Shear Wave Splitting Observed in the Southwestern Part of Fukushima Prefecture, Northeastern Japan

Tomomi Okada,1,* Toru Matsuzawa,1 Satoshi Matsumoto,1 Koichi Nida,2 Akihiko Ito,3 and Akira Hasegawa1

1Observation Center for Prediction of Earthquakes and Volcanic Eruptions, Faculty of Science, Tohoku University, Sendai 980-77, Japan
2Sanriku Observatory for Earthquakes and Volcanoes, Faculty of Science, Tohoku University, Tono 028-05, Japan
3Department of Education of Science, Faculty of Education, Utsunomiya University, Utsunomiya 321, Japan

We have investigated shear wave polarization anisotropy in the southwestern part of Fukushima Prefecture, northeastern Japan. Waveform data analyzed are obtained by a local seismic networks of Tohoku University and Utsunomiya University. We used a cross correlation method to detect the shear wave splitting. For the shallow events beneath the southwestern part of Fukushima Prefecture, observed that fast shear wave oscillation directions (FSODs) are oriented to the NW-SE. The observed delay times are less than 0.1 s and tend to have large values in high seismicity regions. For the intermediate-depth events, observed FSODs are oriented parallel to the dip direction of the subducted slab and most of the observed delay times are less than 1 s. We estimated the location and the cause of anisotropy based on these observations. In the upper crust beneath the southwestern part of Fukushima Prefecture anisotropy is estimated to be caused mainly by preferentially oriented cracks controlled by the tectonic stress.

1. Introduction

The southwestern part of Fukushima Prefecture is one of the tectonically active regions in the northeastern Japan arc. Many shallow earthquakes occur in this region. There are some active faults and some volcanoes in and around the area. Sometimes anomalously low-frequency microearthquakes occur close to the Moho discontinuity in this area; they are considered to be closely related to deep-seated magmatic activity at the bottom of the crust or at the top of the upper mantle (Hasegawa and Yamamoto, 1994; Matsumoto et al., 1993). Iwase et al. (1989) detected reflected seismic S waves (SxS wave) in this region and located an S wave reflector. In their result, the depth to the reflector is about 15 km. Such reflectors are often found in other regions near volcanoes (Mizoue, 1980; Mizoue et al., 1982; Hasegawa et al., 1991; Hori and Hasegawa,
1991; Matsumoto and Hasegawa, 1991, 1994; Inamori et al., 1992) and are thought to be the surfaces of partial melted bodies or magma bodies.

Tohoku University and Utsunomiya University have carried out temporary seismic observation in this region since April 1991. Matsumoto et al. (1993) investigated the low-frequency microearthquakes and the S wave reflector in this region in more detail using the data obtained by observation. In this study, we investigate the shear wave splitting observed by the temporary seismic network.

2. Data Selection

We used digital waveform data from local earthquakes recorded by the temporary seismic observation network. This network consists of five seismic stations: AZK, HNE, OHR, MZH, and SHR. The locations of the stations are shown in Fig. 1 and their coordinates are given in Table 1. Since OHR only has a one-component (up-down component) seismograph, we used the data from the other four, three-component, observation stations in this study.

The details of the observation system are as follows. The eigen frequencies of the seismometers are 1 Hz for all the stations. Waveform data are sent to the station SHR.

Fig. 1. Locations of the seismic stations (solid squares) and the hypocenters (open circles) of shallow events used in this study. (a) Map view. (b) E-W vertical cross sectional view. (c) N-S vertical cross sectional view.
Table 1. List of stations used in this study.

<table>
<thead>
<tr>
<th>Code</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZK</td>
<td>37.0750</td>
<td>139.4235</td>
</tr>
<tr>
<td>MZH</td>
<td>37.0388</td>
<td>139.5178</td>
</tr>
<tr>
<td>HNE</td>
<td>37.0115</td>
<td>139.3845</td>
</tr>
<tr>
<td>SHR</td>
<td>37.1077</td>
<td>139.5167</td>
</tr>
<tr>
<td>OHR</td>
<td>37.1277</td>
<td>139.4775</td>
</tr>
</tbody>
</table>

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3. Method

Shear wave splitting is a phenomenon whereby a shear wave from its source separates into two waves in anisotropic media; the two waves have approximately mutually orthogonal oscillation directions and travel with different velocities. The shapes of the two split shear waves are similar to each other although their amplitudes are usually different. To detect the shear waves that have similar waveforms, we adopted a method using cross correlation coefficients.

The details of this "cross correlation method" are as follows:

1) Rotate the horizontal two components of the observed seismograms of shear wave arrivals in the horizontal plane in azimuths from 0° to 175° with an interval of 5°. The rotated horizontal two components will be called X1 and X2 components. The X1 and X2 component amplitudes of the seismograms are expressed as

\[ A_{X1}(t) = A_{NS}(t) \cos(90° - \theta) + A_{EW}(t) \sin(90° - \theta) , \]
\[ A_{X2}(t) = A_{NS}(t) \sin(90° - \theta) - A_{EW}(t) \cos(90° - \theta) , \]

where \( A_{NS} \) and \( A_{EW} \) denote the north-south and east-west component amplitudes,
respectively, and $\theta$ represents the rotation angle.

2) Calculate the cross correlation coefficient of $X_1$ and $X_2$ components in a certain time window. The cross correlation coefficient is defined as

$$C(t_0; \tau) = \frac{\sum_{t=t_0}^{t_0+T} A_{X_1}(t)A_{X_2}(t+\tau)}{\sqrt{(A_{X_1}(t))^2(A_{X_2}(t))^2}},$$

(a)  

(b)  

(c)  

Fig. 2. An example of seismograms of shallow earthquakes observed at station AZK. (a) UD, NS, EW, fast S, slow S components of the seismogram. (b) Observed particle motion in the time window shown in (a). Thick line indicates the estimated fast shear wave oscillation direction. (c) Particle motion corrected by removing the splitting effects.
where $t_0$, $t_w$, and $\tau$ represent the arrival time of the shear wave, the length of the time window, and the lag time, respectively. The length of the time window ($t_w$) is set nearly equal to one cycle of the wave (0.1–0.2 s). The time window of $X_2$ component is shifted from the time window of $X_1$ component with a step of 0.01 s.

3) When the absolute value of the cross correlation coefficient takes the maximum value, we regard the rotation direction ($\theta_0$) as the fast shear wave oscillation direction (FSOD), and the amount of the lag time ($\tau_0$) as the delay time of the slow shear wave to the fast shear wave.

This cross correlation method is weak for background noises since the data used in this method is sensitive only to the shape of observed seismograms. Actual seismograms are contaminated by background noises and scattered waves. It may be possible that some non-splitted waves accidentally seem to correlate with their coda waves and are regarded as splitted shear waves. To overcome this disadvantage, we adopted a criterion of cross correlation coefficients by assuming that the correlation of such contaminated waves is not very high. If the maximum correlation between $X_1$ and $X_2$ components is lower than the criterion, the seismogram will not be treated as split. We used 0.8 as the criterion in this study.

An example of the observed seismograms is shown in Fig. 2. The particle motion of the shear wave arrival is not polarized linearly (Fig. 2(b)). We regarded this phenomenon to be a result of the shear wave splitting and tried to detect the fast shear

![Fig. 3. Splitting vectors obtained at stations, (a) AZK, (b) SHR, (c) HNE, and (d) MZH. The vectors are plotted on each epicenter. The fast shear wave oscillation directions (FSODs) observed at each station are shown as the orientations of the thick lines. The delay time is proportional to the line length. The locations of the seismic stations are shown by solid squares. Thin lines indicate the active faults.](image)
wave oscillation direction (FSOD) and the delay time by the cross correlation method. Although the splitting is not so clear in the original three-component seismogram, as shown in the top three traces in Fig. 2(a), the horizontally rotated seismograms (the bottom two traces in Fig. 2(a)) show distinct splitting. Figure 2(c) shows the particle motion after removing the effect of splitting by using the obtained parameters. From the comparison of (b) and (c) it is shown that the linearity of the shear wave arrival increases after the correction of the splitting. This feature suggests that we can reproduce original waveforms by removing the splitting effect.

4. Results

First we will show the result from the shallow events. The fast shear wave oscillation directions (FSODs) observed at each station are shown as the orientations of the thick lines in Fig. 3. We will call these thick lines “splitting vectors.” The delay time is proportional to the line length. The splitting vector is plotted on each epicenter in Fig. 3. Many events which can be used for the analysis were recorded at stations AZK and HNE, while we cannot analyze many data recorded at station MZH. The observed FSODs are oriented mainly E-W or NW-SE.

The thin lines in Fig. 4 denote the oscillation directions of the shear waves determined to be non-splitted. For the stations AZK and SHR, most of the observed non-splitted shear wave oscillation directions (NSODs) are parallel to the FSODs but

Fig. 4. Oscillation directions of the shear wave determined to be non-splitted at the stations, (a) AZK, (b) SHR, (c) HNE, and (d) MZH. Thin lines denote the oscillation directions and are plotted on each epicenter. The locations of the seismic stations are shown by solid squares. Thick lines indicate the active faults.

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We observed some NSODs oblique to the FSODs at stations HNE and MZH.

The distribution of the observed FSODs is shown using the rose diagram in Fig. 5. All the data, including those determined to be non-split are plotted in Fig. 5(a). Since the sampling interval of the A/D is 0.01 s, the obtained delay time of 0.01 and 0.02 s may be ambiguous. Thus, we also show in Fig. 5(b) the data whose delay times are larger than 0.02 s. The FSODs are distributed in the E-W or the NW-SE direction at all the stations except MZH. Note that for the station SHR most of the delay times

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The delay time is proportional to the line length. The FSODs whose delay times are greater than 0.02 s for the station SHR are oriented to the NW-SE with some scattering (Fig. 5(a) and (b)). The average of the FSODs for each station listed in Table 2 is also oriented nearly E-W or NW-SE, except the data whose delay time is greater than 0.02 s for station MZH.

The splitting vectors at each station in Fig. 3 are summarized and shown in an azimuthal diagram in Fig. 6. This figure shows that, for station AZK, the largest splitting vector whose delay time is 0.11 s is oriented nearly NW-SE. The figure also shows that the orientations of most of the splitting vectors are distributed in the E-W to NW-SE directions although there are some vectors which are oriented to the NE-SW. For stations HNE and SHR, the distribution of splitting vectors is similar to that for station AZK. The distribution for station MZH seems to be different from the others. However, we will not discuss the data from MZH further here since very few data are available from this station. The average and maximum value of the delay times are also listed in Table 2 for each station. The average values of the delay times for each station is the largest at station AZK (0.03 s) and the smallest at SHR (0.01 s). The average value of the delay times for all the stations is 0.02±0.02 s.

We also investigated the shear wave splitting from some intermediate-depth events. The hypocenters and stations used are shown in Fig. 7. The hypocenter locations used in this study are determined by the routine processing of the seismic network of Tohoku University (Hasegawa et al., 1978). We used the data from six events in the upper
Fig. 7. Locations of the seismic stations (solid squares with station codes) and the hypocenters (open circles) of the intermediate-depth events used in this study. Open and solid circles denote the location of the events on the upper seismic plane and lower seismic plane of deep seismic zone, respectively. (a) Map view. (b) E-W vertical cross sectional view. (c) N-S vertical cross sectional view.

Table 3. Observed FSODs and delay times for the intermediate-depth events.

<table>
<thead>
<tr>
<th>Station</th>
<th>FSOD (deg)*</th>
<th>Delay time (s)</th>
<th>Number of data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave.</td>
<td>Max.</td>
<td></td>
</tr>
<tr>
<td>AZK</td>
<td>114±71</td>
<td>0.22±0.14</td>
<td>0.45</td>
</tr>
<tr>
<td>MZH</td>
<td>145</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>HNE</td>
<td>130</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>SHR</td>
<td>97±38</td>
<td>0.32±0.07</td>
<td>0.40</td>
</tr>
<tr>
<td>Total</td>
<td>114±58</td>
<td>0.27±0.13</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The dip direction of the deep seismic zone is ~N120°E (Orientation of the dip direction of the deep seismic zone is estimated from the result of Hasegawa et al. (1978)).

* FSODs are measured clockwise from north.
seismic plane of the double-planed deep seismic zones and only one event in the lower seismic plane. The obtained FSOD is plotted on the mid-point between epicenter and station as the splitting vector in Fig. 8. The FSODs are distributed mainly in the E-W to NW-SE directions. The average of FSODs and the average and the maximum value of the delay time for each station are listed in Table 3. The average value of delay times for all the stations is $0.27 \pm 0.12$ s and the maximum value is $0.45$ s which is observed at station AZK. Since only one data from the event in the lower seismic plane was available, we could not investigate the difference in shear wave splitting between the data from the upper seismic plane and the lower seismic plane.

5. Discussion

5.1 Relation between seismic activity and shear wave splitting from shallow events

The amount of shear wave splitting from shallow events varies from station to station. On the average, the delay time for AZK is the largest among the three stations. The amount of the delay time observed for SHR is much smaller than the obtained metre.
values for AZK and HNE. To understand the cause of this difference, we compared the seismicity and the pattern of shear wave splitting. Shallow microearthquake activity is very high in this area, the southwestern part of Fukushima Prefecture. Figure 9 shows the epicenter distribution in the region located by the seismic network of Tohoku University for the period from January 1981 to July 1993. There is an active fault, Hinoemata-nishi, to the west of the observation network (Research Group for Active Faults of Japan, 1991) and most of the earthquakes are located near it. The motion of the fault is considered to have a large dip-slip component since the fault has fault scarps facing to the west and some of the events east of the fault have reverse fault type solutions. The two stations at which large splitting is observed, AZK and HNE, are located in the high seismicity region. In contrast, station SHR, where only small splitting is observed, is located in the low seismicity region. In other words, large splitting seems
to occur in the high seismicity region, although the number of stations is too small to be conclusive.

5.2 Relation between tectonic stress and shear wave splitting from shallow events

In the previous studies of shear wave splitting, the correlation between FSOD and tectonic stress has been discussed. Kaneshima (1990) reported that the observed FSODs are approximately parallel to the direction of the maximum horizontal compression ($\sigma_H$) axis. Such a relation between shear wave splitting and tectonic stress is expected also in the southwestern part of Fukushima Prefecture.

We used focal mechanisms of earthquakes in this region to estimate the direction of the $\sigma_H$ axis. The directions of the pressure axes of the focal mechanisms are expected to be nearly equal to the direction of the $\sigma_H$ axis. The two earthquakes whose magnitudes were 3.7 occurred in the region on April 27, 1990. The magnitudes of these earthquakes are large compared with earthquakes that usually occur in this region. The epicenters and focal mechanisms of these two earthquakes are shown in Fig. 10(a) and (b), respectively.

In these focal mechanisms, the direction of pressure axes are oriented NW-SE. Thus, the direction of the $\sigma_H$ axis is estimated to be oriented to the NW-SE. This direction, NW-SE, is similar to the $\sigma_H$ axis trajectories estimated by Ando (1979) in the region and nearly equal to the direction of the majority of the observed FSODs in this study.

5.3 Possible cause of Anisotropy in the upper crust

In the southwestern part of Fukushima Prefecture, the observed FSODs are parallel to the directions of the horizontal maximum compressional axis ($\sigma_H$) and most of the observed delay times are less than 0.05 s. This amount of the delay time corresponds to the anisotropy of 2% if the medium is homogeneously anisotropic in this area.

The previous studies on shear wave splitting from the shallow events in Japan are reviewed by Kaneshima (1990). According to these studies, the observed FSODs are parallel to the $\sigma_H$ directions at most seismic stations in Japan. One of the possible causes of the crustal anisotropy that correlates with the present tectonic stress field is the preferred orientation of microcracks. If vertical cracks are aligned in nearly the same direction in a medium, the medium will show the anisotropic natures macroscopically and shear wave splitting will occur. In this case, the FSODs are oriented to the strike of microcracks when the waves are propagated vertically. The anisotropic features caused by the alignment of microcracks have been confirmed by theoretical and experimental studies (e.g., Hudson, 1980, 1981; Soga et al., 1978). There are two possible mechanisms of the alignment of the cracks. One is the tensile opening of the cracks normal to the minimum compression axis (Crampin, 1987), and the other is the closing of the cracks normal to the maximum and intermediate compression axes (Nur, 1971). In both cases, the anisotropic characteristics are controlled by the present tectonic stress.

In the southwestern part of Fukushima Prefecture, the maximum compression axis is estimated to be oriented to the NW-SE from the analyses of the focal mechanism solutions (e.g., Umino, 1988). In this case, cracks whose strikes are oriented NW-SE will be predominant there. Then the medium including these cracks will show anisotropic
Fig. 10. Epicenter locations of the two relatively “large” earthquakes of April 27, 1990 and their aftershocks. Thick lines with and without nap denote the active faults with certainties II and III, respectively (Research Group for Active Faults of Japan, 1991). (b) Fault plane solutions of these two earthquakes projected onto the lower hemispheres. (After Faculty of Science, Tohoku University, 1990)

behavior. The increase of the delay times in the seismically active regions supports these idea, since the crack density is likely to be high in the active region due to the higher degree of the brittle deformation. Tomographic studies (Zhao et al., 1992; Matsumoto
and Hasegawa, 1989) revealed that the low-V and low-Q regions in the crust correspond to the seismically active region. This feature again probably indicates the high crack density in the seismically active regions.

In the northwestern part of Tochigi Prefecture, which is close to Fukushima Prefecture, similar results were obtained by Tsukada (1991): the FSODs from the shallow events are oriented to the NW-SE and the delay times are up to 0.05 s. This feature suggests that the tectonics in both regions—the southwestern part of Fukushima Prefecture and the northeastern part of Tochigi Prefecture—are very similar to each other.

The distribution of the FSODs for station AZK seems to be divided into two directions: N95°E and N150°E (Fig. 5). The former group (N95°E) is predominant in the north region while the latter (N150°E) is prominent in the south region (Fig. 3). One of the possible causes of this feature is an effect of the fault motion. The strike of the fault is oriented to NNE-SSW in the north region and NE-SW in the south region (see Figs. 3 and 10). The motion of the fault reduces shear stress parallel to the fault. This reduction results in a rotation of the stress field to make the orientation of the $\sigma_\text{H}$ axis near the fault become nearly perpendicular to its strike when the fault plane is oblique to the maximum shear plane expected from the regional stress field (c.f., Zoback et al., 1987). In this case, the strike of the crack and the FSOD are expected to be oriented to WNW-ESE in the north region and NW-SE in the south region. However, we will not discuss the spatial pattern of the FSOD distribution further here since our data are too few. This problem is a subject for further study.

5.4 Non-split shear waves from the shallow events

We also observed some shear waves which are determined to be non-split (Fig. 4). The observed non-split shear wave oscillation directions (NSODs) are thought to reflect the oscillation directions of the shear waves at the focus.

In general, when the non-split arrival of shear wave is observed, we can suppose two cases: (1) the oscillation direction of the shear wave is parallel to the FSOD, or (2) no anisotropic bodies exist in the area. Since both reverse fault type and strike-slip type events are occurring in this area, a variety of NSODs should be observed if the medium has no anisotropy. For stations AZK and SHR, the oscillation of the observed non-split shear waves are parallel to the FSODs. This feature can be explained by case (1). In contrast, for stations HNE and MZH, some of the NSODs are not parallel to the FSODs. This suggests that the anisotropic bodies in these areas have different features or that these small regions locally have features different from the surrounding area. However, it is hard to know whether the exceptional NSODs indicate a loss of the anisotropic nature or a change in its direction since only few exceptional data are available.

5.5 Results from intermediate-depth events

The delay times from the intermediate-depth events (0.27 s) are larger than those from the shallow events (0.02 s). This feature suggests that the anisotropy also exists at depths below the seismogenic upper crust. The observed FSODs are oriented NW-SE which is parallel to the local dip direction of the deep seismic zone beneath this area.
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The average degree of anisotropy is about 1.5% if anisotropic bodies are homogeneously distributed in the mantle wedge. These results are the same as those obtained for the whole part of northeastern Japan by Okada (1993) and Okada et al. (1994), who used a data set independent of the present study. They concluded that a significant anisotropy exists in the mantle wedge beneath the northeastern Japan arc. It is hard to discuss the anisotropy in the descending slab from the data obtained in the present study because only one datum was available from the event in the lower seismic plane of the deep seismic zone.

6. Conclusions

We have analyzed shear wave splitting from shallow and intermediate-depth earthquakes to investigate the seismic anisotropy structure beneath the southwestern part of Fukushima Prefecture. We used the data from a temporary seismic network deployed in the southwestern part of Fukushima Prefecture.

The shear wave splittings with the fast shear wave oscillation directions (FSODs) oriented NW-SE are observed for the shallow events. This direction is approximately parallel to the maximum horizontal compression axis. The observed delay times are less than 0.1 s. For the intermediate-depth events, the observed FSODs are also oriented NW-SE, which is also parallel to the dip direction of the deep seismic zone. Most of the observed delay times are less than 0.5 s.

From these observations of shear wave splittings, we estimated the location and cause of anisotropy. (1) In the upper crust in the southwestern part of Fukushima Prefecture, the anisotropy is probably caused by the preferredly oriented cracks—the subvertical cracks whose strikes are aligned NW-SE, parallel to the maximum compression axis due to the brittle deformation controlled by the tectonic stress. The average degree of anisotropy obtained is about 2% and takes a large value in the region where seismic activity is high. (2) The anisotropy probably exist also in the mantle wedge. The average degree of anisotropy is about 1.5%.

We are deeply indebted to Prof. T. Hirasawa, Prof. H. Hamaguchi, and Prof. M. Ohtake for their helpful suggestions and encouragement. We thanks Dr. N. Umino and Dr. A. Yamamoto for the valuable suggestions. We appreciate the great help of Mr. S. Hori and Mr. T. Kono for installing and maintaining the observation network. Discussions with them were also useful.

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