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Temporal changes in the distinct scattered wave packets and their origin associated with triggered earthquake swarm beneath the Moriyoshi-zan volcano, northeastern Japan

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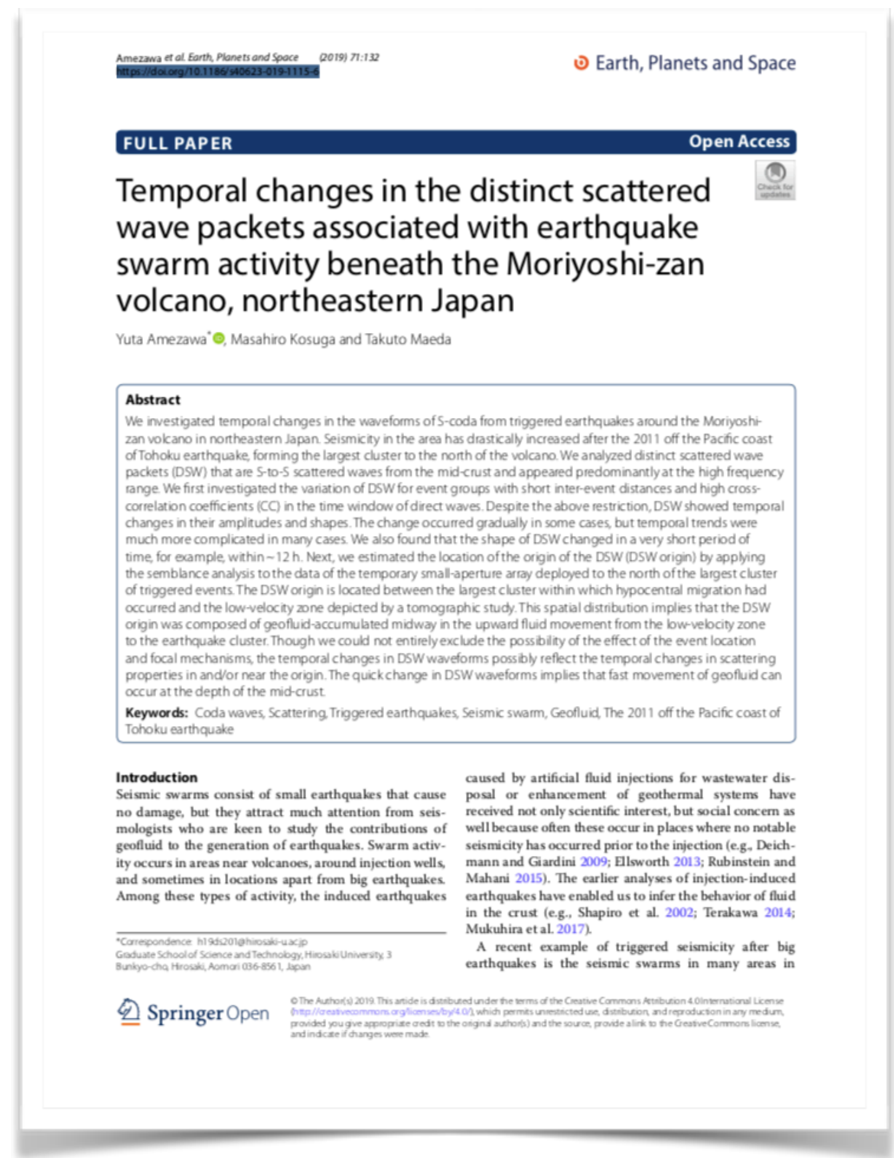
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Temporal changes in the distinct scattered wave packets associated with earthquake swarm activity beneath the Moriyoshi-zan volcano, northeastern Japan

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Abstract
We investigated temporal changes in the waveforms of S-coda from triggered earthquakes around the Moriyoshi-zan volcano in northeastern Japan. Seismicity in the area has drastically increased after the 2011 off the Pacific coast of Tohoku earthquake, forming the largest cluster to the north of the volcano. We analyzed distinct scattered wave packets (DSW) that are S-to-S scattered waves from the mid-crust and appeared predominantly at the high frequency range. We first investigated the variation of DSW for event groups with short inter-event distances and high cross-correlation coefficients (CC) in the time window of direct waves. Despite the above restriction, DSW showed temporal changes in their amplitudes and shapes. The change occurred gradually in some cases, but temporal trends were much more complicated in many cases. We also found that the shape of DSW changed in a very short period of time, for example, within ~12 h. Next, we estimated the location of the origin of the DSW (DSW origin) by applying the semblance analysis to the data of the temporary small-aperture array deployed to the north of the largest cluster of triggered events. The DSW origin is located between the largest cluster within which hypocentral migration had occurred and the low-velocity zone depicted by a tomographic study. This spatial distribution implies that the DSW origin was composed of geofluid-accumulated midway in the upward fluid movement from the low-velocity zone to the earthquake cluster. Though we could not entirely exclude the possibility of the effect of the event location and focal mechanisms, the temporal changes in DSW waveforms possibly reflect the temporal changes in scattering properties in and/or near the origin. The quick change in DSW waveforms implies that fast movement of geofluid can occur at the depth of the mid-crust.

Keywords: Coda waves, Scattering, Triggered earthquakes, Seismic swarm, Geofluid, The 2011 off the Pacific coast of Tohoku earthquake

Introduction
Seismic swarms consist of small earthquakes that cause no damage, but they attract much attention from seismologists who are keen to study the contributions of geofluid to the generation of earthquakes. Swarm activity occurs in areas near volcanoes, around injection wells, and sometimes in locations apart from big earthquakes. Among these types of activity, the induced earthquakes caused by artificial fluid injections for wastewater disposal or enhancement of geothermal systems have received not only scientific interest, but social concern as well because often these occur in places where no notable seismicity has occurred prior to the injection (e.g., Deichmann and Giardini 2009; Ellsworth 2013; Rubinstein and Mahani 2015). The earlier analyses of injection-induced earthquakes have enabled us to infer the behavior of fluid in the crust (e.g., Shapiro et al. 2002; Terakawa 2014; Mukuhira et al. 2017).

A recent example of triggered seismicity after big earthquakes is the seismic swarms in many areas in

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Acknowledgments
We used hypocenter and travel time catalog of the Japan Meteorological Agency and seismic waveforms recorded at Hi-net stations of National Research Institute for Earth Science and Disaster Resilience. We used GISMO (Thompson and Reyes, 2017) for data processing.

Seismic activities triggered by 2011 Tohoku earthquake

Swarm-like seismic activities were triggered by the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0) in many areas (rectangles in the center panel) of Tohoku region.

The red rectangle shows the study area.

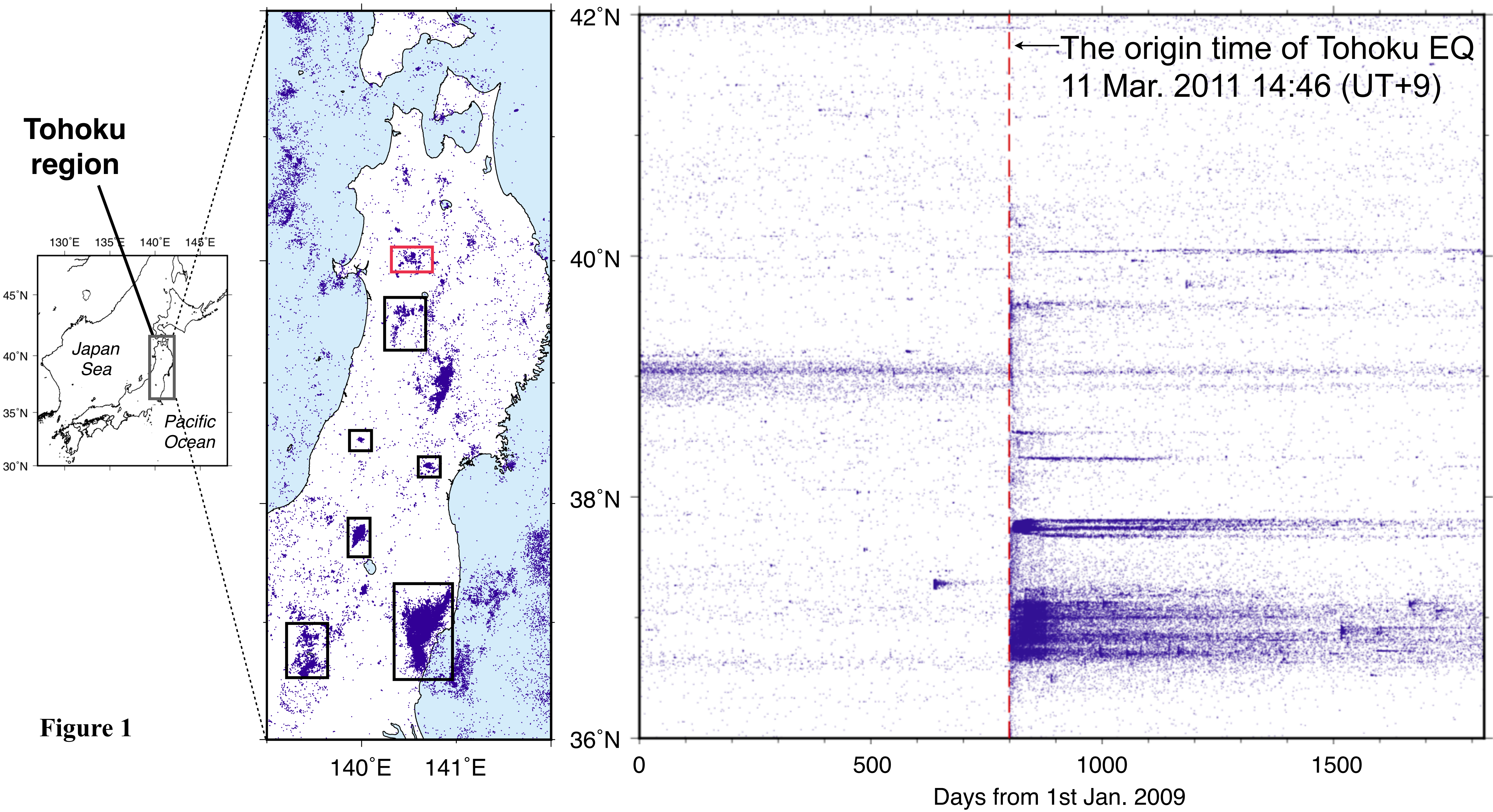


Figure 1

Triggered seismicity around the Moriyoshi-zan volcano

Swarm-like seismicity formed many clusters around the Moriyoshi-zan volcano.

Hypocenter migration was observed in the most massive cluster located to the north of the volcano (black rectangle).

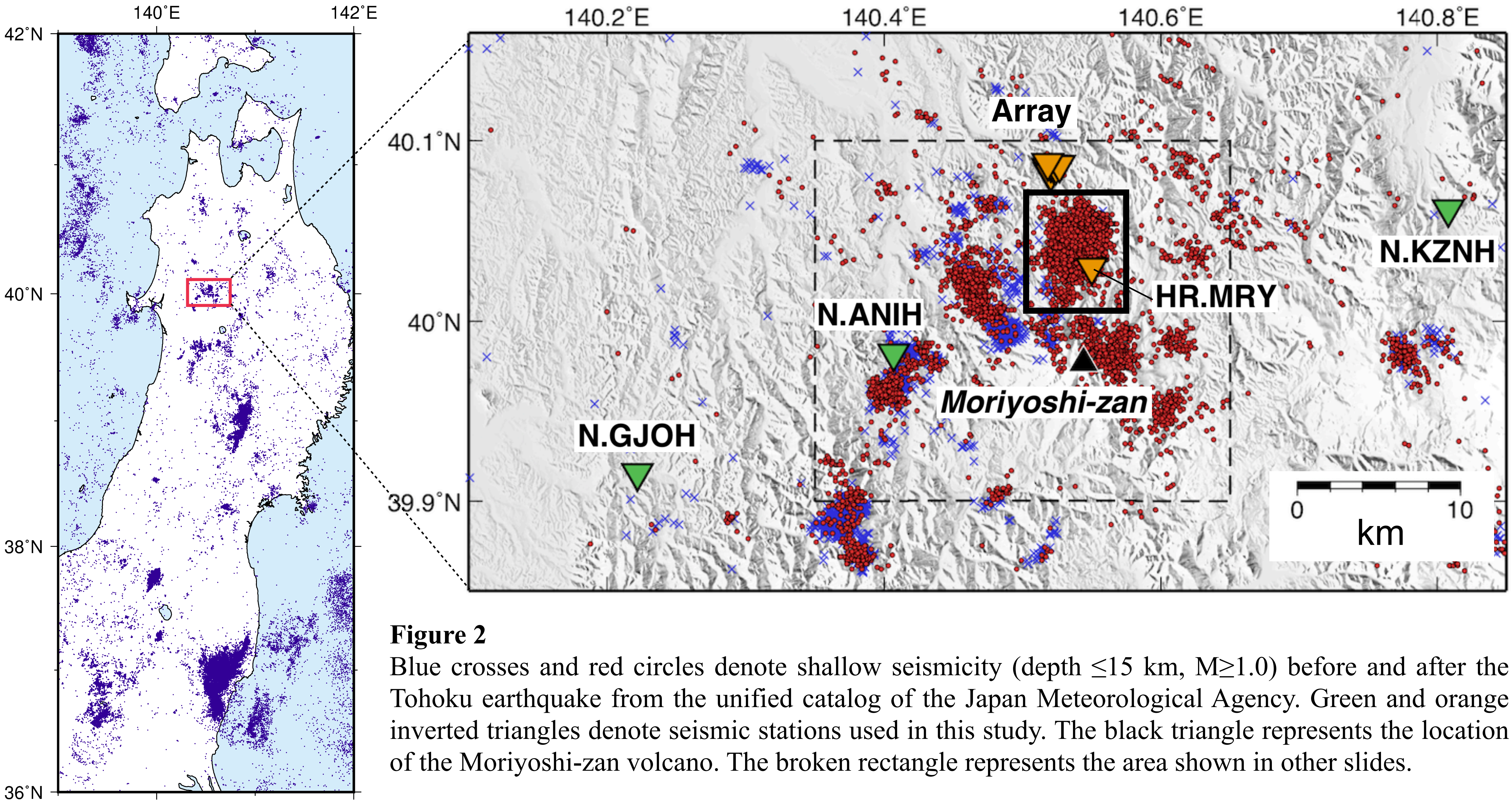


Figure 2
Blue crosses and red circles denote shallow seismicity (depth ≤15 km, M≥1.0) before and after the Tohoku earthquake from the unified catalog of the Japan Meteorological Agency. Green and orange inverted triangles denote seismic stations used in this study. The black triangle represents the location of the Moriyoshi-zan volcano. The broken rectangle represents the area shown in other slides.

Distinct Scattered Wave-packet

S-to-S scattered waves were commonly observed in the seismograms of triggered earthquakes.

In this study, we focus on the origin of these Distinct Scattered Wave-packets (DSW) by

(1) Analyzing the temporal variation of DSW.

(2) Estimating the location of the DSW origin.

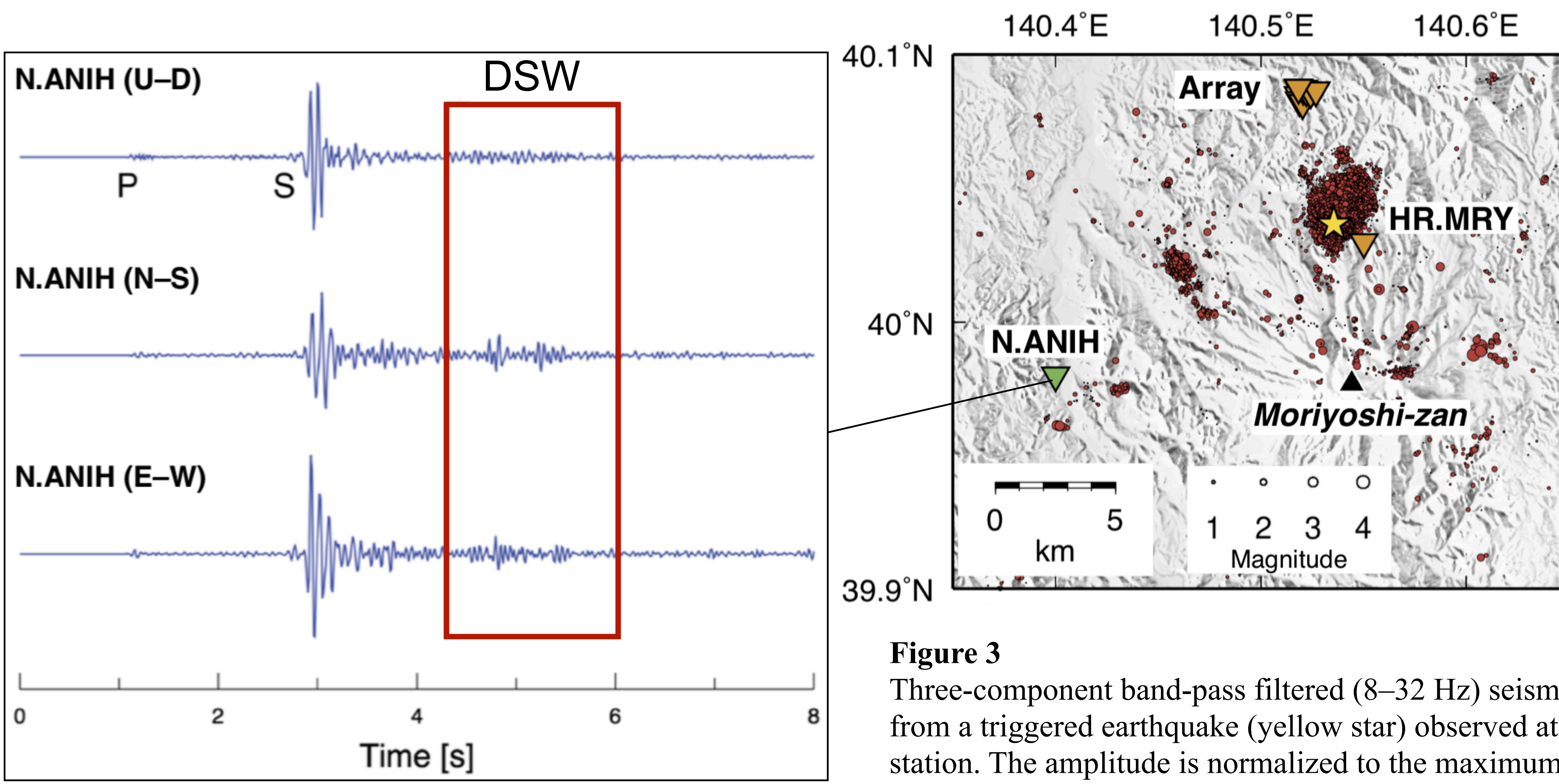


Figure 3
Three-component band-pass filtered (8–32 Hz) seismograms from a triggered earthquake (yellow star) observed at N.ANIH station. The amplitude is normalized to the maximum among the three components.

Temporal changes in DSW

We examined temporal changes in the DSW among events with a similar waveform in the direct P- and S-waves.

The figure (waveform envelope) shows the inter-event variation of DSW.

Change of DSW in a very short time interval implies a rapid change in what produced the DSW (DSW origin).

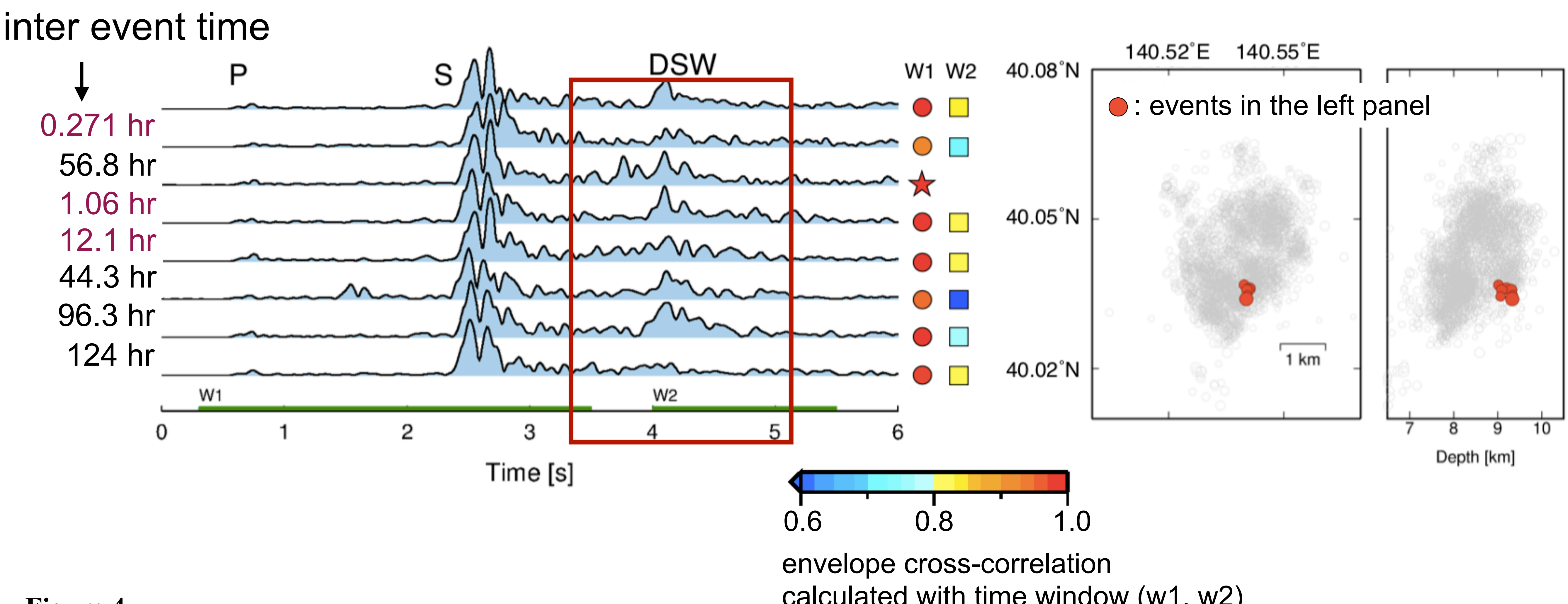


Figure 4

Array observation

We estimated the DSW origin by using data from a seismometer array (right panel) operated during the period from November 2012 to May 2014.

The specification of the array is; the number of sensors: 9, average spacing: 150 m, sensor: three-component 1-Hz seismometer, sampling frequency: 100 Hz, resolution: 24-bit.

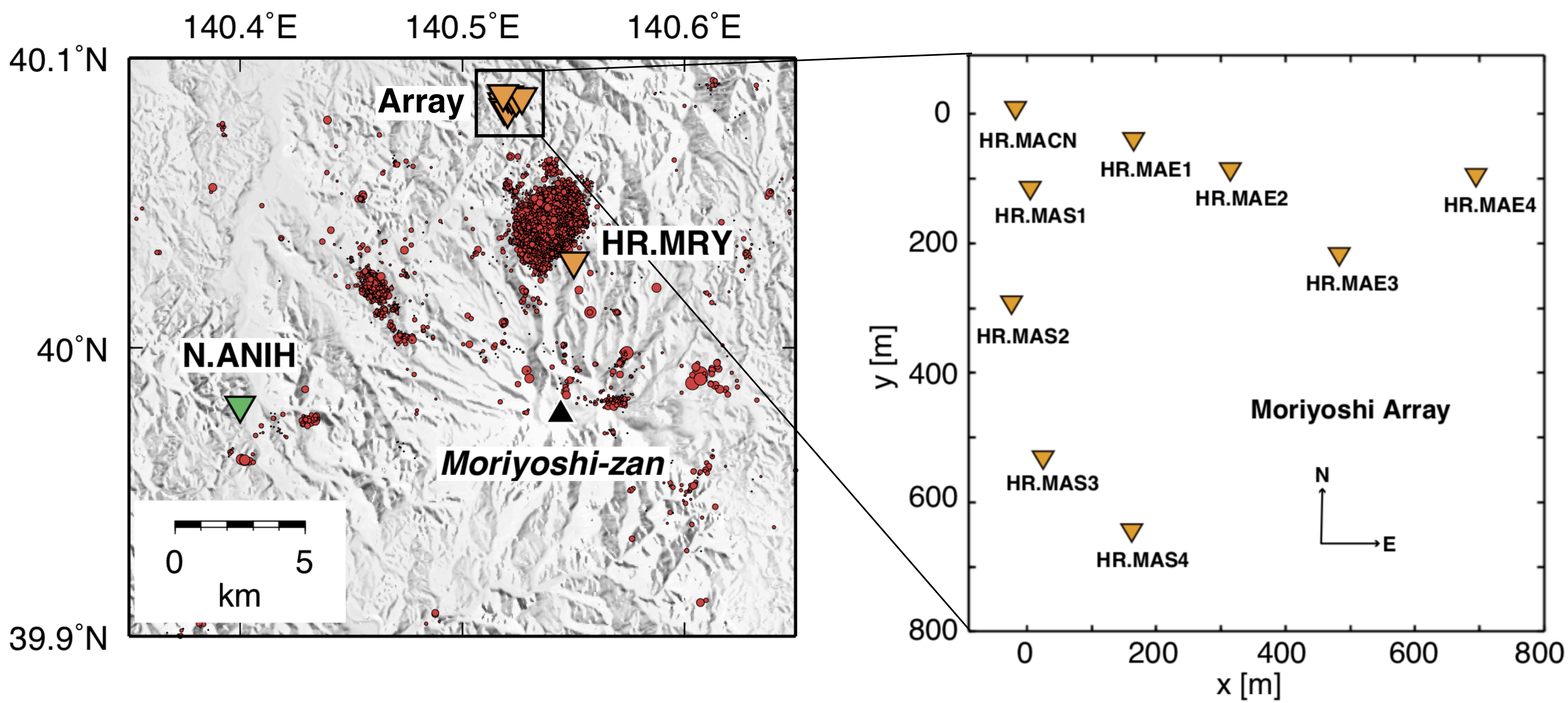


Figure 5

Semblance analysis

We applied the semblance analysis technique (Neidell and Taner, 1971) to DSW.

Estimated back-azimuth and apparent slowness of DSW were ~180°N and ~0.15 s/km, respectively.

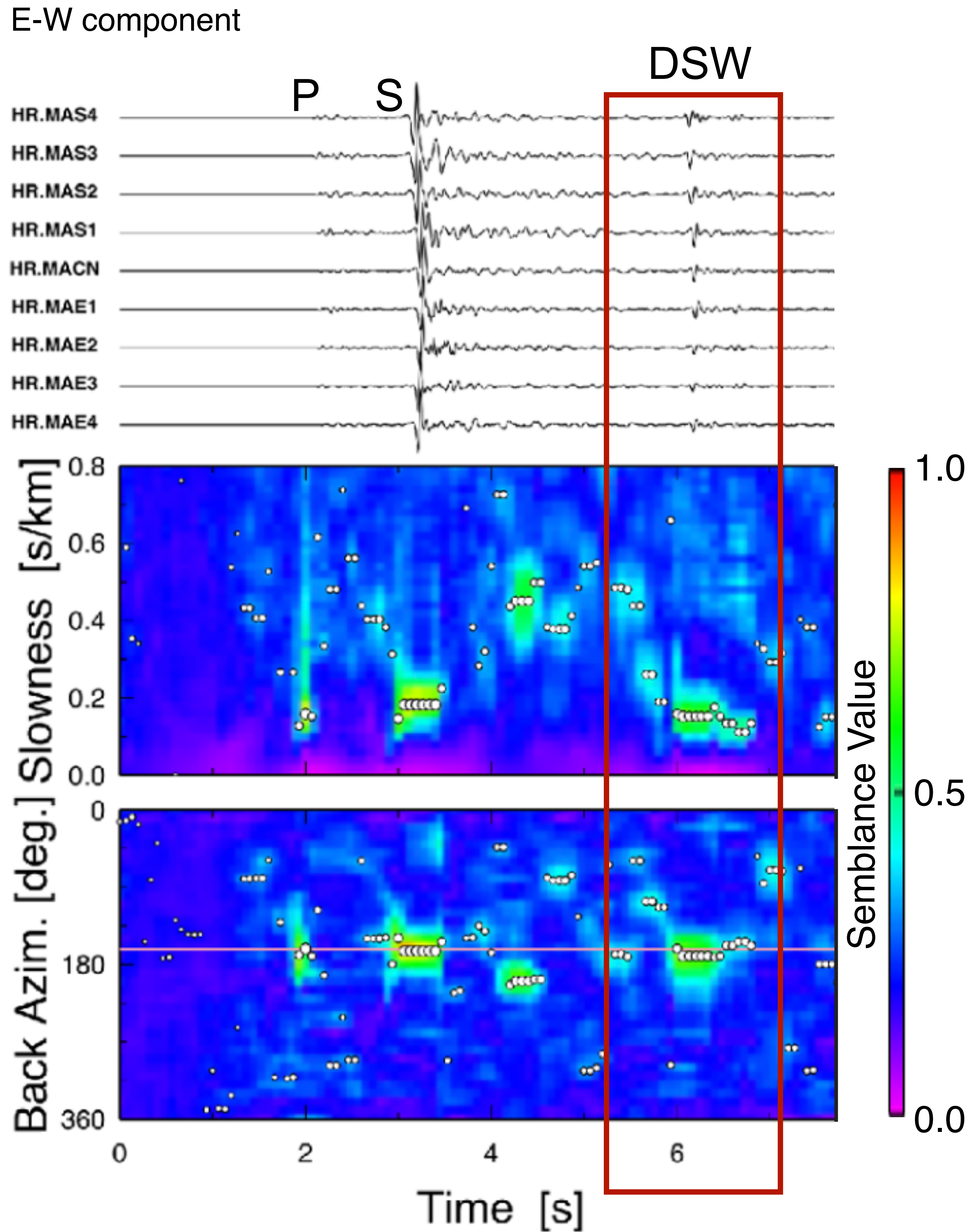
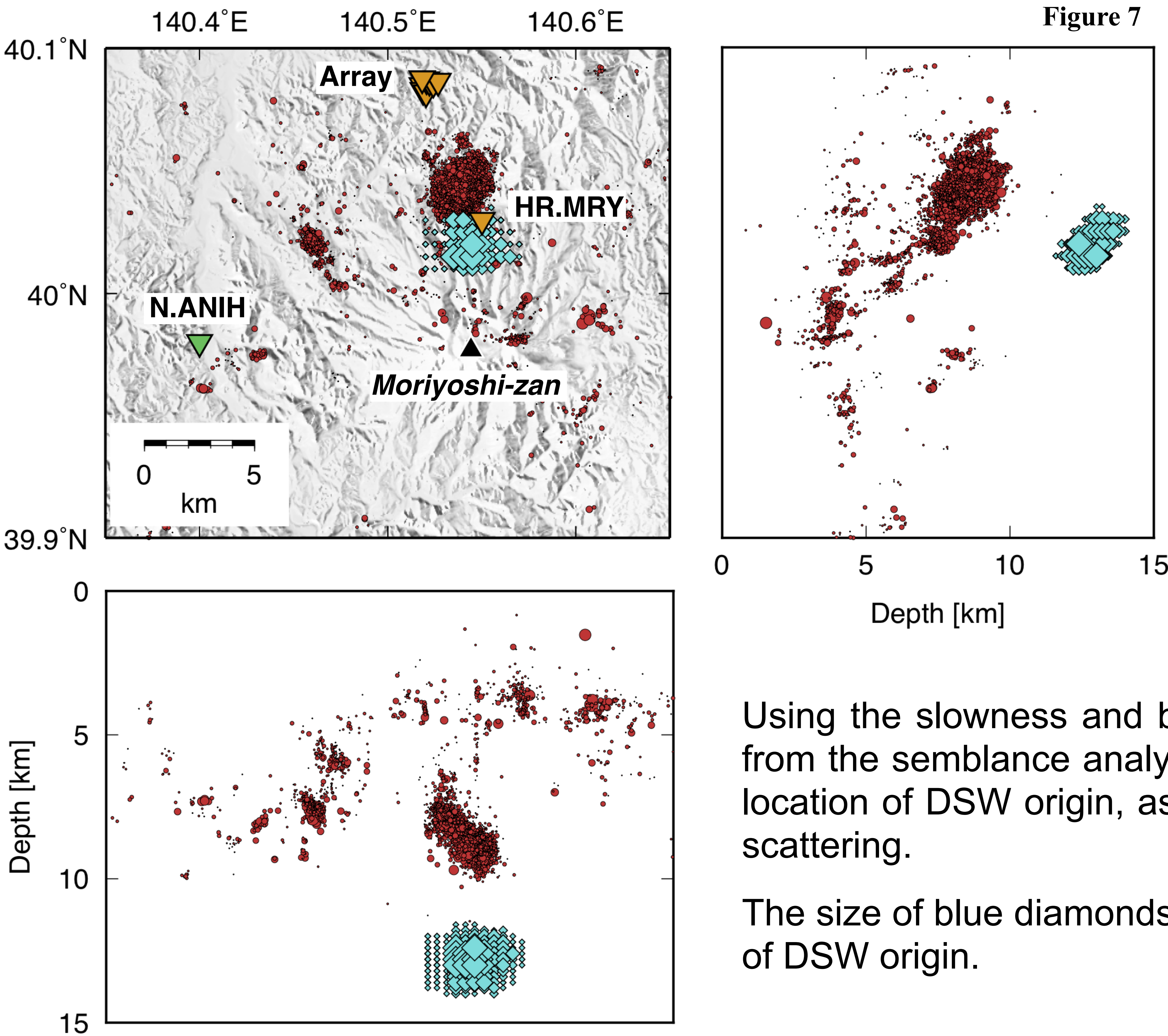


Figure 6
An example of semblance analysis applied to the filtered seismograms in 3–12 Hz band. White circles denote the slowness and back-azimuth with the maximum semblance value in each time step. The pink line in the bottom panel indicates the back-azimuth to the event epicenter.

Estimated location of the DSW origin

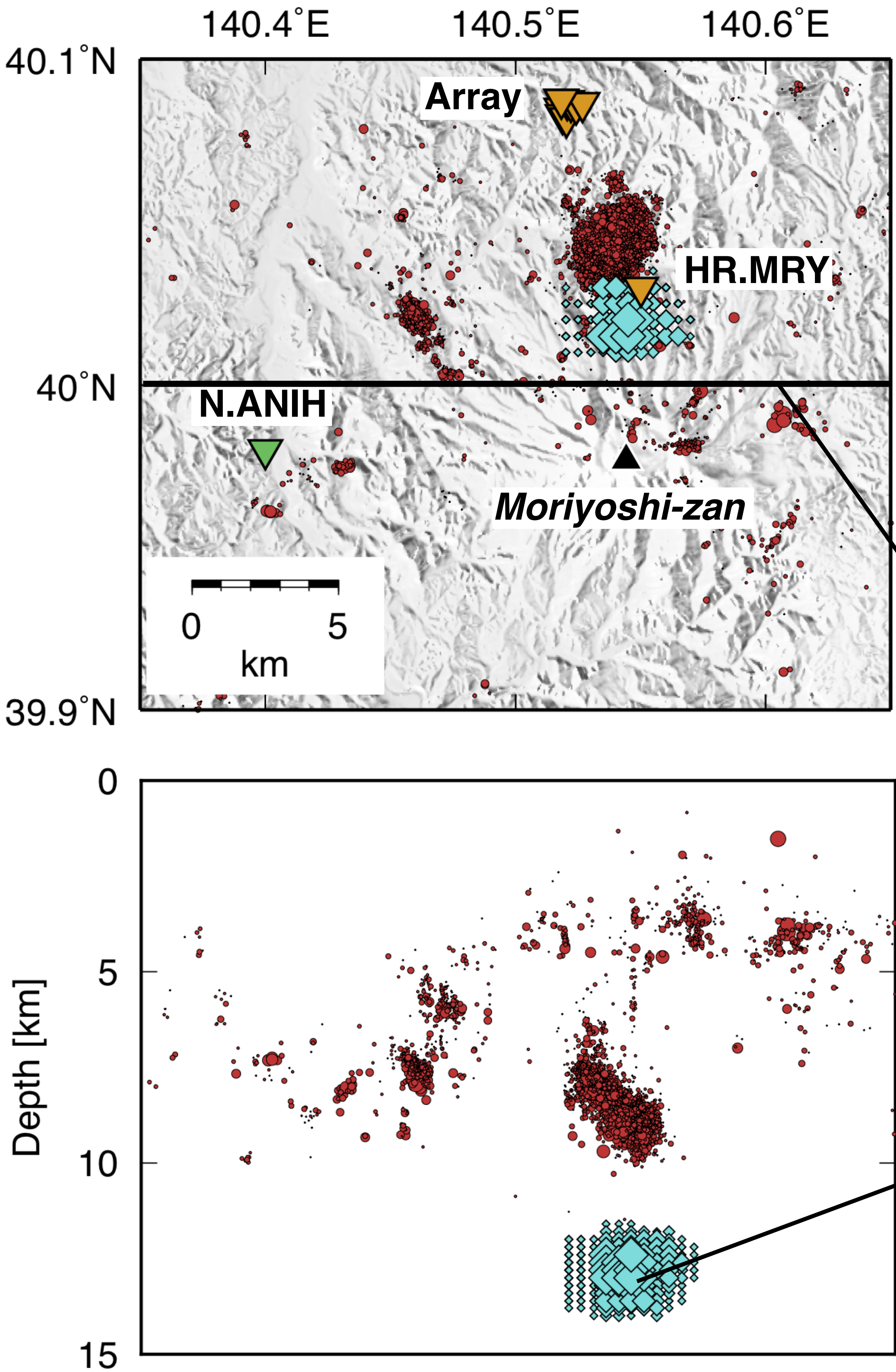
Figure 7



Using the slowness and back-azimuth of DSW from the semblance analysis, we estimated the location of DSW origin, assuming S-to-S single scattering.

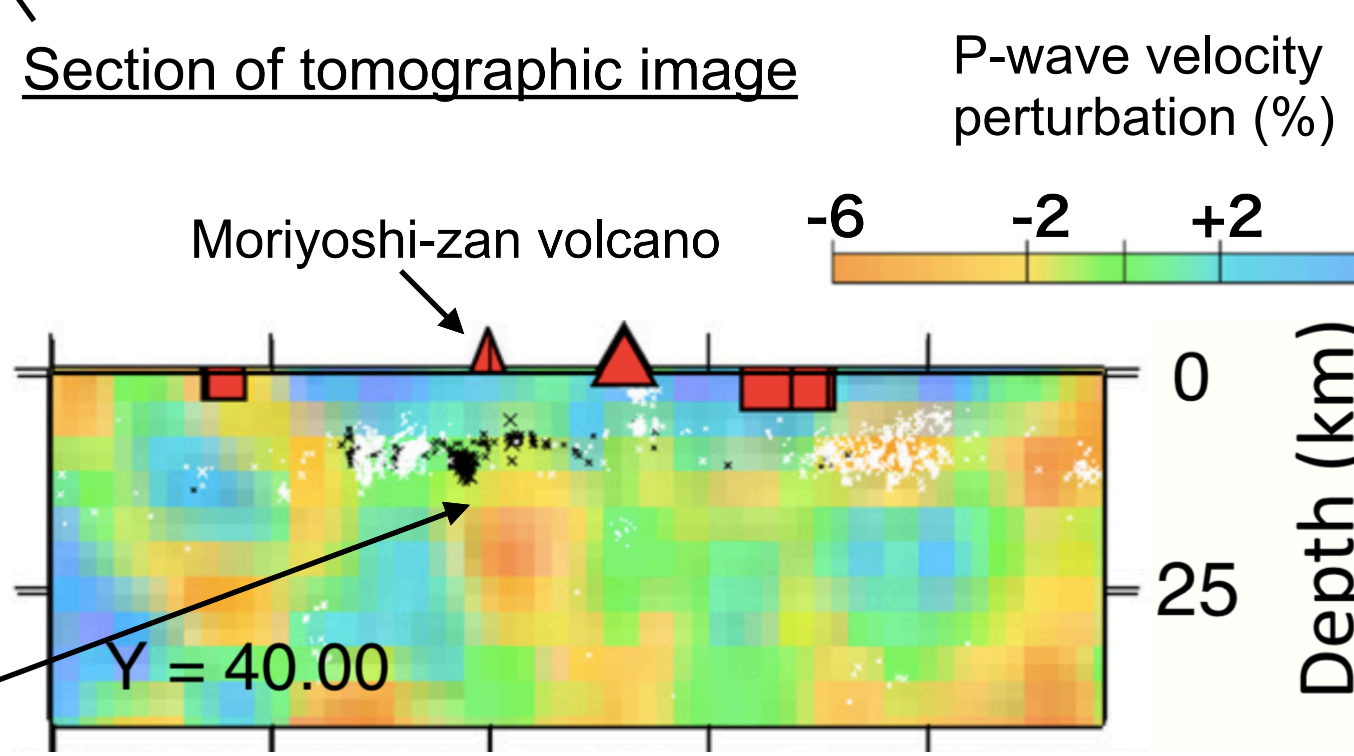
The size of blue diamonds shows the possibility of DSW origin.

Comparison with previous tomographic result



The tomographic study by Okada et al., (2015) shows a low-velocity zone just below the estimated DSW origin.

This zone implies the existence of geofluid near the DSW origin closely located to Quaternary Moriyoshi-zan volcano.



Modified from Okada et al. (2015)

Figure 8

Upward hypocentral migration

Hypocenters in the largest cluster just above the DSW origin migrated upward and away from the origin.

We postulate the DSW origin as a reservoir of geofluid. Stress change due to the great Tohoku earthquake may enhance upward fluid movement that drove swarm activity above the DSW origin.

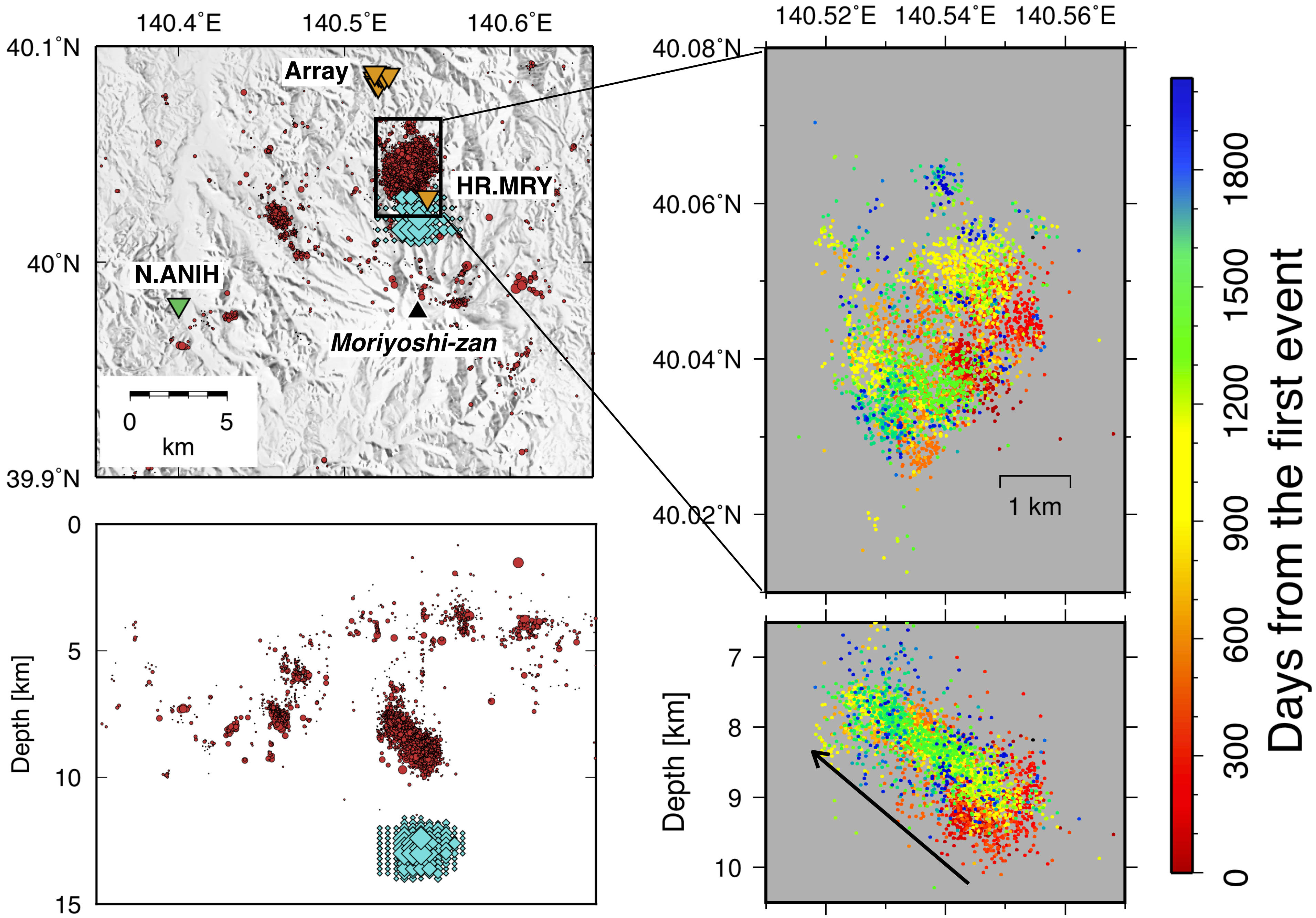


Figure 9

The plausible factors of the temporal changes in the DSW

Summary of Results

Temporal change in DSW waveforms is significant among the events with similar P-and S-waveforms. Sometimes the DSW waveforms changed rapidly.

The DSW origin is located above the low-velocity zone and below the earthquake cluster in which hypocenters migrated upward.

Both the low-velocity zone and hypocentral migration imply the existence of geofluid.

The plausible factors of the temporal changes in the DSW

Temporal changes in DSW can be more plausibly attributed to the path effect rather than the differences in source location or focal mechanisms.

A possible path effect is the temporal change in the attenuation along the ray path and/or scattering properties at the DSW origin.

Rapid temporal changes in DSW suggest a fast movement of a volatile component such as CO_2 in geofluid.

Conclusions

- We investigated the temporal changes in the waveforms of distinct scattered wave packets (DSW) from the triggered earthquakes by the Tohoku earthquake.
- Despite the similarity of direct waves, DSW showed a significant temporal change, sometimes in a very short time interval of ~ 12 hours.
- By applying semblance analysis to array data, we estimated the location of DSW origin to a position beneath the largest seismic cluster in which hypocentral migration was observed.
- A low-velocity zone beneath the DSW origin also suggests the existence of geofluid near the DSW origin.
- We interpret the rapid change in DSW waveforms by a fast movement of geofluid in the DSW origin.

For more information :

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