Envelop broadening characteristics of crustal earthquakes in northeastern Honshu, Japan

Jayant N. Tripathi, Haruo Sato and Mare Yamamoto

Department of Earth and Planetary Sciences, University of Allahabad, Allahabad 211002, India. E-mail: jntripa@yahoo.com
Department of Geophysics, Graduate School of Science, Tohoku University Aramaki-Aza-Aoba 6-3, Aoba-ku, Sendai-shi, Miyagi-ken 980-8578, Japan

Accepted 2010 May 11. Received 2010 May 10; in original form 2009 May 15

SUMMARY
In short period seismograms of microearthquakes, S-wave envelopes are found to broaden with hypocentral distance increasing. For crustal events, envelop broadening is caused not only by multiple scattering due to velocity inhomogeneities but also by the contribution of guided waves and head waves. Intrinsic absorption is also an important parameter to truncate the time duration. Microearthquakes of focal depth less than 40 km and magnitude range from 1.5 to 4.5, which took place in northeastern Honshu, Japan, are used for the study of envelope broadening. Digital data acquired by Hi-net are used for the analysis. We estimated the 90 per cent time duration ($T_{90}$) and the root mean square (rms) time duration ($T_{\text{rms}}$) from the rms traces of horizontal component seismograms for frequency bands 1–2, 2–4, 4–8, 8–16 and 16–32 Hz. The estimated time duration increases with hypocentral distance increasing in both sides of the volcanic front, which runs from south to north in the study area. At reference distance of 100 km, the time duration in the backarc side decreases with frequency; however, that in the forearc side has the minimum at 4 Hz. The time duration at a reference distance in the backarc side is shorter than that in the forearc side especially for frequencies higher than 4 Hz, which can be interpreted by strong intrinsic absorption in the backarc side.

Key words: Coda waves; Seismic attenuation; Wave scattering and diffraction; Wave propagation.

1 INTRODUCTION
Seismograms of local earthquakes well reflect the source rupture process and the propagation effect through the lithosphere. Those in low frequencies give fruitful information for the source process because the medium structure of a large scale is rather simple; however, those in high frequencies especially higher than 1 Hz are very complex caused by scattering due to the velocity inhomogeneities of a small scale. Scattering process not only destroys the phase information but also increases the apparent duration of S seismogram with travel distance increasing even if the source duration time is short. Those envelope-broadening phenomena are seen not only in continent (e.g. Atkinson 1993) but also in subduction zones (e.g. Goto et al. 1984; Kawashima et al. 1985; Sato 1989; Scherbaum & Sato 1991; Gusev & Abubakirov 1999a,b). There have been several studies to characterize the apparent duration of ground oscillation observed.

Sato (1989) and Gusev & Abubakirov (1999a,b) studied the envelope broadening of high-frequency seismograms of local earthquakes of which the focuses are deeper than the Moho on the basis of the multiple forward scattering and diffraction due to random velocity inhomogeneities in the lithosphere. Analysing peak delay times and duration times for S-wave envelopes of microearthquakes in Kanto-Tokai area, Japan, Obara & Sato (1995) found that the envelope broadening in the backarc side of the volcanic front is larger than that in the forearc side. They interpreted the origin of the regional difference that short-wavelength spectral components of random velocity inhomogeneity are significantly rich beneath the backarc side. Analysing precisely the ray path dependence of the peak delay of S-wave seismogram of intermediate depth microearthquakes in northeastern Honshu, Japan, Takahashi et al. (2006) found strong inhomogeneity especially beneath Quaternary volcanoes. Aforesaid studies analysed earthquakes with focuses deeper than the Moho to eliminate large amplitude $Sg$ with $Sn$ precursor and $Lg$ waves as multiply reflected $S$ waves through the crust.

The complexity of high-frequency seismograms of crustal events is not only caused by scattering due to random velocity heterogeneities but also multiple reflections through low-velocity layers in the crust. Even though physical modelling has some difficulty, it is necessary to establish phenomenological characterization for the observed envelope broadening of crustal events. There have been phenomenological studies on envelope broadening for crustal earthquakes. Atkinson (1993) studied the envelope broadening in continental United States, Raoof et al. (1999) studied envelope broadening with increasing travel distance for multiple high-frequency bands in southern California. Petukhin & Gusev (2003) studied those in Kamchatka, Russia.
The target of this paper is to study the envelope broadening characteristics of shallow focus earthquakes in northeastern Honshu, Japan. We briefly describe the seismotectonic condition of this region as follows. The Pacific Plate is descending beneath the Japan arc from east to west. There are many Quaternary volcanoes mostly running from north to south as illustrated by open triangles in Fig. 1. The boundary in the forearc side (east side) of those volcanoes, which is parallel to island arc is called the volcanic front (VF) and located about 112 km iso-depth contour of slab-surface in this area (Tatsumi 1986). An inclined low-velocity region, subparallel to the subducting slab in the mantle wedge beneath the backarc side (west side) reaches to the Moho beneath the volcanic front (e.g. Zhao et al. 1992; Nakajima et al. 2001). The variation of thickness and the strength of velocity anomaly in this inclined low-velocity region correlate well with the Quaternary volcano distribution along the Japan arc (Tamura et al. 2002). Spatial correlation among the VF, seismic velocity structure, hypocentres of low-frequency earthquakes and gravity anomaly has been carefully considered in the modelling of magma genesis and dynamics of slab subduction (e.g. Hasegawa & Nakajima 2004, for detailed review). According to the spectral inversion studies (Umino & Hasegawa, 1984; Tsumura et al. 2000), intrinsic absorption is stronger beneath the VF and the backarc side compared to the forearc region.

We analyse seismograms of earthquakes with shallow focal depths mostly in the land region of the northeastern Honshu, Japan. Splitting this area into the forearc side and the backarc side of the VF, we evaluate the hypocentral distance dependence of envelope-broadening parameters. Finally, we estimate average envelope-broadening parameters at a reference distance as the crustal medium characteristics, and compare with those reported in other regions in the world.

2 METHOD OF ANALYSIS

There are several definitions of parameters to characterize the envelope having a delayed peak and a decaying tail. In previous papers (Sato 1989; Obara & Sato 1995; Saito et al. 2002; Takahashi et al. 2006), the peak delay is used as the time lag from the S-wave onset to the maximum amplitude arrival and the duration as the lag time of the half-maximum from the S-wave onset. These measurements have a merit being independent of the time window length; however, there are large scatters. Instead, here we use more stable measurements for characterizing the envelope broadening as follows.

Signal duration ($T_{90}$), which has been often used in earthquake engineering, is computed as the time difference between 5 and 95 per cent of the final value of the integrated power (squared amplitude) of the bandpass-filtered velocity seismograms. This $T_{90}$ indicates the interval, which contains the 90 per cent of the total power (Trifunac & Brady 1975; Petukhin & Gusev 2003). Raoof et al. (1999) proposed the superiority of $T_{70}$, which is the time difference between 5 and 75 per cent of the final value of the integrated power.

Another measure is the root mean square (rms) duration ($T_{rms}$), which is defined as the normalized second central moment of squared amplitude (Gusev 1983; Petukhin & Gusev 2003):

$$T_{rms}^2 = e_2/e_0 - (e_1/e_0)^2,$$

where

$$e_j = \int_0^\infty t^j A(t)^2 \, dt \quad (j = 0, 1, 2)$$

is the $j$th moment over the lapse time $t$ measured from the S-wave onset. The ratio $e_1/e_0$ means the average peak delay, where the
squared amplitude is used for the probability distribution density. Then $T_{50}$ and $T_{\text{rms}}$ correspond to the 5–95 per cent interquantile range and the variance, respectively.

Earthquake signals can be often treated as the convolution of source- and path-related components by assuming point source and linearity of medium response for the entire frequency band. To support the convolution for the power of signal, one may additionally assume high-frequency band-filtered squared signals are random quasi-stationary signals with approximately random phases (Ishimaru 1978). Petukhin & Gusev (2003) concluded that for the high-frequency part of signals of stronger earthquakes also recorded at longer distances in heterogeneous structures (say, $f > 1$ Hz signal components of $M > 6$ events recorded at distance $R > 30$ km in an island arc), both the source and the path contributions have a stochastic, noise-like character. As the second central moment of convolution is the sum of the second central moments of components (in probabilistic terms, the variance of sum is the sum of variances of components), then it can be written as follows (Gusev 1983):

$$T_{\text{rms, total}}^2 = T_{\text{rms, source}}^2 + T_{\text{rms, path}}^2,$$

where $T_{\text{rms, source}}$ is the rms duration of squared high-frequency source wavelet for a ray to a given receiver, $T_{\text{rms, path}}$ is the rms duration of squared average Green's function of the path, $T_{\text{rms, total}}$ is the rms duration of the recorded signal. Thus, for small earthquakes,

![Figure 2](image_url)
$T_{\text{rms,path}}$ is approximated by the $T_{\text{rms,total}}$, empirically, because the source duration time is very short for small earthquakes.

We will see that each signal duration is proportional to some power of travel distance. The average value of the parameter $T_{\text{ref}}$ at a given reference distance $R_{\text{ref}} = 100$ km is estimated for $T_{\text{parameter}}$ by using the following equation:

$$T_{\text{parameter}} = T_{\text{ref}} (R / R_{\text{ref}})^b,$$  \hspace{1cm} (4)

where $T_{\text{parameter}}$ is taken as the 90 per cent duration-time $T_{90}$, the rms duration time $T_{\text{rms}}$, moment ratios $e_1/e_0$ and $e_2/e_0$. Exponent $b$ will be estimated from the least-square regression analysis of these parameters ($T_{90}$ [s], $T_{\text{rms}}$ [s], $e_1/e_0$ [s] and $e_2/e_0$ [s$^2$]) against hypocentral distance $R$ by using the following equation:

$$\log_{10} T_{\text{Parameter}} = a + b \log_{10} R.$$  \hspace{1cm} (5)

3 DATA AND MEASUREMENTS

Velocity seismogram data (E–W component) from crustal events (focal depth < 40 km) are analysed. Focal depths of the data set are complementary to those of Takahashi et al. (2006), which used intermediate depth earthquakes in northeastern Honshu, Japan. Those seismograms were recorded at 100 Hz sampling rate from June 2002 to December 2007 by Hi-net (High Sensitivity Seismograph Network, Japan) of the National Research Institute for Earth Science

---

Figure 2. (Continued.)

© 2010 The Authors, GJI, 182, 988–1000

Journal compilation © 2010 RAS
Figure 3. Plot of duration times ($T_{rms}$) against the length of time integral window $K$ scaled by the $P$–$S$ time for different distance ranges (20–40, 40–60, 60–80, 80–100, 100–120 and 120–140 km) at different frequency bands.
Envelope broadening of crustal earthquakes

and Disaster Prevention (NIED). We selected crustal events in land, as much as possible in the northeastern Honshu (Tohoku area), Japan (Fig. 1). The hypocentral locations of the unified result provided by Japan Meteorological Agency (JMA) are used in this analysis. The final data set consists of 1473 seismograms from 542 events after strict criteria for the quality, which contains 1098 seismograms from 414 events in the forearc side area (Fig. 1a) and 375 seismograms from 128 events from the backarc side area (Fig. 1b). Hypocentral

Figure 4. Logarithmic plot of estimated parameters against hypocentral distance and their least-square fit ($\log_{10} T_{\text{parameter}} = a + b \log_{10} R$) at frequency bands 1–2, 2–4, 4–8, 8–16 and 16–32 Hz for forearc and backarc: (a) $T_{90}$, (b) $T_{\text{rms}}$, (c) $e_1/e_0$ and (d) $e_2/e_0$.

© 2010 The Authors, GJI, 182, 988–1000
Journal compilation © 2010 RAS
distance varies from 5.7 to 155.2 km, however, the distance range is limited to be larger than 20 km. Epicentres and seismic stations used in this study are plotted in Fig. 1 by grey circles and black dots, respectively along with volcanoes by open triangles. The magnitude of the events ranges from 1.5 to 4.5, which ensures short source durations.

First, we compute rms envelopes at five frequency bands, 1–2, 2–4, 4–8, 8–16 and 16–32 Hz, for velocity seismograms. The
seismograms are filtered from forward and backward directions to avoid any phase delay by using the fourth-order bandpass Butterworth filter. The envelopes are smoothed by applying a moving time window of width twice the central period of the each frequency band. Examples of rms envelopes for different frequency bands are shown in Fig. 2, for the forearc side area and the backarc side area. The $S$-wave arrival is shown by red tick mark for each trace.

(c) Hypocentral Distance ($R$) (km)

Figure 4. (Continued.)
We measure the 90 per cent duration time $T_{90}$ from each smoothed envelope by using the method given in the previous section. We evaluate the moments $e_0$, $e_1$ and $e_2$ from the smoothed envelope, and then calculate the rms duration time $T_{\text{rms}}$ using eq. (1), for the integration window $\Delta t$ starting from the S-wave onset, where $\Delta t$ is taken as $K$ times the $S$–$P$ time $t_s - t_p$ (Petukhin & Gusev 2003). The variations of $T_{\text{rms}}$ for different hypocentral distance ranges with respect to $K$-value are shown in Fig. 3 for each frequency band for

![Graphs showing variations of $T_{\text{rms}}$ for different hypocentral distance ranges](image)

**Figure 4.** (Continued.)
forearc and backarc side. The $T_{\text{rms}}$ value increases with distance increasing for a given $K$-value. The $K$-value dependence in this analysis is a little bit clearer than that in the Kamchatka (Petukhin & Gusev 2003); however, using information regarding the second central moment (eq. 1) is still an attractive idea to estimate the duration time. Therefore, we keep using $T_{\text{rms}}$ as a secondary-quality duration measure for a fixed $K$-value (say, $K = 2$).

4 RESULTS

4.1 Hypocentral distance dependence of envelope characteristics

The variations of $T_{90}$, $T_{\text{rms}}$, $e_1/e_0$ and $e_2/e_0$ with respect to hypocentral distance in the logarithmic scale are shown in Figs 4(a)–(d), for each frequency band for the forearc and backarc side areas of northeastern Honshu, Japan, respectively. Each of the parameters of the 90 per cent duration interval ($T_{90}$), the rms duration ($T_{\text{rms}}$), $e_1/e_0$ and $e_2/e_0$, clearly shows a linear trend with respect to hypocentral distance in the logarithmic plot, that is, each parameter varies according to a power of hypocentral distance.

Estimated coefficients $a$ and $b$ along with their standard deviation, correlation coefficient ($r$) and rms residual error from least-square regression fit by using eq. (5) is listed in Table 1, where correlation coefficients are high in general.

For the time duration parameters $T_{90}$ and $T_{\text{rms}}$, the hypocentral dependence exponent $b$ is always positive, that is, time duration increases with hypocentral distance. The $b$ value remains more or less constant with frequency for the forearc side, however, it decreases with increasing frequency for the backarc side. On the other hand, the exponent $b$ increases with frequency for the moment ratios $e_1/e_0$ and $e_2/e_0$ for the forearc side; however, it remains more or less constant with frequency (no clear trend) in the backarc side. The relation $T_{\text{rms}}$ versus earthquake magnitude is estimated by regression analysis fit with $\log_{10}T_{\text{rms}} = bM + a$. Estimated $a$ and $b$ values with their standard errors and rms residuals are listed in Table 2. We find there is little correlation among the time duration and earthquake magnitude.

4.2 Frequency–distance dependence of envelope characteristics

To see the frequency dependence of envelope characteristics, the value of the parameter at a reference distance $T_{\text{ref}}$ is estimated

### Table 1. Estimated $a$ and $b$ parameters along with their standard deviation, correlation coefficient ($r$) and rms residual from least-square regression fit [log10(parameter) = $a + b\log(R)$] at different frequency bands for (a) $T_{90}$, (b) $T_{\text{rms}}$, (c) $e_1/e_0$ and (d) $e_2/e_0$ for the forearc and backarc sides in northeastern Japan.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Forearc</th>
<th>Backarc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$b$</td>
<td>$SD (b)$</td>
</tr>
<tr>
<td>(a) $T_{90}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>0.89</td>
<td>0.02</td>
</tr>
<tr>
<td>2.0–4.0</td>
<td>0.81</td>
<td>0.02</td>
</tr>
<tr>
<td>4.0–8.0</td>
<td>0.83</td>
<td>0.02</td>
</tr>
<tr>
<td>8.0–16.0</td>
<td>0.87</td>
<td>0.02</td>
</tr>
<tr>
<td>16.0–32.0</td>
<td>0.89</td>
<td>0.02</td>
</tr>
</tbody>
</table>

| (b) $T_{\text{rms}}$ | | | | | | | | |
| 1.0–2.0 | 0.88 | 0.02 | -1.06 | 0.03 | 0.89 | 0.60 | 0.92 | 0.02 | -1.08 | 0.04 | 0.91 | 0.56 |
| 2.0–4.0 | 0.82 | 0.02 | -0.98 | 0.03 | 0.86 | 0.56 | 0.83 | 0.03 | -0.99 | 0.05 | 0.82 | 0.65 |
| 4.0–8.0 | 0.82 | 0.02 | -0.98 | 0.03 | 0.83 | 0.56 | 0.80 | 0.03 | -1.01 | 0.06 | 0.76 | 0.64 |
| 8.0–16.0 | 0.83 | 0.02 | -1.00 | 0.03 | 0.84 | 0.54 | 0.68 | 0.03 | -0.81 | 0.06 | 0.73 | 0.60 |
| 16.0–32.0 | 0.85 | 0.02 | -1.02 | 0.03 | 0.87 | 0.43 | 0.63 | 0.03 | -0.69 | 0.05 | 0.74 | 0.55 |

| (c) $e_1/e_0$ | | | | | | | | |
| 1.0–2.0 | 0.72 | 0.03 | -0.64 | 0.05 | 0.66 | 1.48 | 0.89 | 0.04 | -0.88 | 0.07 | 0.76 | 1.45 |
| 2.0–4.0 | 0.77 | 0.03 | -0.80 | 0.05 | 0.63 | 1.35 | 0.78 | 0.05 | -0.85 | 0.09 | 0.61 | 1.28 |
| 4.0–8.0 | 0.87 | 0.03 | -1.00 | 0.05 | 0.67 | 1.27 | 0.89 | 0.06 | -1.14 | 0.10 | 0.61 | 1.11 |
| 8.0–16.0 | 0.89 | 0.03 | -1.01 | 0.05 | 0.71 | 1.23 | 0.77 | 0.06 | -0.93 | 0.10 | 0.58 | 1.19 |
| 16.0–32.0 | 0.88 | 0.02 | -0.93 | 0.04 | 0.77 | 1.12 | 0.62 | 0.05 | -0.64 | 0.09 | 0.53 | 1.00 |

| (d) $e_2/e_0$ | | | | | | | | |
| 1.0–2.0 | 1.54 | 0.04 | -1.24 | 0.07 | 0.77 | 19.57 | 1.78 | 0.06 | -1.57 | 0.11 | 0.83 | 22.86 |
| 2.0–4.0 | 1.57 | 0.04 | -1.41 | 0.07 | 0.75 | 14.91 | 1.59 | 0.08 | -1.50 | 0.14 | 0.72 | 14.75 |
| 4.0–8.0 | 1.68 | 0.05 | -1.65 | 0.08 | 0.76 | 13.20 | 1.68 | 0.09 | -1.81 | 0.15 | 0.70 | 10.21 |
| 8.0–16.0 | 1.72 | 0.04 | -1.67 | 0.07 | 0.79 | 13.79 | 1.46 | 0.09 | -1.42 | 0.15 | 0.66 | 12.40 |
| 16.0–32.0 | 1.73 | 0.04 | -1.60 | 0.06 | 0.84 | 12.97 | 1.24 | 0.08 | -0.99 | 0.14 | 0.63 | 9.90 |

© 2010 The Authors, *GJI*, 182, 988–1000
Journal compilation © 2010 RAS
by using eq. (4), where we took the reference distance as \( R_{\text{ref}} = 100 \text{ km} \). Table 3 enumerates the estimated \( T_{90}, T_{rms}, e_1/e_0 \) and \( e_2/e_0 \) with their standard deviations for the forearc and backarc sides. They are plotted along with the estimated error in Figs 5(a)–(d) for the forearc and the backarc side, where \( T_{90} \) is added for comparison in Fig. 5(e). It can be seen from Table 3 and Fig. 5 that each of estimated reference parameters \( (T_{90}, T_{rms}, e_1/e_0, e_2/e_0 \) and \( T_{90} \) at frequency 1–2 Hz is large in the backarc side as compared to that for the forearc side, however, it is largest for the forearc side as compared to that for the backarc side for frequencies \( >2 \text{ Hz} \). Frequency dependence is different between the forearc and backarc sides of the VF. The frequency dependence of the \( T_{90} \) (Fig. 5e) for the backarc side is nearly the same as that in southern California (Raoof et al. 1999) for frequencies less than 5 Hz.

### Table 3. Estimated \( T_{90}, T_{rms}, e_1/e_0 \) and \( e_2/e_0 \) with their standard deviations at reference distance \( R = 100 \text{ km} \) for forearc and backarc sides.

<table>
<thead>
<tr>
<th>Frequency band (Hz)</th>
<th>( T_{rms,100} ) (s)</th>
<th>SD(( T_{rms} )) (s)</th>
<th>( T_{90,100} ) (s)</th>
<th>SD(( T_{90} )) (s)</th>
<th>( e_1/e_{0,100} ) (s)</th>
<th>SD(( e_1/e_0 )) (s)</th>
<th>( e_2/e_{0,100} ) (s(^2))</th>
<th>SD(( e_2/e_0 )) (s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Forearc side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>5.10</td>
<td>0.03</td>
<td>16.18</td>
<td>0.10</td>
<td>6.49</td>
<td>0.07</td>
<td>69.51</td>
<td>1.13</td>
</tr>
<tr>
<td>2.0–4.0</td>
<td>4.57</td>
<td>0.03</td>
<td>14.18</td>
<td>0.10</td>
<td>5.49</td>
<td>0.06</td>
<td>52.96</td>
<td>0.86</td>
</tr>
<tr>
<td>4.0–8.0</td>
<td>4.46</td>
<td>0.03</td>
<td>13.88</td>
<td>0.10</td>
<td>5.49</td>
<td>0.06</td>
<td>51.48</td>
<td>0.86</td>
</tr>
<tr>
<td>8.0–16.0</td>
<td>4.64</td>
<td>0.03</td>
<td>14.78</td>
<td>0.10</td>
<td>5.93</td>
<td>0.06</td>
<td>57.96</td>
<td>0.89</td>
</tr>
<tr>
<td>16.0–32.0</td>
<td>4.92</td>
<td>0.03</td>
<td>15.92</td>
<td>0.10</td>
<td>6.84</td>
<td>0.06</td>
<td>72.05</td>
<td>0.95</td>
</tr>
<tr>
<td>(B) Backarc side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>5.66</td>
<td>0.04</td>
<td>18.17</td>
<td>0.12</td>
<td>7.99</td>
<td>0.11</td>
<td>97.89</td>
<td>2.06</td>
</tr>
<tr>
<td>2.0–4.0</td>
<td>4.62</td>
<td>0.05</td>
<td>14.04</td>
<td>0.18</td>
<td>5.09</td>
<td>0.09</td>
<td>48.67</td>
<td>1.33</td>
</tr>
<tr>
<td>4.0–8.0</td>
<td>3.95</td>
<td>0.05</td>
<td>11.52</td>
<td>0.19</td>
<td>4.24</td>
<td>0.09</td>
<td>34.67</td>
<td>1.04</td>
</tr>
<tr>
<td>8.0–16.0</td>
<td>3.66</td>
<td>0.04</td>
<td>10.86</td>
<td>0.16</td>
<td>4.12</td>
<td>0.08</td>
<td>31.40</td>
<td>0.93</td>
</tr>
<tr>
<td>16.0–32.0</td>
<td>3.62</td>
<td>0.04</td>
<td>10.71</td>
<td>0.14</td>
<td>4.04</td>
<td>0.07</td>
<td>29.95</td>
<td>0.84</td>
</tr>
</tbody>
</table>

In Fig. 5, we also plot the duration at a 100 km distance \( T_{rms,100} \) (i.e. \( T_{90} \)) for crustal events in the forearc side of Kamchatka (Petukhin & Gusev 2003) by open boxes for comparison. Their \( T_{rms,100} \) are nearly the same as our estimate of \( T_{rms,100} \) in the backarc side of northeastern Honshu, Japan. We note that Atkinson (1993) estimated \( T_{90} \) at 100 km reference distance plotted by a light grey line in Fig. 5(b) as about 10 s in eastern North America for frequency band 1–10 Hz. Trifuinac & Brady (1975) estimated the \( T_{90} \) at 100 km reference distance for earthquake magnitude 3.0 in California, USA region as 13.55 and 19.15 s for hard and intermediate sites, respectively, for frequency band 0.07–25 Hz. The \( T_{90} \) at hard site in California region by a dark grey line is comparable but a little smaller as compared to that of the forearc side of Japan. As shown in Fig. 5(e), the duration at 100 km distance \( T_{90,100} \) of the backarc side is nearly the same as that in southern California (Raoof et al. 1999) for frequencies less than 5 Hz.

### 5 DISCUSSION

Scattering due to random velocity inhomogeneity and guided wave effects in the crust increase the apparent duration but intrinsic absorption truncates it. A balance of these effects determines the apparent duration time. Intrinsic absorption is known to be stronger in the backarc side (Umino & Hasegawa 1984; Tsumura et al. 2000). Strong intrinsic absorption in the backarc region compared with the forearc region is confirmed from the spatial variation of coda amplitude at a fixed lapse time (Yoshimoto et al. 2006). Analysing the whole S-wave seismogram envelopes of crustal earthquakes, Carcole & Sato (2010), using the multiple lapse time window analysis (MLTWA) with data provided by the Hi-net seismic network, recently showed that intrinsic absorption is strong beneath the volcanic front and the backarc region; however, scattering is strong beneath the VF and weak on both sides for frequencies 1–2 Hz; however, scattering is not always weak on the both sides of the VF for frequencies higher than 4 Hz. Based on the inversion analysis of S envelope broadening (peak delay time) of intermediate depth earthquakes, Takahashi et al. (2009) reported that the velocity fluctuation in the depth range 0–20 km is uniformly large in both sides of the volcanic front in the northeastern Honshu, Japan, where the velocity fluctuation in the depth range 20–60 km is larger especially beneath Quaternary volcanoes as compared to the other side of the VF. These observations mean that the time duration in the backarc becomes shorter because intrinsic absorption is stronger than that of forearc side with increasing frequency; however, the duration is larger in the forearc side because intrinsic absorption is weaker than that of backarc side. In the forearc side, scattering effect or crustal-guided effect dominates over the intrinsic absorption.

### 6 CONCLUSIONS

Parameters characterizing S-wave broadening effect (\( T_{90}, T_{rms}, e_1/e_0, e_2/e_0 \)) for crustal events were analysed in the forearc and backarc sides of the VF in the northeastern Honshu, Japan. Those parameters increase according to a positive power of hypocentral distance for frequencies 1–32 Hz. At a reference distance of 100 km, each of time durations \( T_{90}, T_{rms} \) in the backarc side decreases with frequency; however, those in the forearc side has the minimum at about 4 Hz. The time duration at the reference distance in the backarc side is shorter than that in the forearc side especially for frequencies higher than 4 Hz. These characteristics for crustal events are somewhat different from those reported for deeper events. These envelopes are useful as the empirical Green’s function for the quantitative evaluation of strong motion in high frequencies, where we should note differences depending on focal depths and ray paths in relation to the VF in this area.

### ACKNOWLEDGMENTS

The support extended under the India-Japan Cooperative Science Programme (ICSP) (#DST/INT/JAP/P-41/07) by Department of Science and Technology (DST), Government of India and Japan Society for the Promotion of Science (JSPS) Government of Japan is highly acknowledged. Authors are grateful to the Editor Michael Korn, reviewers Edoardo Del Pezzo and Alexander A. Gusev and an anonymous reviewer for their valuable comments and suggestions that improved the quality of the paper. The authors are also grateful.

© 2010 The Authors, **J. Geol. Soc. India, 182, 988–1000**

Journal compilation © 2010 RAS
Envelope broadening of crustal earthquakes

to those who made efforts to run the Hi-net and data provided by NIED staff in Tsukuba, Japan, and in particular with Takuto Maeda. The hypocentre data of the unified hypocentre catalogue by the Japan Meteorological Agency are used for the analysis. SAC and GMT code are used for data processing and figure plotting.

REFERENCES


© 2010 The Authors, GJI, 182, 988–1000
Journal compilation © 2010 RAS


