 Sumatra earthquake, the main shock triggered many early aftershocks in the crust beneath the back-arc Andaman Sea (Fig. 3E), about 210–250 km east of the subduction plate boundary (Fig. 5D). In the up-dip region of the 2004 Sumatra earthquake, most early aftershocks occurred shallower than 20 km (Fig. 5D).

The along-dip depth-varying features of coseismic slip, energy radiation, and early aftershock distribution of these earthquakes imply depth-dependent frictional properties of the slab interface (4, 20, 21) (Fig. 1). The shallow portion of the slab interface (above about 15 km depth) is characterized by stable or

conditionally stable frictional properties (20) and is the source region for tsunami earthquakes (4). This region typically has very large coseismic slip and slower rupture speed and lacks HF coseismic radiation and early aftershocks. Very large coseismic slip may occur in this regime, probably due to the stability transition of the broad zone of subducted sediments (34), that is, from stable velocity-strengthening behavior at shallower depths to unstable velocity-weakening behavior at greater depths due to fault gouge consolidation and lithification (35) and effects of thermal fluid pressurization (36–38).

At the depth range of about 15–45 km in the subduction zone, the slab interface is characterized by seismically unstable frictional properties (20). The shallower part of this regime (about 15–35 km deep) appears to be the main nucleation region of megathrust earthquakes and typically has large coseismic slip, abundant early aftershocks, and intermediate- to high-frequency radiation, which may be due to the relative larger size of the asperities (4). The deeper part of this regime (35–45 km) is mainly characterized by small coseismic slip, dominant HF seismic radiation, and relatively fewer aftershocks. The sizes of asperities or repeaters (4) are probably much smaller than those within the main seismogenic zone for the depth range of 15–35 km and are the main sources of HF radiation during the main-shock rupture process.

Between the unstable seismogenic zone and the deeper stable sliding zone in the upper mantle, there may exist a conditionally

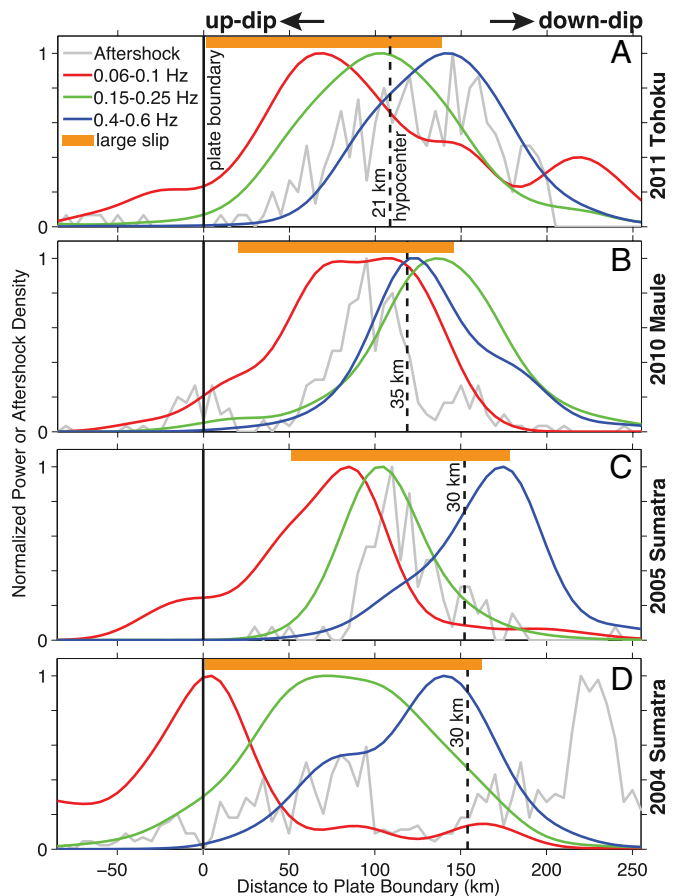


Fig. 5. Comparison of the along-dip average radiated power (normalized) over three representative frequency bands (red, green, and blue curves), the normalized density of early aftershocks (gray curves), and the large coseismic slip region (orange bars) of the four events shown in Figs. 2 and 3. The positions of the plate boundary (solid black) and the hypocenter (dashed black) are shown together with the hypocenter depth next to the dashed line.

stable region (with high fluid pressure) at a depth of about 30–45 km in some young subduction zones (e.g., the Nankai trough and Cascadia), with frequent occurrence of episodic tremor and slip (ETS) and LF earthquakes (39). However, for the source region of the Tohoku, Maule, and the 2005 and 2004 Sumatra earthquakes, ETS has not been reported (39).

Materials and Methods

CS (24–27) recovers sparsely distributed sources using an inverse approach and is an active area of research in signal processing and applied mathematics. In the context of great earthquake rupture, we assume that the seismic energy radiated from the source region at a given frequency and time is spatially sparse in the entire rupture area (24). Seismic radiation within a certain time window during the earthquake is represented by its potential source spectrum $\mathbf{x}(f)$ at a set of M spatial source grid points. The observed spectral data at an array of N stations is $\mathbf{b}(f) = \mathbf{A}(f)\mathbf{x}(f) + \mathbf{n}(f)$. Here, $\mathbf{A}(f)$ is the propagation matrix with its nm th element equal to $\exp(-2\pi f\tau_{nm})$, where τ_{nm} is the travel time from location m to station n . The additive noise $\mathbf{n}(f)$ is zero-mean Gaussian. Note that \mathbf{A} samples all possible source locations, but there are only few active sources. Thus, $\mathbf{x}(f)$ must be sparse.

CS locates the sparse seismic sources $\mathbf{x}(f)$ by minimizing the L2 norm of the difference between the observed $\mathbf{b}(f)$ and modeled spectral data vector $\mathbf{A}(f)\mathbf{x}(f)$ at frequency f , penalized by the L1 norm of the source spectrum vector $\mathbf{x}(f)$, i.e., the following:

$$\hat{\mathbf{x}}(f) = \arg \min \{ \|\mathbf{b}(f) - \mathbf{A}(f)\mathbf{x}(f)\|_2 + \lambda \|\mathbf{x}(f)\|_1 \}. \quad [1]$$

Here, λ is the damping parameter. The sparse problem (Eq. 1) is efficiently solved using convex optimization (28) (SI Text). The L1 norm on the source vector $\mathbf{x}(f)$ in Eq. 1 enforces the sparsity of the estimated source vector $\hat{\mathbf{x}}(f)$ (25–27), that is, only a few elements in $\hat{\mathbf{x}}(f)$ are nonzero (see Synthetic Tests in SI Text). This is different from beamforming approaches, which usually only pick one point with the maximum beam power (29).

For a single source, the conventional linear beamforming (29) is perfect even at low frequencies. However, beamforming may fail for multiple-source problems if the sources are within the Rayleigh resolution cell. CS is superior to the conventional beamforming in resolving two or multiple sources within a Rayleigh resolution cell (25) over a broad frequency band (e.g., 0.06–0.6 Hz) (Figs. S3–S6). Superresolution beamforming, e.g., MUSIC (30, 31), can also resolve multiple sources. However, these methods work best for stationary signals and require many observations to obtain a good cross-spectral density matrix estimate, which is rarely the case for transient earthquake signals. MUSIC also needs to estimate the noise subspace, which is difficult in practice. Although superior to linear beamforming, CS and superresolution methods cannot resolve sources too close or with too low frequencies. CS (24) directly works on signals in the frequency domain for

a single observation (time window) without knowing the number of sources and estimating the noise subspace, thus providing a more direct estimation of source parameters. CS is more reliable for multiple-source localization problems and provides a self-consistent and uniform way to study seismic energy radiation from the source region over a wide frequency range, e.g., the Tohoku earthquake (24).

We use dense seismic array data from the United States to analyze the 2011 Tohoku and 2010 Maule earthquakes and data from the Japanese Hi-net array to study the 2004 and 2005 Sumatra earthquakes (Figs. S1 and S2). A sliding window approach (24) is used to obtain $\hat{\mathbf{x}}(f)$, giving the spatial distribution and power of sparse sources at each frequency (frequency band, 0.06–0.6 Hz) and time window (10 or 20 s long). Please see the SI Text for details on data processing, model parameterization, and inversion procedures. To remove unreliable sources, only sources with amplitudes above 0.1 times the maximum element in $\hat{\mathbf{x}}(f)$ are retained for each frequency and time window.

We define $P_{ij}(\theta, f)$ as the power of the j th retained source (at location θ and frequency f) from the inversion in the i th time window. By combining all of the retained sources P_{ij} from all snapshots (time windows), we obtain detailed spatiotemporal variations in seismic radiation during the earthquake at that frequency (e.g., Figs. 2 B–D and F–H, and 3 B–D and F–H). Then we sum over the radiated power with Gaussian smoothing for all of the retained sparse sources at each frequency in all time windows to obtain the along-dip average radiated power with respect to the distance to the plate boundary (Fig. 4) as follows:

$$P(d, f) = \sum_i \sum_j \exp\left\{-[d_{ij}(\theta, f) - d]^2/L^2\right\} P_{ij}(\theta, f), \quad [2]$$

where d is the given distance to the plate boundary (approximately the trench location), $L = 35$ km is the Gaussian smoothing distance, and $d_{ij}(\theta, f)$ is the distance to the plate boundary of the j th retained source (at location θ and frequency f) in the i th time window. The along-dip average radiated power over a frequency band (Fig. 5) can be obtained by summing the average power at various frequencies (Fig. 4) within that band.

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