Source Rupture Models for the $M_w$ 9.0 2011 Tohoku Earthquake from Joint Inversions of High-Rate Geodetic and Seismic Data

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Abstract  The space–time history of fault slip during the 11 March 2011 Tohoku earthquake ($M_w$ 9.0) is determined using high sample rate three-component Global Positioning System (GPS) recordings from regional stations across Japan, teleseismic broadband $P$ waves, global $R_1$ source time functions determined by empirical Green’s function deconvolutions of short-arc Rayleigh waves, and ocean-bottom deformation observations. Least-squares inversions are performed for models with prescribed rupture-front expansion velocity. Joint inversion yields improved resolution of slip compared with inversions using any single data type for both checkerboard rupture simulations and the actual data. Joint inversion stabilizes inversions with respect to some key parameters, such as the rupture expansion velocity and subfault total rupture durations, due to lower dependence on these parameters of some datasets (mainly the high sample rate [1 sample/s] three-component GPS recordings [hr-GPS] data). The preferred joint inversion model has a seismic moment estimate of $4.2 \times 10^{22}$ N·m ($M_w$ 9.0), with a primary large-slip patch with maximum slip of $\sim 50–60$ m located up-dip of the hypocenter on the shallow megathrust and distributed slip of 20–30 m near the hypocenter. A down-dip low-slip extension to the south is also resolved, with centroid source time later than 110 s.

Online Material: Figures of inverted slip distributions and associated source time functions and centroid times, and waveform fits.

Introduction

The $M_w$ 9.0 2011 Tohoku earthquake is the best-recorded great earthquake to date. Extensive coseismic observations were provided by dense near-field strong ground motion and Global Positioning Systems (GPS) networks, teleseismic body and surface-wave recordings from global seismic networks, deep-water and near-coastal tsunami observations from buoys and pressure gauges, and tsunami run-up and inundation measurements (e.g., Lay and Kanamori, 2011; Mori et al., 2011). These data allow characterization of the rupture process of this huge megathrust event with an unprecedented level of detail. Numerous finite-fault models, capturing aspects of the spatiotemporal evolution of the rupture, have been determined by modeling or inversion of the seismic, geodetic, and tsunami observations both separately and, in some cases, jointly. The focus is now on evaluating intrinsic resolution of different datasets and reconciling differences between the various models. In general, finite-fault models inverted with similar datasets usually yield fairly similar rupture patterns, indicating that the results are not exclusively controlled by the specific inversion techniques and parameterizations, although those can have important effects.

Seismic waves, including teleseismic body waves and surface waves and near-field strong ground motion signals, have been analyzed to determine the overall 2011 Tohoku earthquake source rupture process. Many of the seismic-wave inversions obtain a consistent large-scale large-slip region up-dip and east of the epicenter close to the trench (e.g., Hayes, 2011; Ide et al., 2011; Lay, Ammon, Kanamori, Xue, et al., 2011; Shao et al., 2011; seismic inversions in Simons et al., 2011; Yoshida, Miyakoshi, and Irikura, 2011; Yoshida, Ueno, et al., 2011; Wei et al., 2012). However, some seismic wave inversions place the large slip patch closer to the hypocenter (e.g., Koketsu et al., 2011), with the reasons for the differences not being very clear. Factors such as the assumed fault-model geometry (dip and depth), choice of hypocenter, assumed rupture expansion parameters, and source region velocity structure (particularly the rigidity structure used to map inverted subfault seismic moment estimates to slip) all appear to contribute to the differences between the seismic finite-fault models.

Backprojection methods applied to teleseismic short-period seismic network data indicate locations of coherent
short-period $P$-wave radiation from local regions of the megathrust down-dip, west of the epicenter (Ishii, 2011; Koper, Hutko, and Lay, 2011; Koper, Hutko, Lay, et al., 2011; Meng et al., 2011; Wang and Mori, 2011; Yao et al., 2011, 2012; Zhang et al., 2011). These backprojections do not directly image slip on the fault, as the short-period $P$ waves are more sensitive to variations in slip velocity, but very few localized sources of coherent short-period radiation appear in the region extending from the hypocenter to the trench. The difference in location between areas of large slip shallower on the megathrust and the deeper high-frequency source radiation patches is also indicated by near-field strong ground motion data (e.g., Kurahashi and Irikura, 2011; Yoshida, Miyakoshi, and Irikura, 2011). Varying frequency-dependent seismic radiation between up-dip and down-dip has been observed for other subduction-zone megathrusts and appears to involve systematic depth-dependent behavior (Lay et al., 2012).

Geodetic inversions using the huge dataset from regional GPS static displacement measurements on land to estimate the spatial slip distribution on the fault plane provide unprecedented sampling of the deformation, but no temporal information about the rupture evolution. For the 2011 Tohoku earthquake, the GPS stations all locate westward from the rupture plane, and there is a tendency for these inversions to place the maximum slip west of or centered beneath the epicenter (Inuma et al., 2011; Koketsu et al., 2011; Miyazaki et al., 2011; Ozawa et al., 2011; Simons et al., 2011), although not in every case (e.g., Ito, Ozawa, et al., 2011) and some shallow slip is present in models with deeper main slip patches (e.g., Simons et al., 2011). Offshore observations of seafloor motions from shifts in locations of GPS and OBS stations, and offsets in multichannel reflection profiles (e.g., Fujiwara et al., 2011; Ito, Tsuji, et al., 2011; Sato et al., 2011) provide unique static displacement information right above the epicenter and near the toe of the sedimentary wedge. Inclusion of these observations, treated as elastic deformations, in geodetic inversions tends to shift the maximum slip up-dip toward the trench, similar to many seismic models (e.g., Ito, Tsuji, et al., 2011).

Tsunami observations provide good spatial resolution of the seafloor deformation due to the relatively low propagation velocity of tsunami waves. Matching the absolute arrival times of the tsunami signals is essential for locating the seafloor uplift. Inversion of tsunami observations requires linearization of the nonlinear tsunami-wave equations (Saito et al., 2010). Finite-fault models inverted from tsunami observations consistently locate a large slip patch up-dip on the fault, very close to the trench (Fuji et al., 2011; Koketsu et al., 2011; Maeda et al., 2011; Saito et al., 2011). Iterative forward modeling of tsunami observations using finite-fault models obtained from seismic observations (Lay, Yamazaki, et al., 2011; Yamazaki et al., 2011, 2012) achieves good fits to both the tsunami recordings and teleseismic $P$ waves as long as the largest slip regions are located close to the trench.

Each available dataset provides limited resolution of inverted slip models, as discussed by Yokota et al. (2011), Koketsu et al. (2011), and Wei et al. (2012). Joint inversions of diverse datasets may overcome the limitations of separate inversions, ideally achieving good resolution across the entire fault model, but joint inversion presents challenges with respect to information weighting and self-consistent modeling. Several joint inversions have been performed for the 2011 Tohoku event, with the maximum slip patches tending to locate somewhat up-dip, east of the epicenter, but usually not reaching as far as the trench (Ammon et al., 2011; Koketsu et al., 2011; Lee, 2011; Yokota et al., 2011).

The near-field ground displacements produced by the 2011 Tohoku earthquake were recorded by a dense geodetic network (GEONET) that comprises ~1200 GPS stations deployed across Japan (Grapenthin et al., 2011). Time-varying solutions for ground position with high-rate (1 sample/s) calculation (hr-GPS) record both the transient motions produced by seismic waves and the time evolution of the static offsets. Inversion of hr-GPS data is thus inherently a joint inversion of geodetic and seismic data, requires complete Green’s functions for all motions, and has been found to provide stable slip patterns relatively independent of key inversion parameters such as rupture velocity (Yue and Lay, 2011) and consistent with joint inversions of other datasets (Ammon et al., 2011; Yokota et al., 2011). This paper extends the hr-GPS inversions conducted by Ammon et al. (2011) and Yue and Lay (2011) and discusses the resolution and stability of hr-GPS inversion and the advantage of joint inversion with additional seismic data to achieve a well-resolved rupture model for the 2011 Tohoku earthquake.

Data and Methods

Fault Parameterization

Our source model (Fig. 1a,d) is parameterized with 16 subfaults along strike and 8 along dip on a fault plane with dip that progressively increases with depth from 4.8° to 23°. The dimension of each subfault is 30 km × 30 km, and the total fault dimensions are 480 km × 240 km. The geometry of the varying fault dip (Fig. 1d) was estimated from an east-west seismic reflection profile through the source region near the hypocenter (Miura et al., 2005). We use a 1D layered source structure in the modeling, and have to make some approximations to map the true 3D ocean/wedge/slab geometry into a radially stratified velocity model. The depth below seafloor of each grid point at the center of a subfault in the reflection profile geometry was set equal to the overlying sedimentary prism thickness (Fig. 1d) to give an approximately correct localized depth-phase delay time for the teleseismic $P$-wave Green’s functions, whereas the fault dip was preserved to give correct radiation patterns for all phases. The epicenter (38.107°E, 142.916°N) determined by the mainshock relocation of Zhao et al. (2011) (Fig. 1a), is associated with the sixth node along strike, and fourth node
along dip (at a depth below seafloor of 17 km), defining the geographic location of the fault plane. We reference distance along strike from the northeastern corner of the model and along-dip down from the trench side of the model.

For each subfault, the source time function (STF) is parameterized with 10 symmetric triangles with 5-s half-durations staggered by 5 s each. The seismic moment of each triangle on which the slip is occurring is accounted for during the inversion, allowing variable rake within that range for each subfault subevent.

hr-GPS Data

We obtained hr-GPS ground-motion records from 1 Hz GEONET data, provided by the Geospatial Information Authority of Japan (GSI). We assume an initial rupture-velocity of $V_r = 1.5$ km/s outward on the fault plane from the hypocenter to a distance of 100 km, and then increase $V_r$ to 2.5 km/s, based on prior backprojection imaging (Koper, Hutko, and Lay, 2011). We assume an initial rupture-expansion velocity of $V_r = 1.5$ km/s outward on the fault plane from the hypocenter to a distance of 100 km, and then increase $V_r$ to 2.5 km/s, based on prior backprojection imaging (Koper, Hutko, and Lay, 2011; Koper, Hutko, Lay, et al. 2011) and finite-fault modeling of teleseismic and regional signals (Ammon et al., 2011; Lay, Ammon, Kanamori, Kim, et al., 2011; Yue and Lay, 2011; Wei et al., 2012). In our previous work, we used two slip-vectors to parameterize rake-varying slip on each subfault and applied a non-negative least square inversion (Lawson and Hanson, 1995); however, including $R_1$ STFs obtained by empirical Green’s function deconvolution in the inversions requires use of a single rake angle. Thus, our inversions that include the surface waves use a fixed rake of 90°, which was found to be the optimal choice. Injoint inversions using hr-GPS and teleseismic P-wave data, Green’s functions for rakes of 45° and 135° on each subfault are used in the inversion, allowing variable rake within that range for each subfault subevent.
distance, which are insignificant for the 80 mHz (12.5 s) limit of the signal spectrum. We applied a fourth-order low-pass Butterworth filter with a corner at 25 s to both the raw data and the Green’s functions to eliminate noise in the processed data and mode sum truncation ringing, respectively. The parameters used in this study are the same as used by Yue and Lay (2011), who found stability in hr-GPS-only inversions using many permutations of station subsets from the large number of hr-GPS stations that are available; the total number of stations used in our inversions is about twice that of the earlier study. The results we show here are not significantly dependent on the precise choice of stations as long as similar azimuthal and spatial distributions are used.

Teleseismic P-Wave Data

The teleseismic P-wave dataset comprises 38 broadband ground motions from stations of the Federation of Digital Seismic Networks (FDSN), accessed through the Incorporated Research Institutions for Seismology (IRIS) data center. The data were selected from hundreds of available FDSN seismograms to have good azimuthal coverage (Fig. 1c) and high signal-to-noise ratio. A 200-s-long time window was extracted from the raw data, starting 10 s prior to the arrival of the P waves. The initial motions of the P waves were aligned manually, relative to the USGS-NEIC reported origin time (05:46:24 UTC). The USGS origin time is 5–6 s later than local determinations, primarily due to existence of a very weak initial seismic energy release that can only be seen in local high-frequency stations. We shifted the teleseismic P-wave data first arrival alignments by a corresponding amount to ensure consistency with the hr-GPS reference origin time from Zhao et al. (2011). Because the grid spacing is 30 km and the rupture velocity is low (initially 1.5 km/s), the hypocentral subfault will still capture the P-wave onsets even if there is a delayed onset of visible far-field ground displacement.

Teleseismic P-wave Green’s functions were generated using the layered propagator matrix code of Kikuchi and Kanamori (1991) for the PREM velocity structure, again ensuring consistency with the source structure used for the hr-GPS Green’s function. This choice of PREM velocity structure is significant in that the near-surface crustal layer in PREM does not have as low a rigidity as assumed in some P-wave inversion studies for this event (e.g., Lay, Ammon, Kanamori, Xue, et al., 2011), which can lead to differences in slip estimates near the trench. The Green’s functions and data were both filtered by a Butterworth low-pass filter with a corner at 1 s and the seismograms were decimated to 0.5-s time sampling. Considering the relatively long source duration of ~150 s for the Tohoku event (Yue and Lay, 2011), fixed teleseismic P-wave windows can have some contamination from PP-wave arrivals for stations at shorter epicentral distances. The P-wave windows were cut manually to avoid the PP arrivals, as were corresponding Green’s functions, such that joint inversions only use hr-GPS, more distant P-wave data, and surface-wave data for constraining later parts of the source solution.

$R_1$ STF Data

725 short-arc Rayleigh wave ($R_1$) relative source time functions (STFs) were extracted from the mainshock observations by deconvolving empirical Green’s functions (EGFs) (e.g., Ammon et al., 1993) given by signals at the same stations for the 9 March 2011 $M_w$ 7.3 foreshock. The $R_1$ signals were isolated using a wide group velocity window, and the deconvolutions used an iterative time-domain procedure with positivity constraint, based on the method of Kikuchi and Kanamori (1982). A low-pass Gaussian filter ($\alpha = 0.1$ Hz) was applied to the deconvolved signals to reduce short-period noise in the resulting time series. These relative $R_1$ STFs isolate the differential source effects of the larger and EGF events, with accurate estimation of the larger event properties for periods longer than about 30 s. All relative STFs were azimuthally binned in $10^\circ$ azimuth windows and stacked; yielding 29 average STF traces with good distribution (Fig. 1b). The stacked relative STFs were each convolved with a 30-s-wide triangle function that approximated the $R_1$ STF for the foreshock event based on finite-fault inversion for that event, providing estimates of the true mainshock STFs. These stacked $R_1$ STFs were used in separate and joint inversions. A 400-s-long time window was extracted from the STFs, and the data were decimated to 5-s sampling. The processing of the $R_1$ STFs presents some challenges for joint inversion. By deconvolving EGF signals that are associated with a specific faulting geometry, the STFs are affected by any differences in the model faulting geometry (dip and/or rake, and depth) for the larger event’s rupture relative to the smaller event. For finite-fault inversion with a model that varies in dip $\delta$, we apply subfault moment corrections proportional to $\sin(2\delta_{\text{EGF}})/\sin(2\delta_{\text{SUBFAULT}})$ to account for varying subfault contribution to the overall synthetic STFs. We hold the rake constant for all subfaults when inverting the surface-wave observations. Both Green’s functions and STFs are weighted by the $R_1$ wave radiation pattern to minimize the effect of noise for traces near radiation nodes.

Ocean-Bottom GPS Data

Coseismic displacements of the ocean floor at five stations near the epicenter were determined using a GPS/ acoustic technique (Sato et al., 2011), providing valuable offshore constraints on static deformations of the upper plate. It was shown that the maximum horizontal slip near the hypocenter is ~25 m, and the maximum vertical displacement near the hypocenter is ~3 m. The three-component displacements for these five ocean-bottom GPS (OBGPS) stations were used in our joint inversion. Static displacements obtained from stacking the normal modes, as used for time-varying hr-GPS Green’s functions, provided Green’s functions for inversion of the OBGPS data.
Finite-Fault Inversions

We ran two basic sets of inversions with different combinations of datasets: joint inversion with hr-GPS data, teleseismic $P$-wave data, $R_1$ STFs, and OBGPS data using a constant rake of $90^\circ$, is designated the GTS inversion; joint inversion with hr-GPS data and teleseismic $P$-wave data, allowing variable rake on the subfaults, is designated the GT inversion. Before considering results of data inversions, we demonstrate the generic resolution of single- and joint-dataset inversions for simple slip model distributions.

Checkerboard and Inversion Stability Tests

Checkerboard tests provide a convenient visualization of relative resolution for different datasets, but have to be used cautiously as there are many parameters, which can trade off in finite-source models. The synthetic data for our checkerboard tests were computed using the actual station distributions and the same Green’s functions as used in the data inversions shown subsequently. When no damping is applied and no noise is added, each inversion resolves exactly the same slip distribution as the input model, because the inversion matrix is fully ranked. However, when applying any regularization technique, even for noise-free data, slip locations and magnitudes with intrinsically low spatial resolution for the data and model configuration will be smeared out by the regularization effect. For most inversion problems, resolution is controlled by the degree of similarity of the eigenvectors of the inversion matrix, described as its associated covariance matrix. Essentially, if the eigenvectors are similar between two parameters and they contribute to the fit to the same data, the two parameters cannot be differentiated by the inversion. For the specific case of finite-fault model inversions, the similarity between the Green’s functions of different subfaults determines their relative resolution.

Regularization is necessary to ensure inversion stability for most finite-fault source-model inversions. We applied a Laplacian regularization, which constrains the second order gradient for each parameter to be zero. The strength of regularization influences the slip expansion and peak slip amplitude, and our selection of a preferred regularization parameter is based on two factors: the maximum slip amount near the up-dip limit of the fault should not exceed the ocean floor displacement ($\sim 60$–$80$ m) observed at the toe of the upper wedge; and the model slip distribution should be compatible with the intrinsic spatial resolution indicated in the checkerboard tests.

Figure 2 shows results for representative checkerboard inversions with relatively large-scale slip patterns with dimensions greater than the model parameterization. The rupture velocity for the synthetics and the model are the same, and the smoothing regularization is the same as used in the data inversions. The rake is constant in this case. The hr-GPS dataset involves time-varying growth of the static offset and the arrival of the little-dispersed surface-wave motions with relatively low horizontal velocities ($\sim 4$ km/s).

The timing information (which is not included in geodetic static offset inversions) greatly enhances the spatial resolution of slip; however, for the Tohoku earthquake, all hr-GPS stations are located on one side of the hypocenter, which leads to an up-dip/down-dip trade-off between the subfault slip time and the slip location.

The upper plate vertical static displacement for a thrust event changes sign with epicentral distance from each subfault, whereas the horizontal static displacement does not. For the Tohoku event GPS-station distribution, the up-dip (near trench) and down-dip (near coast) regions of slip on the megathrust produce opposing vertical static displacements, which interfere to shape the weak overall vertical ground motions, whereas the large eastward component displacements result from constructive interference of fault motions at all depths. Inversion with three-component static displacements thus provides more sensitivity to the slip
distribution along dip than inversion using only the horizontal components. Generally the resolution of hr-GPS data comes from both the difference of interference of three-component static ground displacements and the timing information of the time-varying (seismic) signals. The hr-GPS checkerboard tests recover the input patterns well on the down-dip part of the fault model, but the up-dip slip pattern is smeared in the along-strike direction in the smaller-scale checkerboard test (Fig. 2). It has been well established that static displacements with observations on one side of the fault provide very limited resolution of the near-trench fault slip (Yokota et al., 2011; Wei et al., 2012). In our case, the resolution of the hr-GPS data is improved relative to using just the static GPS data, especially in the along-dip direction, due to accounting for the time-varying signals. The along-strike resolution is still limited, particularly toward the south (right side of the plots in Fig. 2) due to the absence of stations along strike of the rupture zone.

For teleseismic P-wave inversions, directivity effects are relatively minor due to the high apparent velocity (~20 km/s) of teleseismic P waves. The checkerboard tests of teleseismic P-wave inversions still show fairly good resolution throughout the entire fault plane (Fig. 2), mainly due to the relatively short-period (5–20 s) signal information. The P-wave Green’s functions vary most rapidly with depth; however, for very shallow regions of the fault plane the interference between P and pP depth phases produces low-amplitude Green’s functions, which can give rise to instability in the slip resolution, particularly if the fault geometry (dip) is inaccurately specified. The resolution of the checkerboard inversion for the P-wave simulation in Figure 2 is for the correct rupture velocity; it is well known that teleseismic P-wave inversions will have only limited spatial resolution if the rupture velocity is not known and if kinematic constraints incorrectly force the solution toward a slip pulse behavior (e.g., Lay et al., 2010). It is important to recognize that when the rupture velocity, or spatial location of slip in any region of the fault plane, is correctly resolved by independent data (as may be the case in joint inversions) and a sufficiently flexible parameterization is provided so as not to kinematically over-constrain the solution, the intrinsic timing resolution and depth sensitivity of relatively short-period teleseismic P waves actually manifest, leading to significant contribution to the joint solution.

For the azimuthally well-distributed $R_j$ STF data inversion, which emphasizes long-period Rayleigh-wave energy with low phase velocity (~4 km/s), the spatial resolution is potentially quite good, as seen in Figure 2. Whereas the EGF technique accounts for overall dispersion, attenuation, and aspherical effects effectively, actual variations in excitation due to a curved fault plane and finite depth distribution of the source will degrade the ideal resolution (the solution in Fig. 2 uses completely consistent Green’s functions for the synthetics and inversions over the entire fault plane, which is not realistic). The resolution of shallow slip toward the south is still somewhat limited by the data distribution.

The checkerboard test for joint inversion of the different simulation datasets using the relative weighting applied to the actual data provides better resolution than any individual dataset (Fig. 2). The complementary sensitivity of the different datasets is exploited in the joint inversions, with, for example, the relatively good along-dip resolution provided by the P waves offsetting the weak up-dip resolution from the hr-GPS data. It is important to keep in mind that the example in Figure 2 is for the correct rupture velocity, which provides compatible resolution of the slip model for each dataset.

Figure 3 provides checkerboard tests for a simple slip distribution for which a rupture velocity of 1.5 km/s was used in the simulations, whereas either correct or overestimated rupture velocities were used in the inversions. In this case, the hr-GPS data still provide intrinsically good spatial resolution that stabilizes the solution even for very inaccurate choice of rupture velocity, as long as the STF durations are sufficiently long-lasting for each subfault such that the slip distribution is not kinematically constrained to prematurely expand outward within a rupture annulus. The pronounced deterioration of the recovered models for the separate teleseismic P wave and $R_j$ STF inversions occurs despite having the long subfault duration flexibility because these data simply have lower intrinsic resolution when the rupture velocity is incorrect. The joint inversions for all choices of rupture velocity strongly resemble the hr-GPS inversions due to the high spatial resolution intrinsic to the regional geodetic information in the hr-GPS signals, as discussed by Yue and Lay (2011). It is important to observe that the joint inversions are not corrupted by the inclusion of the teleseismic signals even when a grossly incorrect rupture velocity is assumed because the model allows those data to be fit by the same spatial pattern as required by the hr-GPS data. This is ensured by using a sufficiently long subfault source-duration parameterization. Whereas the teleseismic data may contribute little to the spatial distribution of the model in such cases, those data can still contribute to the temporal resolution of slip.

The checkerboard tests in Figures 2 and 3 use the same Green’s functions for generating synthetic data and for the inversion matrix, and provide guidance on relative resolution of different datasets under ideal circumstances. The fault geometry is often held fixed in finite-fault inversions due to the many parameters involved. To test the inversion stability for perturbations of the fault model, we considered three models: a single dip (10°) planar fault model as used by Lay, Ammon, Kanamori, Xue, et al. (2011), a planar fault model with variable subfault dip, and our preferred multidip curved fault model with correct effective depth relative to the bathymetry. We performed three joint inversions of the entire dataset using these source-model parameterizations, and the resulting slip distributions are plotted in Figure S1 (available in the electronic supplement to this article). The differences in slip pattern between these models are relatively subtle, but slip becomes more concentrated in the up-dip portion of the fault plane as increasingly realistic representations...
of the varying dip of the megathrust are adopted. We use the variable dip model from Figure 1 in all subsequent models.

We also tested the influence of varying the STF duration of each subfault, as this controls the rupture window annulus, in combination with the rupture velocity. For this test, we considered three cases using 5, 10, or 15 symmetric triangles each with 5-s rise time and 5-s relative shifts to parameterize each subfault STF. This allows total subfault STF durations of 30, 55, and 80 s, respectively. The inverted slip distributions and subfault STFs are shown in Figure S2 (see supplement). When the parameterized source time is sufficiently long, about 50 s or more, the inversions prove very stable and the main slip domain is spatially compact, as indicated by many studies. We adopt a 55-s-total subfault source-duration parameterization in our final models, based on these results and similar investigations of individual datasets. The data inversions often use only portions of the allowed subfault duration.

We now move on to actual data inversions for which the results can be appraised in the context of these inversion tests. We first consider the overall slip distributions and then address the time evolution of slip in the preferred models.

GTS Inversion Slip Pattern

Separate inversions of hr-GPS, teleseismic P-waves, and \( R_1 \) STF datasets, and joint-inversion results with hr-GPS, teleseismic P wave, \( R_1 \) STFs, and OBGPS datasets for constant rake models (\( \lambda = 90^\circ \)) are shown in Figure 4. The rupture velocity is 1.5 km/s out to 100 km from the hypocenter and then 2.5 km/s beyond that, the subfault-rupture durations are 55 s, and the preferred model geometry and smoothing parameters noted above are used in all cases.

In the hr-GPS inversion, two slip patches are resolved, one large slip patch near the trench with maximum slip of \( \sim 60 \) m, spread \( \sim 200 \) km along the strike direction; the other slip patch with slip greater than 10 m extending from near the hypocenter about 200 km laterally along strike. The hr-GPS data also indicate a down-dip region of slip of less than 10 m extending to the south a further 150 km. The timing and waveshape of the time-varying portions of the hr-GPS signals and the static offsets are very well-matched by this model as in Figure S3a,b,c (see supplement). The solution is basically similar to that found by Yue and Lay (2011), although the two-patch character is more pronounced in the solution here.
Teleseismic P-wave data inversion gives a more concentrated up-dip slip pattern with maximum slip of greater than 60 m located near the trench and a region of large slip extending bilaterally along strike over ∼250 km. Down-dip slip is less than 20 m below the hypocenter. This model has close similarities with other teleseismic inversions (e.g., Hayes, 2011; Ide et al., 2011; Lay, Ammon, Kanamori, Xue, et al., 2011; Lee, 2011; Lee et al., 2011; Shao et al., 2011; seismic inversions in Simons et al., 2011; Yoshida, Miyakoshi, and Irikura, 2011; Yoshida, Ueno, et al., 2011; Wei et al., 2012), but it is important to recognize that the absolute values of slip here are obtained by use of PREM rigidity structure compared with, for example, the slip distribution of Lay, Ammon, Kanamori, Xue, et al. (2011), which used lower rigidities at shallow depth and inferred larger peak slip. The waveforms are very well matched by this solution as in Figure S3d (see supplement). The down-dip low-slip region extending to the south indicated by the hr-GPS inversion is not spatially resolved by the P-wave dataset; weak slip is distributed over the full width of the fault model toward the south. There is substantial variability in finite-fault models in the southern part of the megathrust among the published body-wave inversions, some of which may be attributed to contamination from PP phases that we have suppressed explicitly.

Separate inversion of the bin-averaged $R_1$ STFs yields an intermediate rupture pattern with a single concentrated slip patch up-dip similar to the up-dip region of the hr-GPS inversion, with maximum slip of ∼60 m and ∼200-km extent along the strike direction. The distribution of slip along dip is similar to the P-wave inversion, with about 20 m of displacement near the hypocenter, and less than 10 m further down-dip. The STFs indicate weak down-dip slip extending to the...
similar to the hr-GPS inversion. The basic waveshape variations of the observed $R_1$ STFs are very well predicted by this model as in Figure S3e (see supplement).

Our joint inversion of all of these datasets (Fig. 4), supplemented by the OBGPS static offsets, preserves the common features of the separate inversions, indicating a maximum slip near the trench of $\sim 50$ m with large slip distributed along strike for 150 km, a broad region of 10–30-m slip near the hypocenter and a down-dip lower slip patch extending to the south an additional 150 km. The joint inversion suppresses the two-patch nature of the hr-GPS inversion alone, indicating a more gradual decrease in slip down-dip from the trench consistent with the $P$-wave and $R_1$ STF inversion, but more slip near the hypocenter consistent with the hr-GPS inversion. The joint solution is close to our previous inversion of hr-GPS data alone (Yue and Lay, 2011) which appears to reflect the reduced degree of smoothing applied in the current inversion with a larger dataset and use of a constant rake.

Figure 5 indicates a selection of waveform fits for the joint inversion, illustrating the variable nature of the different datasets and representative fits to the data. All waveform and static motion comparisons for the joint inversion are shown in Figure S4a–f (see supplement).

Figure 5. Comparison of a subset of observed (black lines) and predicted (gray lines) waveforms for the preferred constant-rake joint inversion model in Figure 4 using hr-GPS, teleseismic $P$ waves, $R_1$ STFs, and OBGPS data. For the three-component hr-GPS data, station azimuths, $\phi$, and epicentral distances, $\Delta$, are labeled. For teleseismic $P$ waves, station name, epicentral distance and azimuth are labeled. For azimuthal bin stacked $R_1$-STFs the bin azimuths are labeled. The time windows used were 500 s (hr-GPS), 200 s ($P$ waves), and 400 s ($R_1$ STFs). All waveforms are shown in Figure S4a–f (see supplement).
supplement), indicate the viability of the joint model as an overall representation of the faulting process.

Relative to other published finite-fault models for the Tohoku event, our model is very consistent with the inversions of seismic observations which tend to resolve a single large slip region near the trench (e.g., Hayes, 2011; Ide et al., 2011; Lay, Ammon, Kanamori, Xue, et al., 2011; Lee, 2011; Lee et al., 2011; Shao et al., 2011; Yoshida, Miyakoshi, and Irikura, 2011; Yoshida, Ueno, et al., 2011) with maximum slip of ~60 m. This shallow slip is consistent with the large horizontal seafloor offsets observed near the toe of the upper wedge. The broad region of 20–30-m slip near the hypocenter is generally consistent with the slip solutions based on geodetic inversions (Iinuma et al., 2011; Miyazaki et al., 2011; Simons et al., 2011), even though such models do not resolve the large shallow slip region further offshore. By including the OBGPS static motions in our inversions, we find models that are similar to geodetic static inversions that include the offshore data, which also indicate large slip near the trench (Ito, Ozawa, et al., 2011; Wei et al., 2012). Comparisons of inversion results for various datasets with and without the OBGPS observations are shown in Figure S5 (see supplement). The most dramatic difference is for the hr-GPS data inversion, for which the inclusion of the offshore data increases the region of large up-dip slip and suppresses the two-patch slip separation. This is also evident in the joint inversion. We infer that the large up-dip slip is a consistent requirement of the teleseismic body-wave, surface-wave, and complete geodetic datasets. We have not attempted to simultaneously invert the regional tsunami-waveform datasets due to the nonlinearity of the time-varying seafloor up-lift tsunami-excitation problem, but all quantitative modeling efforts that account for absolute tsunami travel times are consistent with having a 150-km-long region of 50–60-m slip concentrated within 50 km of the trench, as in our joint model.

In our joint inversion, the down-dip low-slip region extends further along-strike than the up-dip slip patch, which is not consistently found in previous teleseismic inversion results, and is constrained here by the combined hr-GPS and $R_1$ STF data. The southern extension of rupture is widely observed in high-frequency backprojection results and is also resolved by near-field strong motion inversions (e.g., Kurahashi and Irikura, 2011; Yoshida, Miyakoshi, and Irikura, 2011). A similar down-dip southern extension of low slip was resolved by previous joint inversion studies (Ammon et al., 2011; Koketsu et al., 2011; Yokota et al., 2011). However recent joint inversions by Wei et al. (2012), using static GPS and OBGPS observations together with near-field strong ground motion observations, locate the southern slip up-dip closer to the trench. The tsunami observations along Fukushima favor early arrivals that support a down-dip location of the slip in the southern region (e.g., Yamazaki et al., 2011).

Joint inversions of different datasets always raise issues of weighting and quantitative comparison of models. The model fit can be expressed by the normalized power of waveform-misfit residual, but this is a relative measure, which may not capture the degree of fit between different data types. The normalized power of the waveform-misfit residuals of the separate inversions of hr-GPS, teleseismic $P$ waves, and $R_1$ STFs are 0.6%, 6%, and 2%, respectively, whereas the waveform-misfit residual power of the joint inversion for hr-GPS, teleseismic $P$ waves, $R_1$ STFs, and OBGPS data are 2%, 11%, 11%, and 2%, respectively. These numbers are best appreciated by comparing the waveform predictions in each case as in Figures S3a–e and S4a–f (see supplement). The joint-inversion residuals are increased, as expected, with the relative increases reflecting the weighting assigned to each data type (we put lower weight on the $R_1$ STFs in the joint inversion due to larger uncertainty associated with the EGF process described above). Many different weights were explored, and the final model represents a choice based on our sense of distributing the misfit in proportion to our confidence in the approximate Green’s functions used for each data type, and our experiments on sensitivity to model parameterization. Aspects of these criteria are discussed further below.

**GT Inversion Slip Pattern**

Our preferred model has a constant rake for all sub-events, which is a significant simplification of the model. We evaluate this by allowing the rake to vary, which requires exclusion of the $R_1$ STF data. The overall slip distributions for separate and joint (GT) inversions for rake-varying models as in Figure S6 (see supplement) are generally similar to the slip pattern of the fixed-rake inversions. In the hr-GPS separate inversion and GT joint inversion, the maximum slip amount is smaller than for the corresponding fixed-rake inversions. This is attributed to the effective regularization factor. The summed power of Green’s functions differs between fixed-rake and variable-rake inversions, so even though we applied the same regularization factor to the data, the effective regularization applied to the Green’s functions scaled by the weights for each parameter differs. The subtle effect of different regularization can then either extend the rupture area with a low slip amount, or focus slip into spatially concentrated large-slip regions. But the regularization does not change the power of the Green’s function matrix, so the average slip or summed seismic moment is stable. The seismic moment for the varying-rake GT joint inversion is $4.6 \times 10^{22}$ N·m, compared with a seismic moment for the fixed-rake GTS joint inversion of $4.2 \times 10^{22}$ N·m. Although we allowed rake variation in the separate teleseismic $P$-wave inversion, the rake varied little from 90°, and it averaged around that value for the separate hr-GPS inversion. In the separate hr-GPS inversion the slip vectors at shallow depth fan away from the hypocenter, which was also found by Yue and Lay (2011), but this feature is not required to fit the data (constant rake inversions fit the data very well as noted above). While totally uniform rake cannot be demonstrated to be required, we find no basis for preferring
inversions with variable rake for the Tohoku event for our joint inversions.

Source Time Functions

The source time functions for each subfault differ systematically between up-dip and down-dip regions for these inversions, particularly for the hr-GPS inversions as in (Figs. 4 and S6, see supplement) and the $R_1$ STF inversion (Fig. 4). The shallowest two rows of subfaults tend to be dominated by a single source function pulse with a lower amplitude secondary pulse spread over about 40 s, whereas near the hypocenter (third to fifth rows of nodes along dip) most subfaults show more balanced double source function pulses, for both individual and joint inversions as in (Figs. 4 and S6, see supplement). Similar STF complexity was resolved by the teleseismic data inversions of Ide et al. (2011) and Lee et al. (2011), who interpreted this as a two-stage rupture, with the second stage of down-dip slip being driven by the very large slip up-dip. This is plausible for our model, given the maximum up-dip slip of $\sim 50$ m, but resolving slip front behavior in detail is limited by the smoothing in the inversions.

The down-dip subfaults (sixth to eighth rows of nodes along dip) have STFs that exhibit multiple pulses with shorter durations (10–20 s) that are more variable between individual and joint inversions. These complex time-function pulses could be interpreted as either several spatially limited asperities rupturing at slightly different times, or several re-rupturing patches in the down-dip region driven by surrounding quasistatic slip. The kinematic model is too limited to resolve this issue, but we prefer the first notion, as it is consistent with interpretations that have been advanced to explain the migrating concentration of sources of coherent short-period radiation from the deeper part of the megathrust detected by backprojection of short-period signals (e.g., Ishii, 2011; Koper, Hutko, and Lay, 2011; Koper, Hutko, Lay, et al. 2011; Meng et al., 2011; Wang and Mori, 2011; Yao et al., 2011, 2012; Zhang et al., 2011, Lay et al., 2012). Our finite-fault models do not resolve fine-scale structures, but are consistent with features comparable to the down-dip ruptures in the 1978 and 2005 Miyagi-Oki earthquakes, with $M_w \sim 7.2$–7.4. This is clearly on a spatial scale smaller than the larger uniform-slip regions at shallower depths.

For hr-GPS inversions, the STF centroid time contours are somewhat more widespread up-dip and more spatially concentrated down-dip. This is not apparent in teleseismic P-wave inversions and is suppressed in the joint inversions (Fig. 4). Widely spread contours indicate that the rupture has slip occurring during the same time interval over a large area. If this is the case, it is plausible that short-period radiation emanates from a corresponding large rupture front, and will not be imaged by the backprojection methods, which seek point-wise coherent alignment of intervals of short-period signal. This may explain why the up-dip large slip region lacks coherent short-period radiation. Waveform Fitting and Relative Weighting between Datasets

Joint inversions always present challenges for relative weighting of different datasets. Some inversions use proportionate weighting after normalizing the data (e.g., Koketsu et al. 2011), but this may fail to account for relative modeling error for each dataset. For our joint inversions, we preferred to give more weight to datasets with less expected modeling error. The error of hr-GPS Green’s functions comes primarily from the 1D reference-model inaccuracy, which is reduced by using a low-pass filter that suppresses periods shorter than 25 s. Although the estimated data error of vertical displacements ($\sim 0.04$ m) is larger than for horizontal displacements ($\sim 0.02$ m), these values are still on the same scale, so our three-component hr-GPS waveforms are equally weighted. Teleseismic P waves have higher frequency content, which improves resolution of the source radiation details, but reference-model inaccuracy increases for shorter period signals as well. The $R_1$ STF dataset has errors stemming from the EGF deconvolution technique being applied to a rupture with a large span of source depths and possible dip and rake variations.

GPS/acoustic (OBGPS) static deformations indicate significant slip below the epicenter and provide important constraints on the shallow slip, as we have demonstrated. The estimated coseismic slip of these stations was obtained from 28 March to 5 April, which is 17–25 days after the earthquake, thus the displacements may be contaminated by after-slip, aftershocks, or ocean-bottom landslides. Only five stations are available for these ocean-bottom static displacements, compared with much larger numbers of observations for hr-GPS, P-wave, and STFs data. The scale of the OBGPS displacements is extremely large after being normalized by the number of samples. Thus, if we apply the same weight to the OBGPS dataset as to the hr-GPS data, the inversion will primarily fit the OBGPS data. So we applied a much lower weighting to the OBGPS dataset. In our GTS joint inversions, the weights used for hr-GPS, teleseismic P waves, $R_1$ STFs, and OBGPS datasets are 1, 0.2, 0.2, and 0.1, respectively. We applied this relatively weighting to each dataset to achieve reasonably balanced data-misfit residuals ranging from several percent to around 10% as noted above. Our preferred weighting was obtained by performing dozens of tests to evaluate the waveform fits for each dataset, but there is typical subjectivity in deciding what weights are optimal. For our chosen weighting, the overall rupture area is mainly controlled by the low-frequency content of the hr-GPS and the $R_1$ STFs, whereas the short-wavelength details are mainly constrained by the teleseismic P-wave dataset and the OBGPS dataset. The weighting directly influences how well each dataset is matched. For our preferred weights, we fit the $P$ waves quite well in general without sacrificing the match to the waveform information of both the dynamic and static part of the hr-GPS data as in (Figs. 5, S3a–d, and S4a–d, see supplement).
The overall shape of the $R_1$ STFs is well fit, but not all of the waveform details are accounted for as in (Figs. 5, \textcircled{6} S3e, and S4e, see supplement), which reflects our caution about the dependence on the EGF procedure.

The preferred GTS joint inversion model is plotted in map view in Figure 6, along with observed and predicted horizontal static ground motions from the hr-GPS and OBGPS stations. The direction and magnitude of the static motions is well matched, as expected from the time-varying comparisons in Figure 5. The fits indicate that the assumption of uniform rake is generally acceptable for this model representation, but marginal gains could be had by allowing rake variations of up to 5°. The large near-trench slip is located where there is a seaward bulge in the upper wedge, and this is the area where large seafloor motions have been inferred from bathymetry offsets.

**Discussion and Conclusions**

Using joint least-squares inversions of hr-GPS data, teleseismic $P$-wave data, $R_1$ STF data, and OBGPS data, we obtained slip models for the 2011 Tohoku event consistent with the time-varying and static datasets. The joint inversions tend to compensate for limitations of each dataset, yielding good combined resolution of slip on the fault plane and models that fit the collective datasets to reasonable levels.

The Tohoku event has large-scale regions of large slip (~50 m) up-dip near the trench, 20–30 m of slip near the hypocenter, and a region of minor slip (<10 m) down-dip on the southern part of the megathrust. Variations in rake on the fault appear to be small, and our preferred model assumes uniform rake of 90°. Subfault STFs in the up-dip region show a dominant early pulse with a weaker secondary shoulder and a spatially widespread centroid time contour, suggestive of slip occurring over a large area simultaneously. The central portion of the megathrust has two distinct moment rate pulses, each with about 25-s duration. This may represent repeated slip of the subfaults driven by very large slip up-dip, or some other rupture irregularity. STFs for the down-dip subfaults have multiple shorter duration pulses, possibly related to the region having medium- to small-scale fault heterogeneities that generate spatially coherent short-period seismic wave radiation when patches fail in either isolated moderate-size events or as part of a great rupture such as the 2011 event.

Our joint inversion model supports the suite of finite-fault inversions that place the primary slip in the Tohoku event in a 200 km $\times$ 200 km region with a factor of 2 to 3 larger slip within 75 km of the trench. This region of large slip is the primary source of seafloor motions that generated the large tsunami pulse recorded in regional tsunami sensors, and is distinctive in having ruptured with very little coherent high-frequency seismic radiation. With the rupture velocity being low in this region, 1.5 km/s or less, the shallow portion of the rupture has the characteristics of a tsunami earthquake, as has been argued by many investigators. Finite-fault models that place primary slip deeper on the megathrust must demonstrate that they can match the observed tsunami arrival times; our model does so because it is very similar to direct inversions of tsunami waveforms and forward modeling of similar seismic models. We have confirmed this with forward modeling calculations performed by Yoshiki Yamazaki. The up-dip portion of the megathrust offshore of Fukushima (south of the main slip patch) appears to have had very little slip, and is a concern for future large earthquakes, potentially as a tsunami earthquake similar to the 1896 Sanriku event to the north; however, it is not clear that there is a large slip deficit in this region and offshore geodetic measurements are needed to address the deformation state in this region. There appears to be significant postseismic slip in the up-dip region to the south, offshore of Chiba (Ozawa et al., 2011), just as there is to the north on the down-dip part of the megathrust (Ye et al., 2012). The coseismic slip zone for our final model does have modest down-dip slip off of Fukushima, in the region of the 1938 under thrusting events (Abe, 1977) and just north of the largest 2011 aftershock with $M_w$ 7.9. Whereas uncertainty in the seismic hazard of adjacent portions of the subduction zone persists, the superb seismic and geodetic datasets for 2011 Tohoku are largely accounted for by the relatively simple overall rupture model from our joint inversion.
Data and Resources

The hr-GPS data used in this paper were obtained by GEONET, provided by the Geospatial Information Authority of Japan (GSI), which is openly available from (http://www.rtgps.com/rtnet_pppar_honshu_eq.php; last accessed September 2012). The teleseismic P-wave data, the short-arc Rayleigh-wave data of the main event, and EGF used for $R_I$ STFs calculations, were obtained from the Federation of Digital Seismic Networks (FDSN), accessed through the Incorporated Research Institutions for Seismology (IRIS) Data Management System (DMS), which are openly available (http://www.iris.edu/dms/; last accessed September 2012). Some plots used General Mapping Tools (GMT; http://gmt.soest.hawaii.edu/; last accessed September 2012); and the seismogram processing used Seismic Analysis Code (SAC; http://www.iris.edu/software/sac/; last accessed September 2012), both of which are openly available software.

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References


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