Fracture induced shear wave splitting in a source area of triggered seismicity by the Tohoku-oki earthquake in northeastern Japan

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Abstract

We observed shear wave splitting probably induced by the fracturing of microearthquakes triggered by the 2011 Off the Pacific coast of Tohoku Earthquake. We analysed seismograms observed at two temporary stations in one of the source areas of triggered seismicity in the Akita Prefecture, northeastern Japan. We used a grid search to find the polarisation direction of fast S-wave and the delay time between the fast and slow waves. The delay time is around 0.015 s at a station located just above the earthquake cluster, while it is close to 0 s at a station about 5 km off the cluster. Many previous studies have shown that the crustal polarisation is nearly parallel to the direction of maximum horizontal stress. However, our results indicates the polarisation nearly parallel to the strike of nodal planes of focal mechanisms, which suggests the contribution of fracturing of triggered seismicity to the formation of anisotropy.

Keywords: shear-wave splitting, anisotropy, triggered earthquake, stress field, fracture

BACKGROUND:

Seismic anisotropy is one of the fundamental properties of Earth materials. Shear-waves travelling in an anisotropic medium are separated into fast and slow waves (Figure 1) and can be detected from seismic observations. The parameters that characterises the splitting is the polarisation (ϕ) of fast shear-wave and the time difference (δt) between the two waves. Previous studies have shown that the polarisation in the crust is generally parallel to the direction of maximum horizontal stress in the area. It is thought that the crustal anisotropy is caused by cracks that are open in the direction parallel to the maximum

Figure 1. Schematic illustration of shear-wave splitting. Shear-waves travelling in an anisotropic medium are separated into fast and slow waves. The parameters that characterise the splitting is the polarization (ϕ) of fast shear-wave and the time difference (δt) between the two waves.
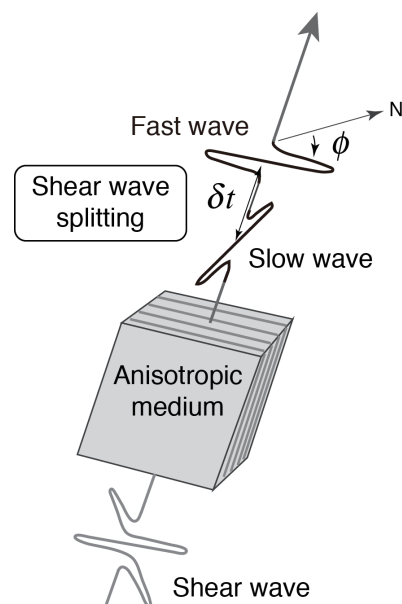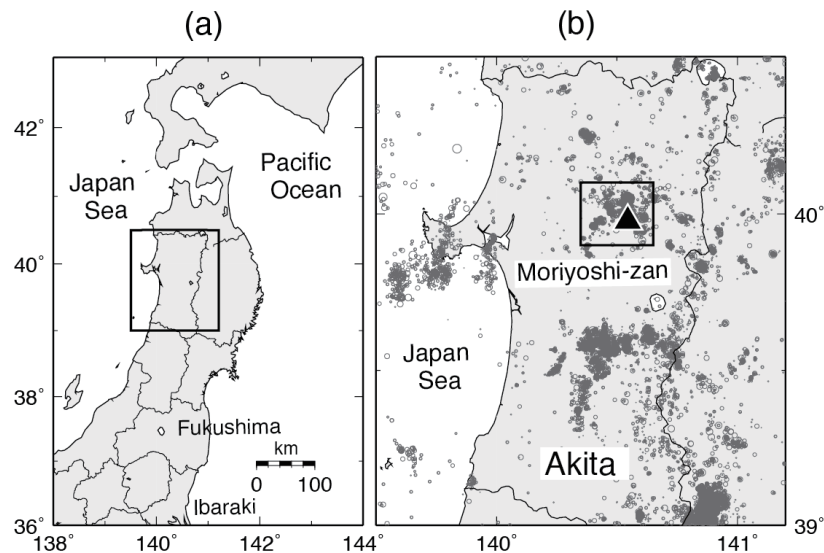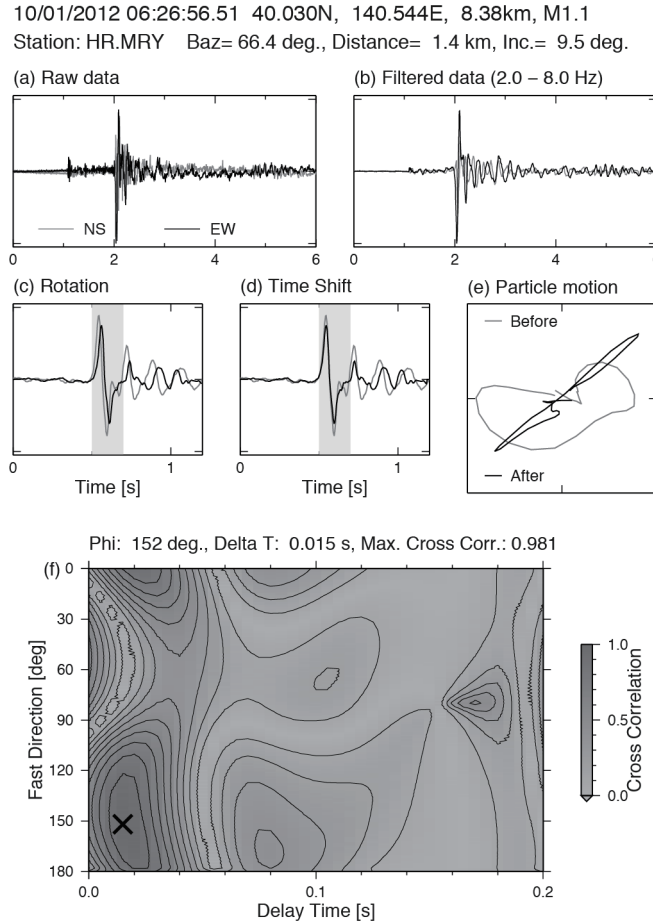
Figure 2. Map of northeastern Japan (a) and Akita prefecture (b) showing the study area. Grey circles in (b) show seismicity after the 2011 Tohoku-oki earthquake. Seismicity in the rectangle in (b) is shown in Figure 3.
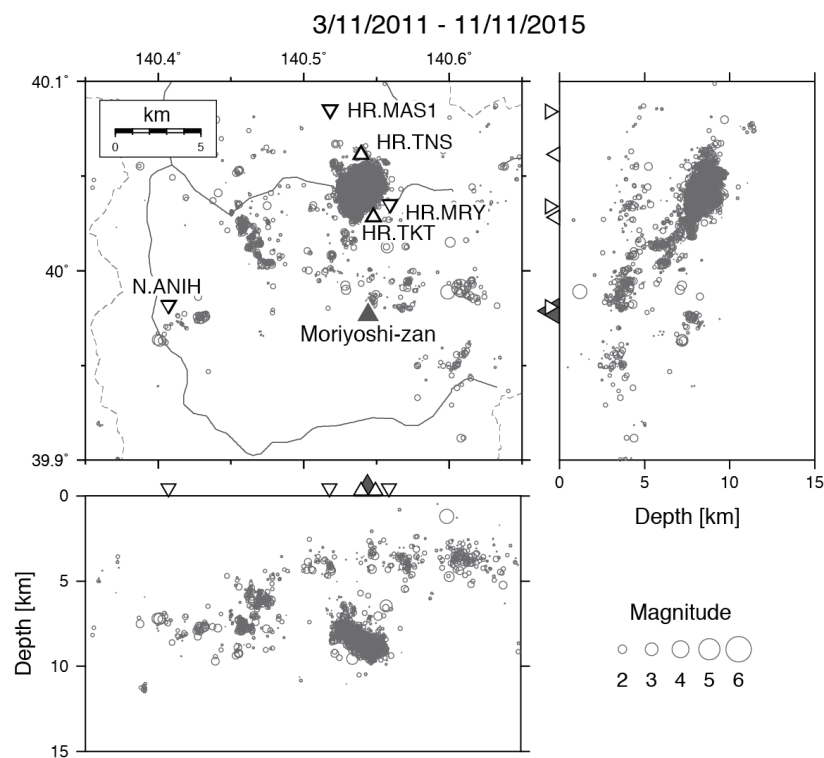
Figure 3. Seismicity in the study area after the Tohoku-oki earthquake. Triangles show the location of stations. N.ANIH is a permanent Hi-net station.

principal stress (e.g., Kaneshima, 1990). Thus the measurement of shear-wave splitting is a useful tool to understand the stress field in an area.

The 2011 Off the Pacific coast of Tohoku (Tohoku-oki) Earthquake (M = 9.0) caused increased seismic activity in many areas in Japan (e.g., Hirose et al., 2011). An area near the Moriyoshi-zan volcano in the Akita Prefecture, northeastern Japan, is one of the areas of triggered seismicity (Figure 2). The seismicity is characterised by a long duration more than five years, migration of hypocentral location, and distinct

10/01/2012 06:26:56.51 40.030N, 140.544E, 8.38km, M1.1
Station: HR.MRY   Baz= 66.4 deg., Distance= 1.4 km, Inc.= 9.5 deg.

(a) Raw data

(b) Filtered data (2.0 – 8.0 Hz)

— NS   — EW

(c) Rotation

(d) Time Shift

(e) Particle motion

— Before

— After

Phi: 152 deg., Delta T: 0.015 s, Max. Cross Corr.: 0.981

(f)

Figure 4. An example of splitting measurement. (a) Raw seismograms of horizontal components. (b) Band-pass filtered seismograms. The passband is 2–8 Hz. (c) Rotated seismograms. Grey rectangle shows the time window for the calculation of cross-correlation coefficients. (d) Rotated and time shifted seismograms. (e) Particle motions before and after the correction of anisotropy. (f) Plot of cross-correlation coefficients on $\phi - \delta t$ plane. The cross marks a pair of ϕ and δt that gives the maximum cross-correlation.

scattered waves that appear after S-wave, which suggests the contribution of geofluid to seismogenesis (Kosuga, 2014). To further invesigate the effect of active seismicity to crustal properties, we analysed shear-wave splitting in the source area of triggered seismicity.

DATA AND METHOD:

We analysed seismograms of more than 2000 earthquakes observed at two temporary stations (HR.MRY and HR.MAS1) near the largest cluster of triggered seismicity (Figure 3) in the period from September 2012 to July 2016. Hypocenres in Figure 3 were relocated by the hypoDD method (Waldhauser and Ellsworth 2000) applied to a combined data set from permanent and above two temporary stations. The sampling frequency of data acquisition is 200 Hz and 100 Hz for the temporary and the permenat stations, respectively. We analysed seismograms with incident angles smaller than 35˚.

We applied a cross-correlation method to obtain the splitting parameters, polarisation (ϕ) of fast shear-wave and the time difference (δt) between the two waves (Figure 4). This method utilises the characteristics that the splitted fast and slow waces are nearly orthogonal with similar shape. We used a grid search to find the
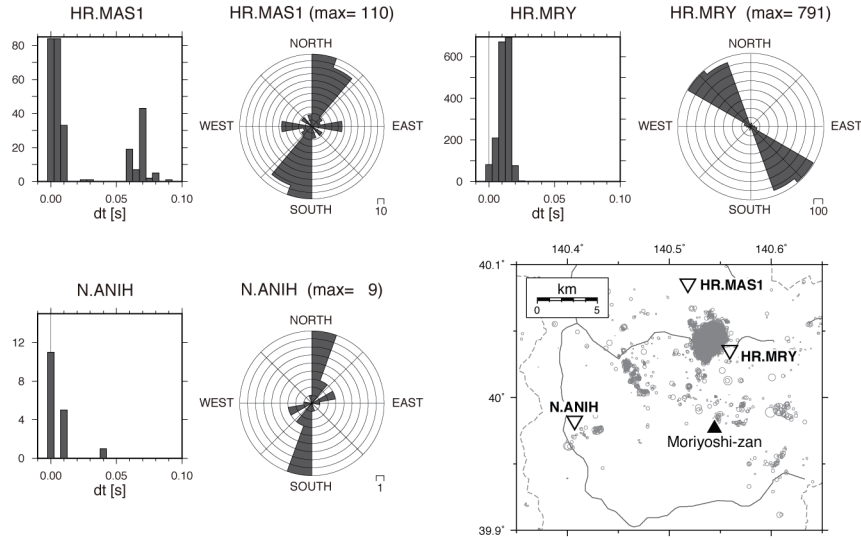
Figure 5. Result of splitting measurement at three stations shown by inverted triangles in the map. Rose diagrams show polarization (ϕ) of fast shear-wave and histograms display the time delay (δt) between the fast and slow waves.
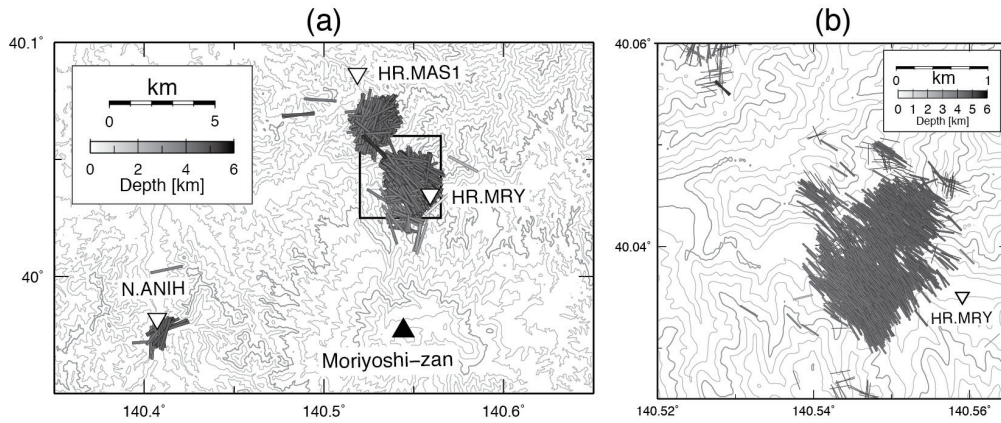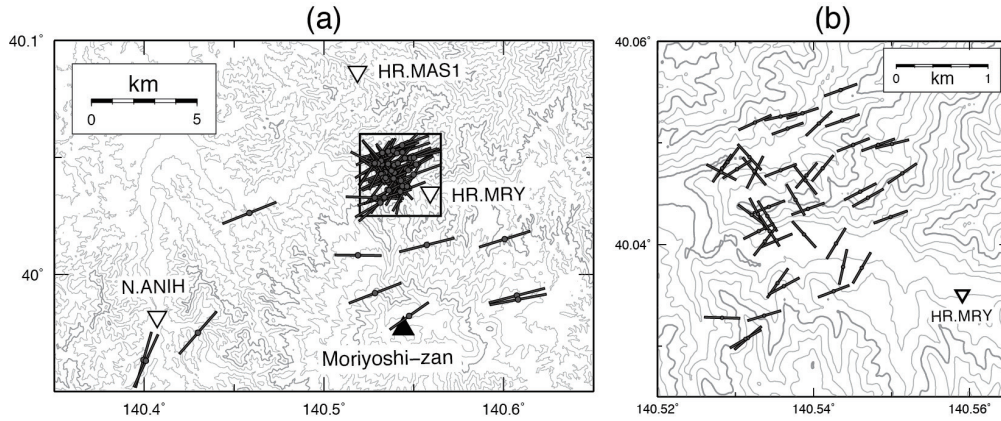

Figure 6. Spatial distribution of polarisation of fast shear-wave (ϕ) plotted at midpoints from hypocenter to station. Grey scale of bars shows the depth of midpoints. (b) is a close-up view in the box in (a).

parameters that give two identical pulses with orthogonal polarisation. Particle motion after correcting for ϕ and δt is linealy polarised (Figure 4(e)).

RESULTS:

Splitting parameters measured at three stations around the major cluster of triggered seismicity are summarised in Figure 5. The result shows clear difference in polarisation parameters between the two temporary stations. The polarisation is NW-SE and the delay time is around 0.015 s at a station (HR.MRY) located above the cluster. On the other hand, the polarisation is nearly N-S and the delay time is close to 0 s at a station (HR.MAS1) situated about 5 km to the north of the cluster. Though the delay time at HR.MRY is quite short (just threefold of sampling interval of data acquisition), rose diagrams of polarisation and histograms of delay time suggest that the difference between the two stations is significant. The slitting parameters at HR.MAS1 have common characteristics to those observed at a permanent station (N.ANIH) located about 10 km WSW of the cluster. Because the ray paths from deeper events to the

Figure 7. Spatial distribution of P-axis of focal mechanism solutions. (b) is a close-up view in the box in (a).
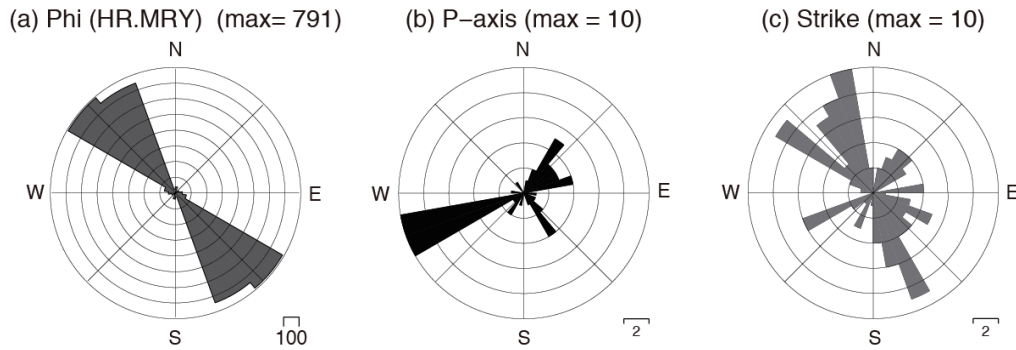

Figure 8. (a) Rose diagrams showing distribution of polarisation of fast wave (ϕ) observed at HR.MRY station located above the main cluster. (b) Trend of P-axis of focal mechanisms. (c) Distribution of strike of two nodal planes of focal mechanisms. Plots of (b) and (c) are for earthquakes shown in Figure 7(a).

HR.MRY traverse vertically the source location of major cluster, the anisotropy observed at the station is probably related to the seismic activity of triggered earthquakes. An observation that supports the idea is that the delay time is slightly larger from deeper earthquakes.

DISCUSSION:

To compare the polarisation of fast shear-wave (Figure 8(a)) with the stress field, we determined focal mechanism solutions in the study area using P-wave first motion, and obtained 59 well constrained solutions. The trend of P-axis of focal mechanisms is mainly ENE-WSW (Figure 7 and Figure 8(b)). The polarisation of fast shear-wave is not parallel to the trend of P-axis.

The above observation is not consistent with many previous crustal splitting measurements in Japan. Previous studies have shown that the polarisation of fast shear-wave is nearly parallel to the maximum horizontal stress (e.g, Hiramatsu et al., 2010; Kaneshima, 1990; Salah et al., 2009; Savage et al., 2016), and has been attributed to cracks that are open in the direction parallel to the maximum stress. However, Iidaka and Obara (2013) showed another example of polarisation that is not consistent with the above idea. The anomalous area is near the border of Fukushima and Ibaraki prefectures (Figure 2) where seismicity was activated by the Tohoku-oki earthquake. To explain the observation, they discussed four models: fracture model, local stress
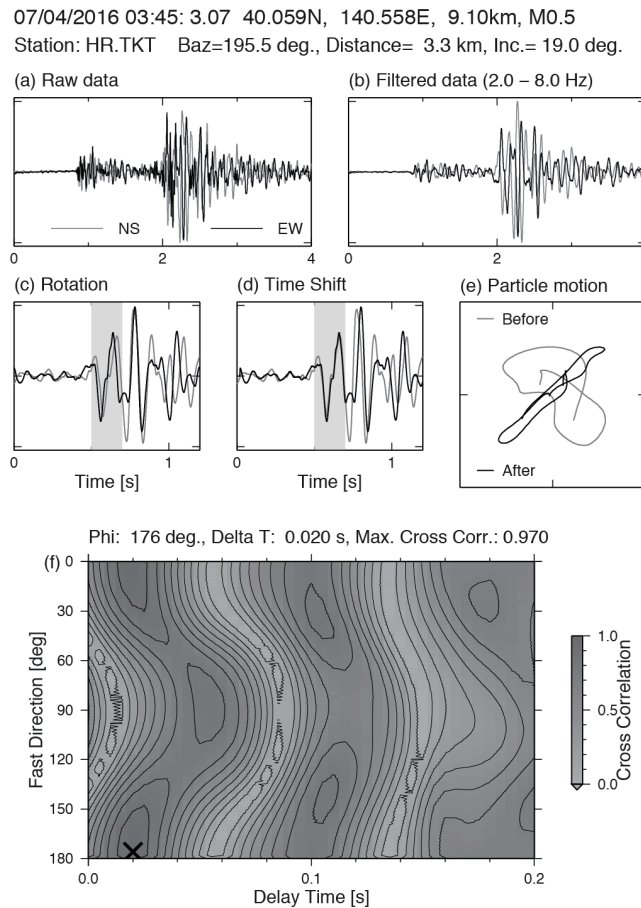
Figure 9. An example of splitting measurement at station HR.TKT in Figure 3. The sampling frequency of data acquisition is 1000 Hz.

model, gravity model, and bending of plate. Kaneshima (1990) proposed three models for crustal anisotropy: stress-induced microcracks, cracks or fractures in the vicinity of active faults with parallel orientation to the fault planes, and intrinsic rock anisotropy resulting from preferred orientation of minerals.

Among the above models, we prefer the fracture model because the porarisation is nearly parallel to the strike of nodal planes of focal mechanisms (Figure 8(c)). Consedering the fact that the seismicity was triggered by the Tohoku-oki earthquake, one simple interpretation is that the fracturing by the triggered seismicity caused the anisotropy in the area.

To obtain additional data to examine our idea, we started new observation from July 2016 by reinstalling temporary stations (HR. MRY and HR.MAS1) at different location (HR.TKT and HR.TNS)(Figure 3). Though the data is insufficient so far, the result from the new observation is generally consistent with the previous result. We also started the observation with a sampling frequency of 1000 Hz to investigate the delay time that is as short as 0.015 s in average. One example of analysis (Figure 9) shows the delay time of 0.020 s, which suggest that the short delay time in Figure 5 is significant. Thus the data from the present observation are useful to examine whether the crustal anisotropy was cause by the seismic activity.

CONCLUSIONS:

We measured shear-wave splitting in one of the source areas of triggered seismicity in the Akita Prefecture, northeastern Japan. Polarisation and delay time at a station above

the active cluster are systematically different from those at stations off the cluster. The polarisation at the former station is not consistent with the trend of P-axis, which suggest that the anisotropy is not stress origin. Since the porarisation is nearly parallel to the strike of nodal planes of focal mechanisms, we expect that the fracturing by the triggered seismicity formed the anisotropy.

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