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Source Model of the 2002 Miyagi-Oki Interplate Earthquake (Mw = 6.4) Obtained by Strong Ground Motion Simulation Using Empirical Green's Function Method

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Introduction

Previous studies show that broadband strong motion records can be successfully simulated using aftershock records as empirical Green's function assuming rectangular source model with uniform slip (e.g. Kamae and Irikura, 1998; Miyake et al., 1999, 2003; Asano et al., 2003). This area, which we call strong motion generation area (SMGA), is smaller than total slip area estimated from aftershock distribution. For crustal earthquakes, Miyake et al. (2003) showed the SMGA corresponded to the asperity deduced by kinematic waveform inversion, and that its size could be expected from scaling relation between the size of the asperity and the seismic moment proposed by Somerville et al. (1999). Asano et al. (2003) analyzed shallow intraslab earthquakes in the similar manner and observed that the size of SMGA was smaller than that expected for crustal earthquake with the same seismic moment. They also observed that the ratio of the derived size and the expected one decreased with focal depth. According to their conclusions, this showed the possibility that the stress drop on the asperity depended on the focal depth. The stress drop on the asperity is one of important parameters to characterize source model for strong ground motion prediction.

Because of its location on convergent plate boundary, many interplate earthquakes have hit Japan and sometimes caused heavy damage. Thus, many studies on source process have been carried out, however, most of them have used long period, or teleseismic waves. Because strong motion whose period is around 1 s causes damage to low- and middle-rise buildings, a source model which is considered to be valid up to shorter period would be needed for strong motion prediction. In November 3, 2002, an Mw = 6.4 earthquake (focal depth was about 45 km) occurred in Miyagi-Oki region, northeast of Japan. This event was thought to be interplate earthquake according to the moment tensor solution and aftershock distribution. To examine source characteristics of interplate earthquakes, we simulate strong motion record up to 10 Hz and determine the size and the rise time of the SMGA.

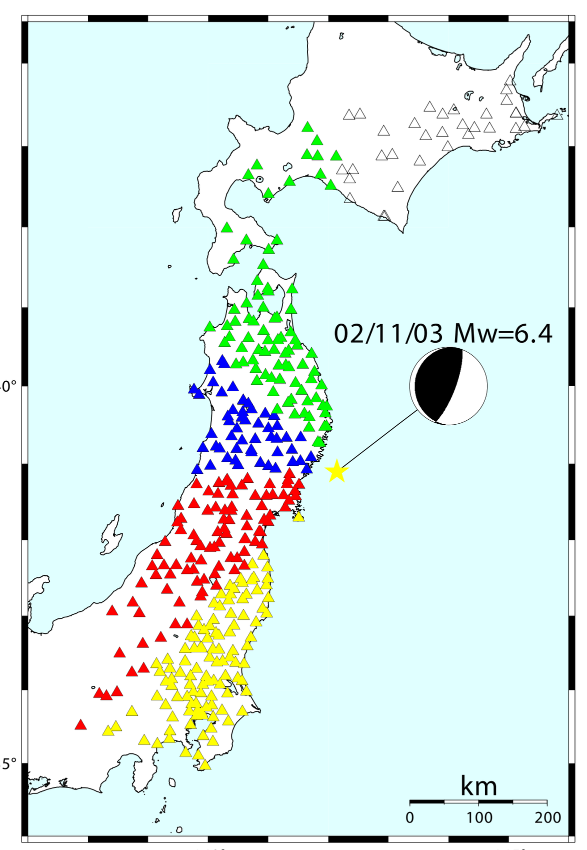


Figure 1

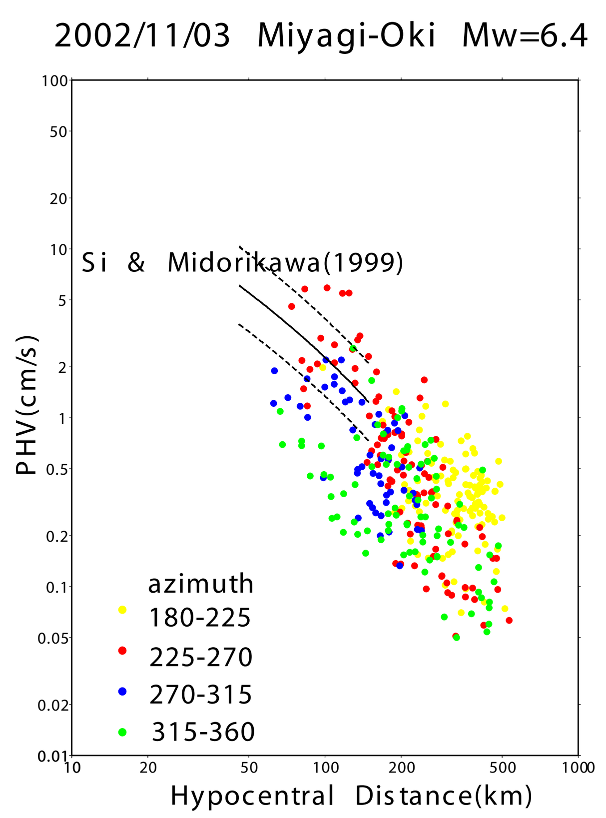
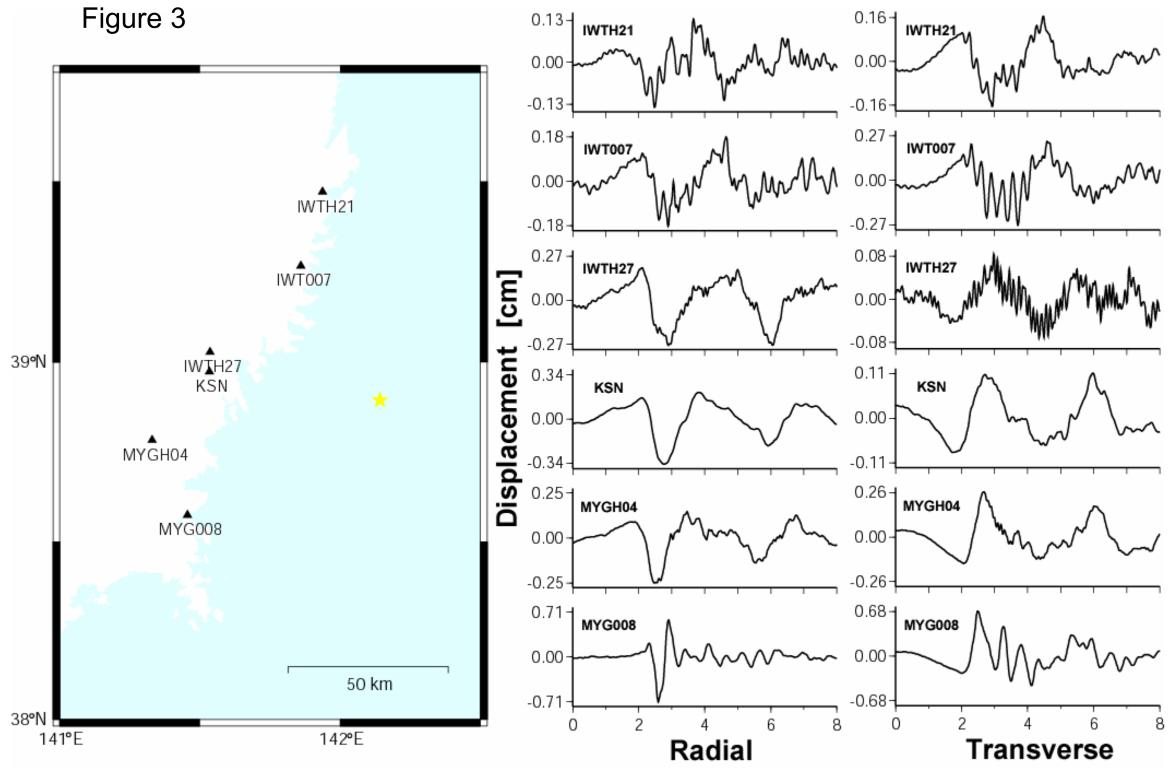


Figure 2

Figure 1 shows the epicentral location of 2002 Miyagi-Oki earthquake and triggered strong motion stations (K-NET and KiK-net). Moment tensor solution is determined by F-net. Stations are colored according to their azimuth from the epicenter. Figure 2 shows azimuthal dependence of peak horizontal velocity (PHV) together with the attenuation relation by Si and Midorikawa (1999). PHVs of southern stations tends to be larger than those of northern stations. In displacement waveform of southern station, we can see a short period pulse in Figure 3. These observations seem to indicate that rupture propagated from the north to the south.

Figure 3



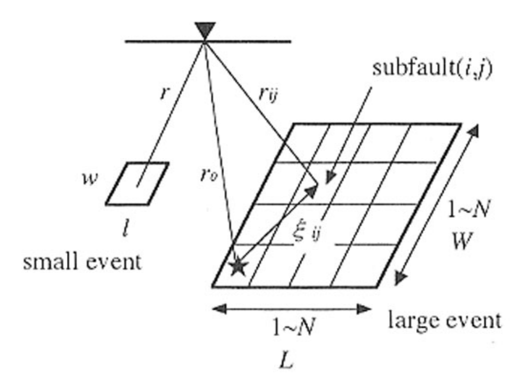
Empirical Green's Function Method

Seismic motion whose sources are close to each other can be thought to be affected by the same propagation effect and site response. So using a small event record as Green's function, we can simulate ground motion up to high frequency where ground motion is much affected by detailed underground structure. Based on the scaling law of parameter (Kanamori and Anderson, 1975) and omega-squared model (Aki,1967), Irikura (1986) formulated synthesized record of large earthquake $U(t)$ summing up small event record $u(t)$

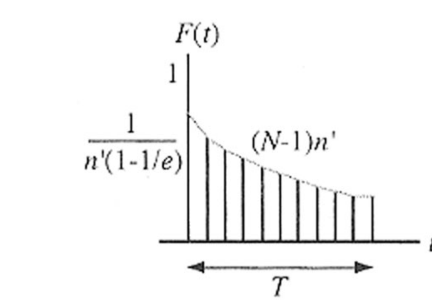
$$U(t)=\sum_{i=1}^{N}\sum_{j=1}^{N}(r/r_{ij})\cdot F(t)*(C\cdot u(t))$$

$$F(t)=\delta(t-t_{ij})+\frac{1}{n'(1-e^{-1})}\sum_{k=1}^{(N-1)n'}\left[\exp\left\{-\frac{k-1}{(N-1)n'}\right\}\cdot\delta\left\{t-t_{ij}-\frac{(k-1)T}{(N-1)n'}\right\}\right]$$

$$t_{ij}=(r_{ij}-r_0)/V_s+\xi_{ij}/V_r$$



After Miyake et al. (1999)

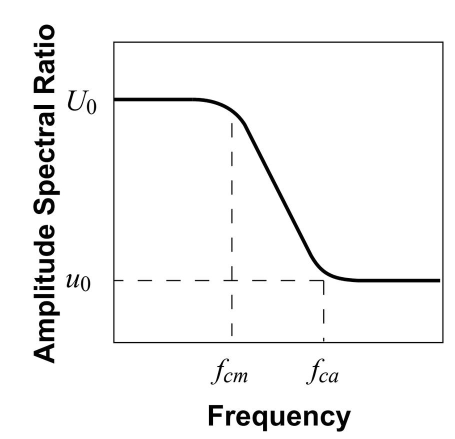


$F(t)$ is a correction function to adjust the difference in slip velocity function between large and small events. T is the rise time of large event. n' is an appropriate integer to weaken artificial periodicity.

SMGA of large earthquake is divided into $N \times N$ subfaults, which have the same dimension as small event. Stress drop of large and small event could be different by the ratio, C. N and C are determined from the spectral ratio of two events.

$$M_0 / m_0 = U_0 / u_0 = CN^3 \qquad (1)$$
$$A_0 / a_0 = CN \qquad (2)$$

M_0 and m_0 is seismic moment, U_0 and u_0 is flat level of displacement spectra, A_0 and a_0 is the flat level of acceleration spectra. Capital letter denotes large earthquake. Ideally, spectral ratio will be shaped like left figure. f_{cm} and f_{ca} is corner frequency of large and small event, respectively.



Application to 2002 Miyagi-Oki earthquake

Our target is to estimate the 4 parameters of the SMGA:
- length (assumed to be along the fault strike)
- width (assumed to be along the fault dip)
- rise time
- rupture starting subfault (with assuming radial propagation)

For the frequency band of 0.25 to 10.0 Hz, we obtained the SMGA using 4 stations (red triangles in Figure 5).

We use an Mw = 4.7 aftershock that occurred on the next day with a similar focal mechanism as a small event.
We have assumed following parameters.
- fault plane (strike = 184° dip = 15° rake = 74° , from F-net)
- S wave velocity = 3.9 km/s
- rupture velocity = 3.6 km/s

For equation (1), we used moment ratio determined by F-net
$CN^3 = 300$,
and for (2), from Figure 4
$CN = 13$,
then we determine the parameter
- $N = 5$
- $C = 2.5$

We search length and width to 10 km, rise time to 2.5 seconds by comparing observed and sythetic waveform refering following residual function.

$$res=\sum_{station}\sum_{component}\left[\frac{\sum_t(u_{obs}-u_{syn})^2}{\sqrt{\sum_t u_{obs}^2\sum_t u_{syn}^2}}+\frac{\sum_t(e_{obs}-e_{syn})^2}{\sqrt{\sum_t e_{obs}^2\sum_t e_{syn}^2}}\right]$$

u : displacement waveform
e : acceleration envelope

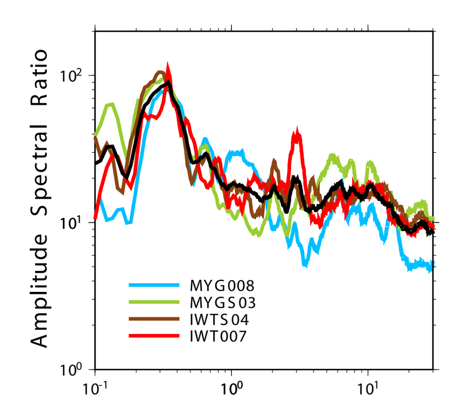
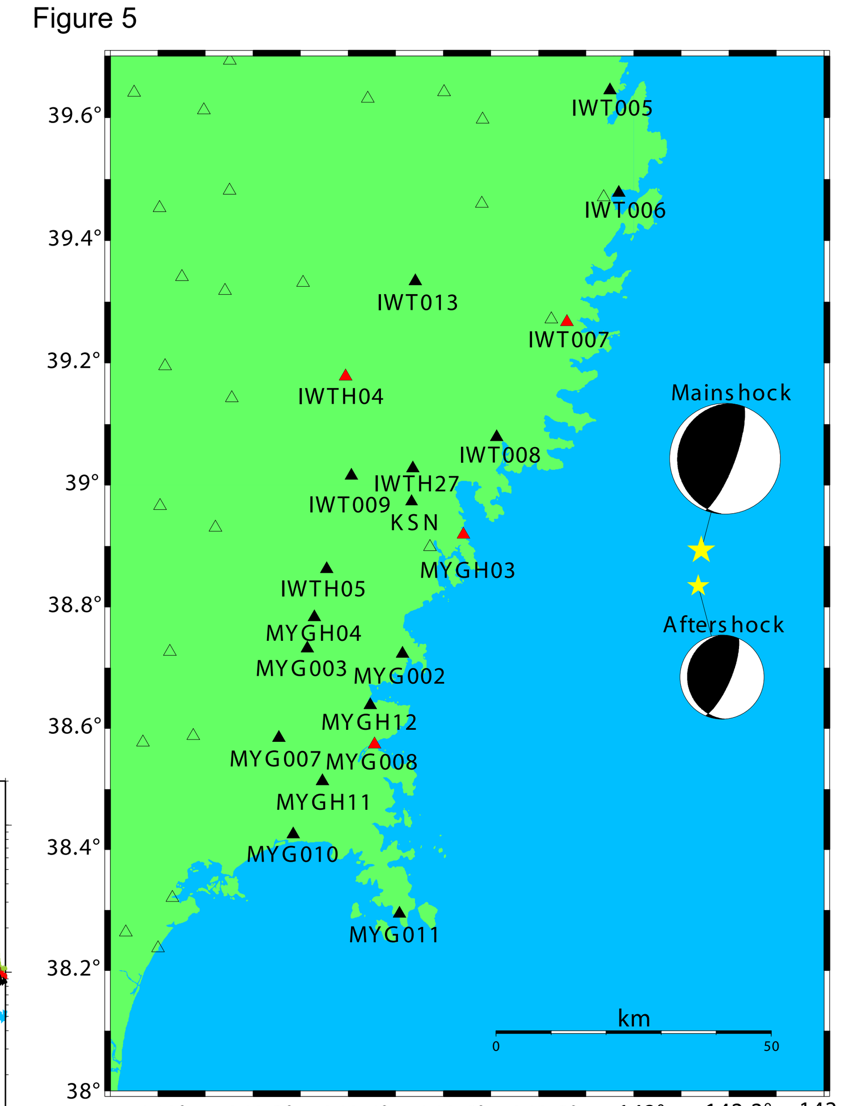


Figure 4

Figure 5



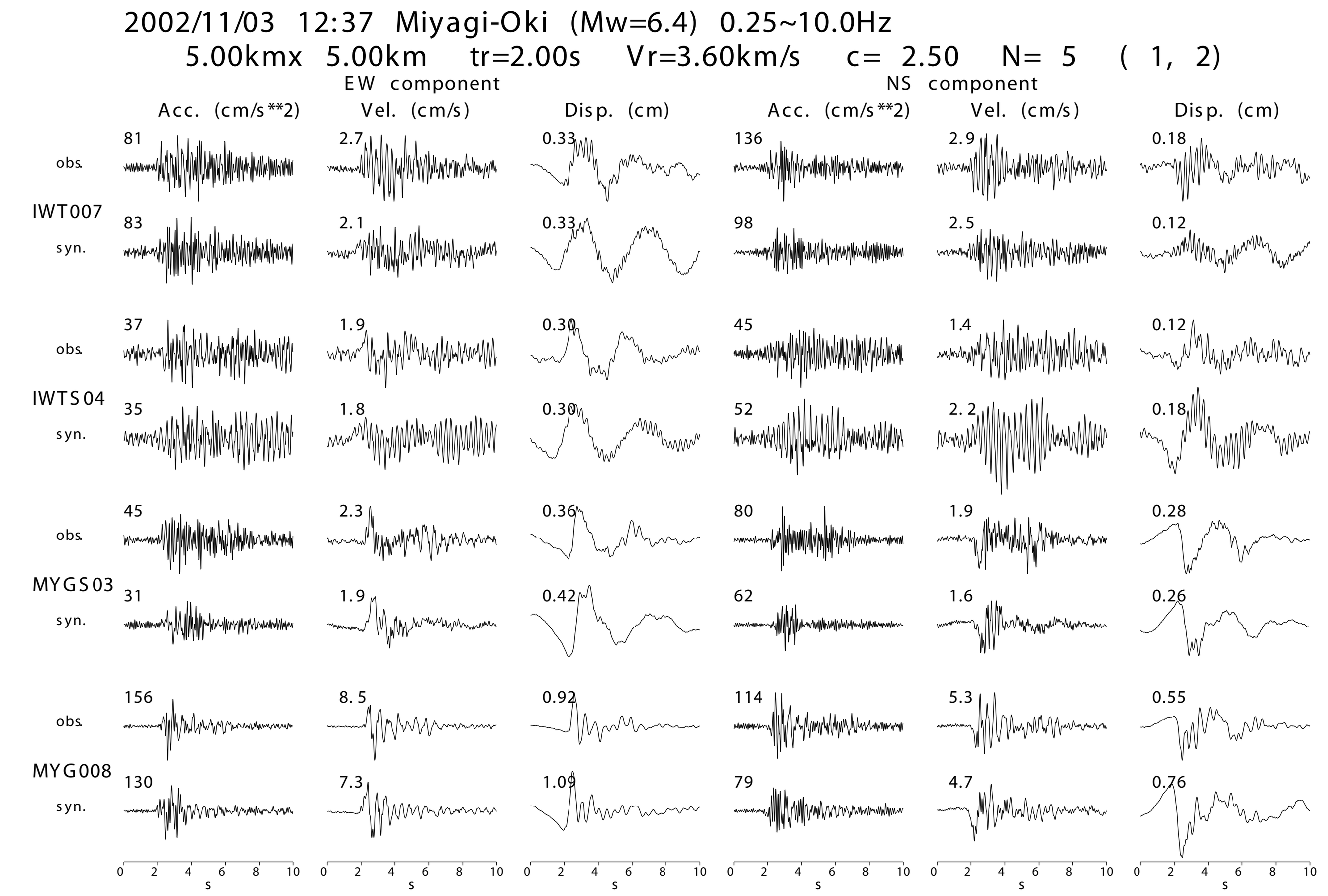


Figure 6

We use 4 station which are plotted in Figure 5 as red triangle to derive the source model. This shows comparison of observed record and waveform simulated with derived model for these 4 stations.

Results

Our result shows that the SMGA is a square of length 5 km, rise time is 2.0 seconds and that the rupture starting point is located on the second shallowest subfault on the northern end. Figure 6 shows waveform fitting for 4 reference stations. To examine the validity of this model, we check the waveform fitting at other stations using that model (shown in Figure 7). Also we check the variance of residual value when we change the size of the SMGA (shown in Figure 8). Although precision of width estimation is not high because of the distribution of stations, our model seems to be reasonable.

Our model indicates that the rupture propagated as expected from the azimuthal dependency of waveforms and PHV previously shown in Figures 2 and 3.

A 2.0 seconds rise time is longer than results of previous studies on crustal and intraslab earthquakes of the same size. It may indicate that the slip velocity of interplate earthquakes is smaller, in other words, interplate earthquakes slip more slowly on the asperity than intraplate earthquakes.

The location of the SMGA seemed to correspond to the area where the moment release was large as deduced by Tohoku University (Figure 9). SMGA size we derived is about half of the asperity size that is expected from scaling relation for crustal earthquakes by Somerville et al. (1999). This indicates that the stress drop on the asperity of this event is higher than that of crustal earthquake as long as the SMGA is regarded as an asperity. This supports the possibility that stress drop on the asperity depends on the focal depth pointed out by Asano et al. (2003).

We consider the small event as a circular crack and calculate its stress drop. By multiplying the C value, we calculated the stress drop of the SMGA to be 80 MPa. In conducting a strong motion evaluation of a potential earthquake expected to occur to the south of the Miyagi-Oki event, it is needed to assume that the effective stress on the asperity is more than 70 MPa in order to reproduce the observed records. Therefore we should not neglect the possibility that the high stress drop could be a regional characteristic.

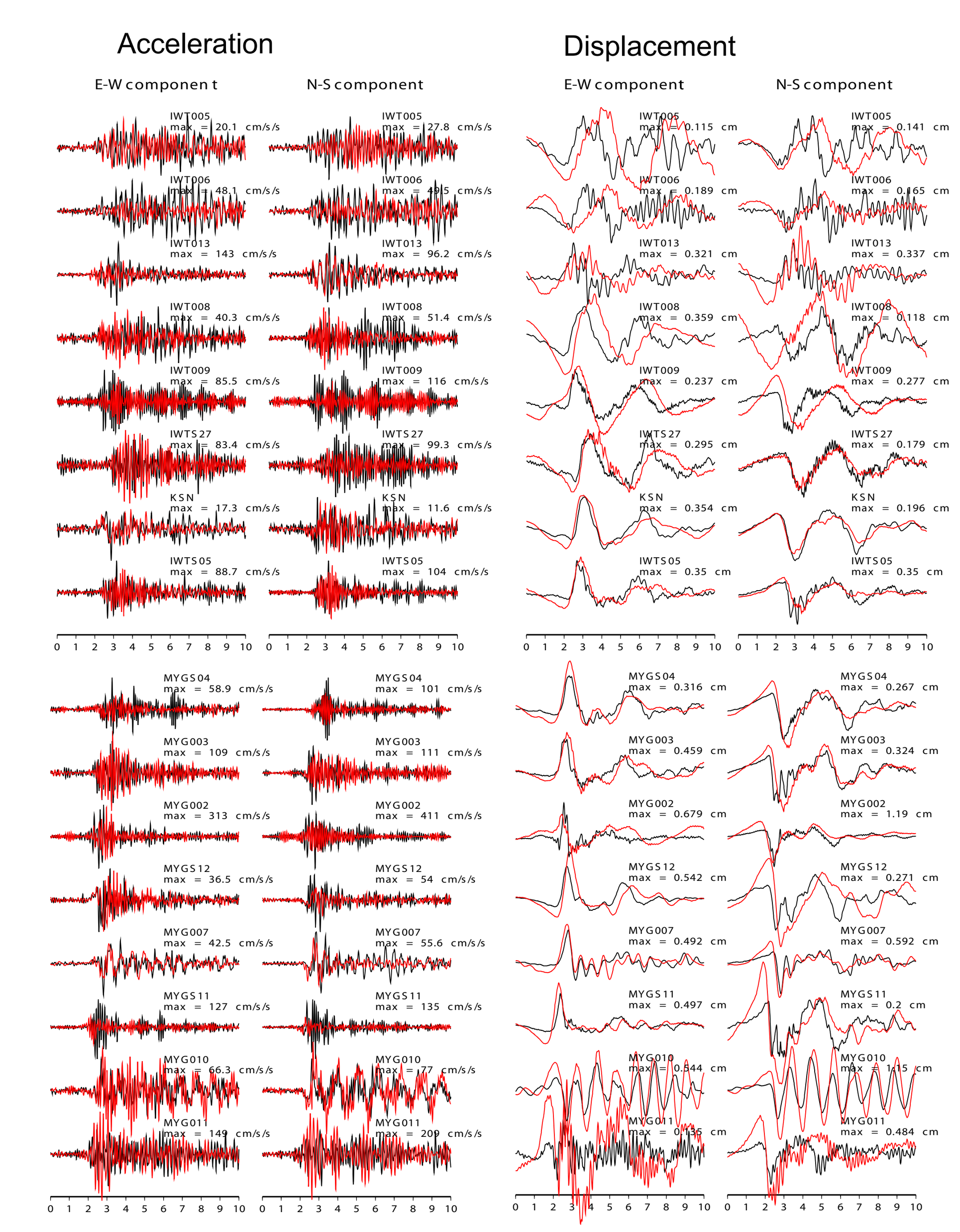


Figure 7

Comparison of observed (black line) and synthetic (red line) waveforms of black triangle stations in Figure 5. To check broadband waveform fitting, we draw both acceleration and displacement waveforms.

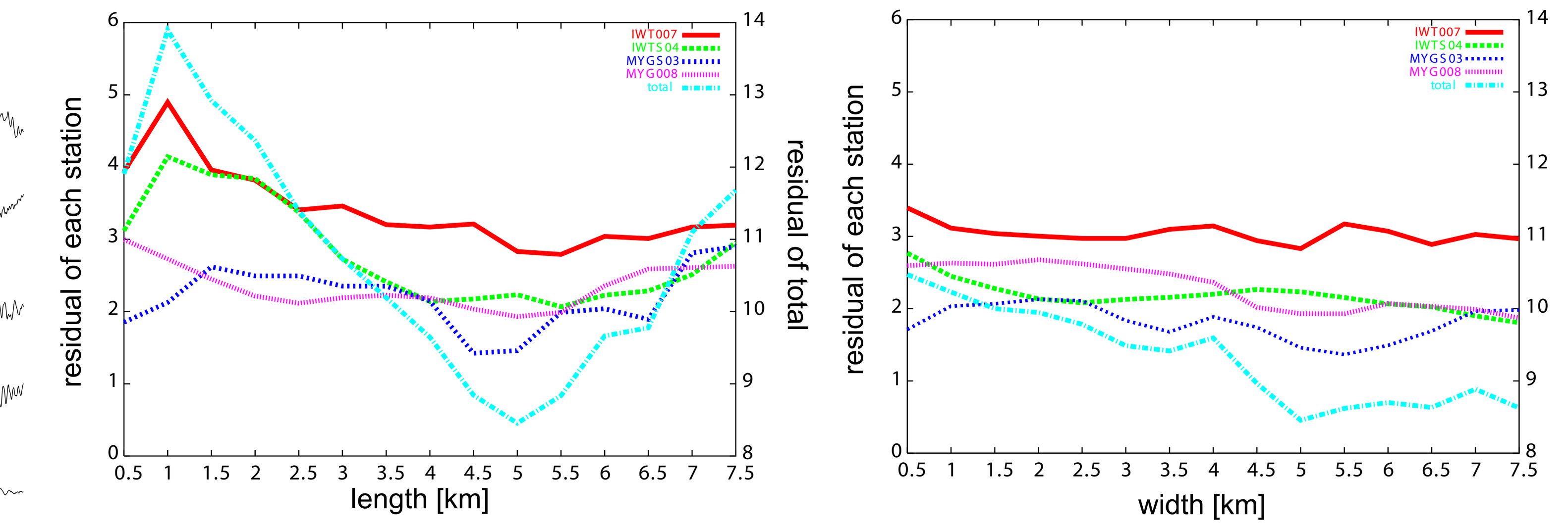


Figure 8

We calculate sum of residual value of acceleration envelope and displacement waveform for two horizontal component to see the variation of waveform fitting as the size changes. Rupture starting point and rise time are fixed to the value of derived model. Left figure shows how residual value changes when length varies (width is fixed to 5 km). Right figure is the case that width varies. In both figures, we can see that residual value take minimum around the size we choose (5 km ×5 km). Residual value of width is not as sensitive as that of length, because our choice of station is along the length.

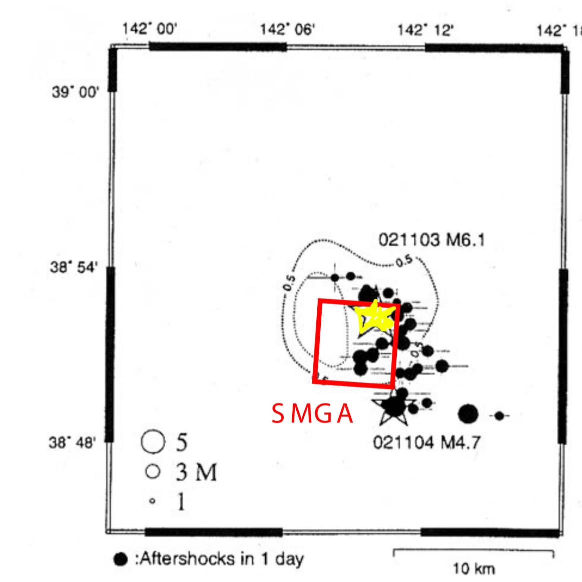


Figure 9

Comparison of our source model to slip distribution obtained by waveform inversion. Red square is SMGA we derived projected onto horizontal plane. Yellow star is the epicenter of mainshock The contour shows distribution of moment release deduced by Tohoku University (2002). Contour is normalized by the maximum value.

Conclusion

We derive the 5-km-square SMGA that ruptures with 2.0 seconds rise time from subfault of first along strike and sencond along dip for the source model of 2002 Miyagi-Oki earthquake. Stress drop on the SMGA is estimated to be 80 MPa which is much larger than that expected for crustal earthquake of the same magunitude. Rise time derived here is longer than that derived from crustal and intraslab earthquake of the size. It indicates the possibility that interplate earthquakes slip more slowly on the asperity than intraplate earthquakes. We need to analyse more events (e.g. 2003 Tokachi-Oki earthquake) in the similar manner to examine whether large stress drop on the asperity reflects dependency on the focal depth or is a regional characteristic, and also check if long rise time is general property of interplate earthquakes.

Acknowledgement

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