Catalog of small repeating earthquakes for the Japanese Islands

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Express Letter

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Abstract

Groups of repeating earthquakes, which occur in approximately the same location and possess a similar focal mechanism, have been extracted in various tectonic environments worldwide. Their recurrence interval has been used to estimate the spatiotemporal evolution of aseismic slip along major tectonic boundaries. Furthermore, slight changes between the waveforms of repeating earthquakes have been analyzed to delineate temporal changes in the local seismic velocity structure. Here we construct a long-term catalog of small repeating earthquakes in the central Japan since 1981 and throughout the Japanese Islands since 2001 (2001–2019) based on waveform similarity and relative source locations. Most of the long-duration sequences are located near the strongly coupled areas of the Philippine Sea and Pacific plates as they subduct from the Ryukyu-Nankai-Sagami and Kuril–Japan trenches, respectively. Many of the repeating sequences that occur in shallow crustal environments are short-lived. This repeating earthquake catalog allows us to estimate the slip history along each tectonic boundary. We believe that this and similar catalogs will be useful for future investigations of source processes, temporal slip and stress changes along faults, and local velocity structures, thereby providing new insights into earthquake generation mechanisms.

Introduction

Groups of similar earthquakes and repeating earthquakes have been detected in various tectonic environments worldwide (Uchida and Bürgmann, 2019). Similar earthquakes are defined as events possessing similar waveforms, and repeating earthquakes consist of similar earthquakes that occur in approximately the same location and possess nearly identical focal mechanisms. Many repeating earthquakes occur regularly at plate boundaries, whereas some occur as short-lived burst-type activity in shallow inland crustal environments (e.g., Igarashi, 2010).

Repeating earthquakes are useful for understanding earthquake generation mechanisms, monitoring the local structural changes, and testing the earthquake predictability. Both the spatial distribution and temporal changes in their source processes have been revealed via analyses of repeating earthquakes (e.g., Okada et al., 2003; Ariyoshi et al., 2014). The earthquake repetition over a long period is used to estimate the spatiotemporal evolution of interplate aseismic slip (e.g., Igarashi, 2010; Kato et al., 2016) and test the earthquake predictability (e.g., Uchida and Bürgmann, 2019). Slight changes among the waveforms of repeating earthquakes often indicate temporal changes in the local seismic structure (e.g., Niu et al., 2003; Rubinstein et al., 2007; Taira et al., 2009; Tkalčić et al., 2013). The matched filter technique can detect frequent repetitive sources embedded in the seismic record, even if the waveforms have undergone moderate changes, and thereby improves the completeness of the hypocenter catalog (e.g., Kato and Nakagawa, 2014). Nearby earthquakes can also be efficiently extracted from high-seismicity areas where many of the earthquakes possess similar waveforms.

Early approaches to similar earthquake extraction were based on the visual inspection of seismogram records (e.g., Omori, 1905; McEvilly and Casaday, 1967; Stauder and Ryall, 1967; Tsujiura, 1973;

Hamaguchi and Hasegawa, 1975; Geller and Mueller, 1980). Their recurrence at approximately the same location was investigated using other information, such as the S-P time, which is the time difference between the P- and S-wave arrivals (e.g., Hamaguchi and Hasegawa, 1975), and the source size, which is estimated from the corner frequency (e.g., Geller and Mueller, 1980).

Large-scale analyses of similar earthquakes based on waveform similarity have been made possible by the accumulation of vast digital seismogram data volumes and advanced computing capabilities. Aster and Scott (1993) investigated the features related to waveform similarity using 4569 seismic records from ten seismic stations in the ANZA network (Southern California, USA) over a 9.5-year period (October 1, 1982 to April 14, 1992). Those authors analyzed 1,121,332 earthquake pairs with an inter-event distance of ≤10 km, and identified similar earthquakes when the earthquake pairs had a median cross-correlation coefficient of ≥0.725. They detected 290 similar earthquake sequences (1255 events) based on the threshold.

Schaff and Richards (2004) extracted similar earthquakes from ~14,000 earthquakes that occurred in China between 1985 and 2000 using ~130,000 waveforms that were recorded at 115 neighboring seismic stations. The maximum interevent distance was 150 km, resulting in ~1,200,000 analyzed earthquake pairs. Similar earthquakes were identified when the cross-correlation coefficient between an earthquake pair was ≥0.8 at a given station. They detected 494 similar earthquake sequences (1303 events).

Igarashi (2010) identified similar earthquakes throughout the Japanese Islands using waveforms obtained from a nationwide seismic network over an eight-year period (January 2002 to December 2009). He analyzed 428,156,998 earthquake pairs using the waveforms from 168,425 earthquakes that were recorded by up to 1105 stations. Similar earthquakes were identified when the cross-correlation coefficient was ≥0.95 at two or more stations. This paper detected 2356 similar earthquake sequences (6638 events).

Dodge and Walter (2015) extracted similar earthquakes using global seismic data from the Lawrence Livermore National Laboratory waveform database over a 43-year period (1970–2013). They analyzed ~310,000,000 waveforms from 3,745,879 events and 6266 seismic stations, with ~1,485,000,000 event pairs possessing an inter-event distance of ≤50 km. Similar earthquakes were determined when the correlation coefficient was ≥0.6 at any station. The number of events exceeding the threshold was 14.5% of the total (542,405 events).

Several studies have investigated the degree of colocation or overlap between the source areas of each earthquake pair to accurately identify repeating earthquakes. For example, Lees (1998) used the travel time difference obtained via cross-spectral and coherence calculations. Chen et al. (2008) also validated the overlap between two source areas by imposing the following conditions: the cross-correlation coefficient is ≥0.85 and the S-P time is <0.012 s. Li et al. (2011) extracted candidates for repeating earthquakes when the relative distance calculated from the S-P differential times and assumed velocity structure was less than the rupture dimensions of each earthquake.

Here we update the similar earthquake catalog that was constructed by Igarashi (2010) to analyze the long-term earthquake activity throughout the Japanese Islands that is associated with the subducting Pacific and Philippine Sea plates, and overriding Amur and Okhostk plates. Furthermore, we improve this small repeating earthquake catalog by imposing the colocation or overlapping constraints onto the rupture areas of each similar earthquake pair. We then compare these two catalogs in terms of the average slip-rate distribution along the entire Japanese Islands.

Methods

We basically followed the same procedure as proposed by Igarashi (2010) for detecting similar earthquakes. This procedure calculates the cross-correlation coefficients between the observed seismograms at each station. We first picked up all of the earthquake pairs with an epicentral separation of ≤20 km. The time window included waveform data from the P-wave onset to 3 s after the direct S-wave arrival, with the maximum time window duration and epicentral distance set to 50 s and 400 km, respectively. We then bandpass-filtered the waveforms prior to the cross-correlation coefficient calculation using 1–4, 2–8, and 4–16 Hz passbands. Similarities are identified in 1–4 Hz passband for M≥3 earthquakes, in 1–4 and 2–8 Hz passbands for M2.5-2.9 earthquakes, and at all passbands for M<2.5 earthquakes. The selected passbands are set as the quarter wavelength of the S wave, which roughly corresponds to the source size of the analyzed earthquake, as shown in Igarashi et al. (2003). A candidate for a repeating pair is selected when their cross-correlation coefficients are ≥0.95 at two or more stations.

The colocation or overlap of the source areas must be confirmed to identify repeating earthquakes. However, the resolution of the source process analysis depends on the station network geometry, fault plane setting, assumed seismic velocity structure, and analysis method. The source size depends on the assumed stress drop. Most interplate earthquakes occur in the subduction zone offshore of the Japanese Islands, which makes it difficult to determine the exact source process such as hypocenter and main moment release area using the current land-based seismic network. Therefore, we searched for pairs that satisfied both the waveform similarity and small S-P differential time thresholds to extract the repeating earthquakes, as proposed in previous studies (Chen et al., 2008; Li et al., 2011).

We computed the S-P differential times for the earthquake pairs that satisfied the above-mentioned waveform similarity criterion. A 2-s time window was used for both the P- and S-arrival computations. We assumed a circular patch model with a constant stress drop of 3 MPa to calculate the radius of each event. We identified a repeating pair when the median value of the S-P differential time between the event pairs for stations with the cross-correlation coefficients of ≥0.6 was less than the time difference estimated from the source radii and P- and S-wave velocity structures at the hypocentral depths of the event pair. Events were grouped into the same repeating earthquake sequence when multiple pairs shared the same event. Figure 1 shows an example of a repeating earthquake sequence identified in the present study. Note that the waveforms of these repeating earthquakes are very similar to each other, despite the occurrence of the Mw 9.0 Tohoku-Oki Earthquake in March 2011. The normalized amplitude shown on the right does not correspond to the magnitude shown on the left. This may be due to the magnitude uncertainty and/or the difference in frequency characteristics of each earthquake.

The observed repeating earthquake patterns can be roughly classified as either continual- or burst-type events (Igarashi et al., 2003). Continual-type events occur at an approximately constant recurrence interval throughout the analyzed period, whereas burst-type events only occur over short periods, generally spanning from one day to several months.

Data

The seismogram records used in this analysis were selected from the seismic stations operated by the National Research Institute for Earth Science and Disaster Resilience (NIED) (National Research Institute for Earth Science and Disaster Resilience, 2019), Japan Meteorological Agency (JMA), and Earthquake Research Institute (ERI) of the University of Tokyo. We used vertical component seismograms from $M \geq 1.5$ earthquakes in the JMA hypocenter catalog for the period from July 11, 2000 to December 18, 2019. The hypocenter information reported by ERI was used to extend the analysis period to July 18, 1981. We computed the cross-correlation functions for ~39 billion earthquake pairs from 1523 seismic stations and 1,080,664 events. Figure 2 shows the starting time of our analysis across the Japanese Islands. The ERI regional earthquake catalog allowed us to extend the central Japan analysis to the 1980s. The target area has continued to expand since the start of the study period due to the addition of new seismic stations and instrument upgrades to the seismic networks, with the seismic networks spanning the entire Japanese Islands since 2001.

Results

The spatial distribution of 11,677 similar earthquake sequences (41,735 events), which were extracted using the cross-correlation coefficient information, is shown in Figure 3a, and the spatial distribution of 10,019 repeating earthquake sequences (36,029 events), which were verified by their small S-P difference times, is shown in Figure 3b. These catalogs can be provided in the additional files.

The spatial distribution of similar and repeating earthquakes is basically the same as that in Igarashi (2010). Most of the long-duration, continual-type sequences are located in inter-plate coupling areas on the Philippine Sea and Pacific plates as they subduct from the Ryukyu-Nankai-Sagami and Kuril–Japan trenches, respectively. The focal mechanisms for most of the continual-type sequences, which are derived from the F-net moment tensor solutions (Fukuyama et al., 1998), indicate low-angle thrust faulting and reveal the dip angles of the plate boundaries. Conversely, many of the inland shallow sequences are short-lived (≤1 day).

Approximately 86% of the similar earthquakes match with repeating earthquakes. Approximately 54% of the earthquakes (3067 events) that were excluded from the repeating earthquake catalog occurred at shallow crustal depths beneath the Japanese Islands. Earthquakes that either occurred immediately after large earthquakes or were detected in poor observational environments due to low signal-to-noise ratios also tended to be excluded from the repeating earthquake catalog. While ~42% of the excluded earthquakes (2389 events) occurred before 2001, the repeating earthquakes during this early period (1981–2000) with limited seismic network coverage accounted for only ~7% of the repeating earthquake catalog, indicating that the excluded earthquakes do not have a strong impact on the overall behavior of repeating earthquakes in the region. No noticeable magnitude dependence was found between similar and repeating earthquake catalogs. In M1.5-1.9, approximately 84% of the similar earthquakes match with repeating earthquakes.

Discussion

We have constructed two earthquake catalogs based on waveform similarity. One could argue that there would be a systematic difference between the interplate aseismic slip and/or slip rate estimated from the two catalogs. Therefore, we investigated the differences in the spatial distribution of slip rate between the catalogs. We basically applied the same procedure as that used by Igarashi (2010) to each catalog to estimate the interplate slip rate. The amount of slip for each event was calculated from the relationship between seismic moment and slip, as proposed by Nadeau and Johnson (1998). The scalar moment was converted from magnitude using a magnitude–scalar moment relationship (Hanks and Kanamori, 1979). We assumed that the slip rate within each interseismic period of repeating sequences was constant, based on the slip-predictable earthquake model (e.g., Shimazaki and Nakata, 1980). The average slip rate was extrapolated when either the previous or subsequent earthquake would have occurred outside of the analysis period.

Figures 4a and 4d show the spatial distributions of the average slip rates for the 19-year period since 2001 based on the similar earthquake catalog, and Figures 4b and 4e show the corresponding results based on the repeating earthquake catalog. Figures 4c and 4f show the differences in the estimated average slip rates between the two catalogs. While the slip-rate changes in some areas are due to a decrease in the number of extracted repetitive earthquakes, the relative lateral slip-rate variations are quite similar between the two sets of results. Furthermore, there are only minor absolute differences in the slip rates (generally <10 mm/yr). Therefore, the differences between the two catalogs are not significant enough to change the interpretation on the interplate aseismic slip of Igarashi (2010), which is based on slip rates estimated from a similar earthquake catalog.

Figure 4 extends the time series for determining the average slip rates across the Japanese Islands from 2010 (figure 2 of Igarashi, 2010) to 2019, thereby allowing temporal changes in the average slip rates to be inferred. The areas where large earthquakes did not occur during the analysis period are illuminated by either large slip deficits during the interseismic periods or a lack of slip areas. The slip rate has decreased around the source region of the 2003 Mw 8.0 Tokachi-Oki Earthquake due to the decay of the afterslip signal. The slip rates in many areas are lower than those reported by Igarashi (2010), possibly reflecting the extended time series and better-constrained recurrence intervals. However, our results reiterate the observation of Igarashi (2010) that it is not yet possible to determine the slip-rate distribution along most of the Nankai Trough and the shallow depths of the Kuril Trench where no similar/repeating earthquakes have been detected to date.

The area of large coseismic slip relating to the 2011 Tohoku-Oki Earthquake (Kato and Igarashi, 2012), as indicated by the red line in Figures 4a and 4b, is another area that did not host significant aseismic slip. Conversely, the slip rates of the surrounding areas have been higher due to the afterslip induced by the Tohoku-Oki Earthquake; the higher slip rates in the downdip (deeper) extension of the large area of coseismic slip are particularly notable. This slip acceleration on the Pacific Plate boundary extends from ~40°N to the southern limit of the Japan Trench. The slip rate also increased locally at the northeastern edge of the Philippine Sea Plate.

Similar earthquakes have not been detected during the early time period in several regions (e.g., 2000-2003 in Ryukyu Islands) despite the available seismic waveform records. The extraction of similar earthquakes may be affected by temporal changes in the frictional properties of the source region, the velocity structure along the propagation path, and the equipment at each seismic station. The similar earthquakes extracted in this analysis account for only ~4% of the total number of analyzed earthquakes. We should therefore investigate the causes of the variations in the correlation coefficient values of adjacent earthquakes in greater detail.

The repeating earthquake sequences at the plate boundary are considered to be caused by repeated slip on small asperities that are surrounded by aseismic slip (creeping) areas (e.g., Chen and Lapusta, 2009). This indicates that we can monitor fault creep at depth using waveform data. However, the interactions between repeating earthquakes and other earthquakes (e.g., static and dynamic stress transfer) are poorly understood. Furthermore, our analysis period is much shorter than the recurrence interval of large earthquakes. Long-term seismic monitoring networks are therefore essential to advancing our understanding of complex slip behavior on faults.

The present analysis and compilation of similar/repeating earthquakes throughout Japan is ongoing, with the waveform and hypocenter information, along with the similar/repeating earthquake results, being updated daily and stored in our detection system. The cross-correlation coefficient calculation can be optimized by using precisely determined hypocenters and incorporating the information on existing similar earthquakes. Relative hypocenter information would improve the accuracy of the extracted similar earthquakes and provide more detailed earthquake recurrence characteristics. It is therefore desirable to use precisely determined hypocenters in the detection system in the future. At that timing, we must consider how to maintain event files from multiple catalogs and links to this information. A more detailed investigation of the operational conditions of the seismic stations and their acquired waveforms is also needed for the efficient detection of repeating earthquakes.

We believe that these similar/repeating earthquake catalogs will be invaluable in future diagnoses of the source processes, slip, and stress changes along faults, local structural changes, and test of earthquake predictability, thereby providing further insights into complex fault behavior.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations

ERI: Earthquake Research Institute; JMA: Japan Meteorological Agency; NIED: National Research Institute for Earth Science and Disaster Resilience

Availability of data and materials

The waveform data used in this study are available from NIED (https://hinetwww11.bosai.go.jp/auth/?LANG=en), JMA (http://www.data.jma.go.jp/svd/eqev/data/bulletin/index_e.html, http://www.data.jma.go.jp/svd/eqev/data/daily_map/index.html), and ERI (http://tkypub.eri.u-tokyo.ac.jp/harvest). The hypocenter catalogs used in this study are available from JMA (http://www.data.jma.go.jp/svd/eqev/data/bulletin/index_e.html, http://www.data.jma.go.jp/svd/eqev/data/daily_map/index.html).

Competing interests

The author declares no competing interests.

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Author's contributions

TI conducted the data analysis and interpretation of the results, and drafted the manuscript.

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Figures

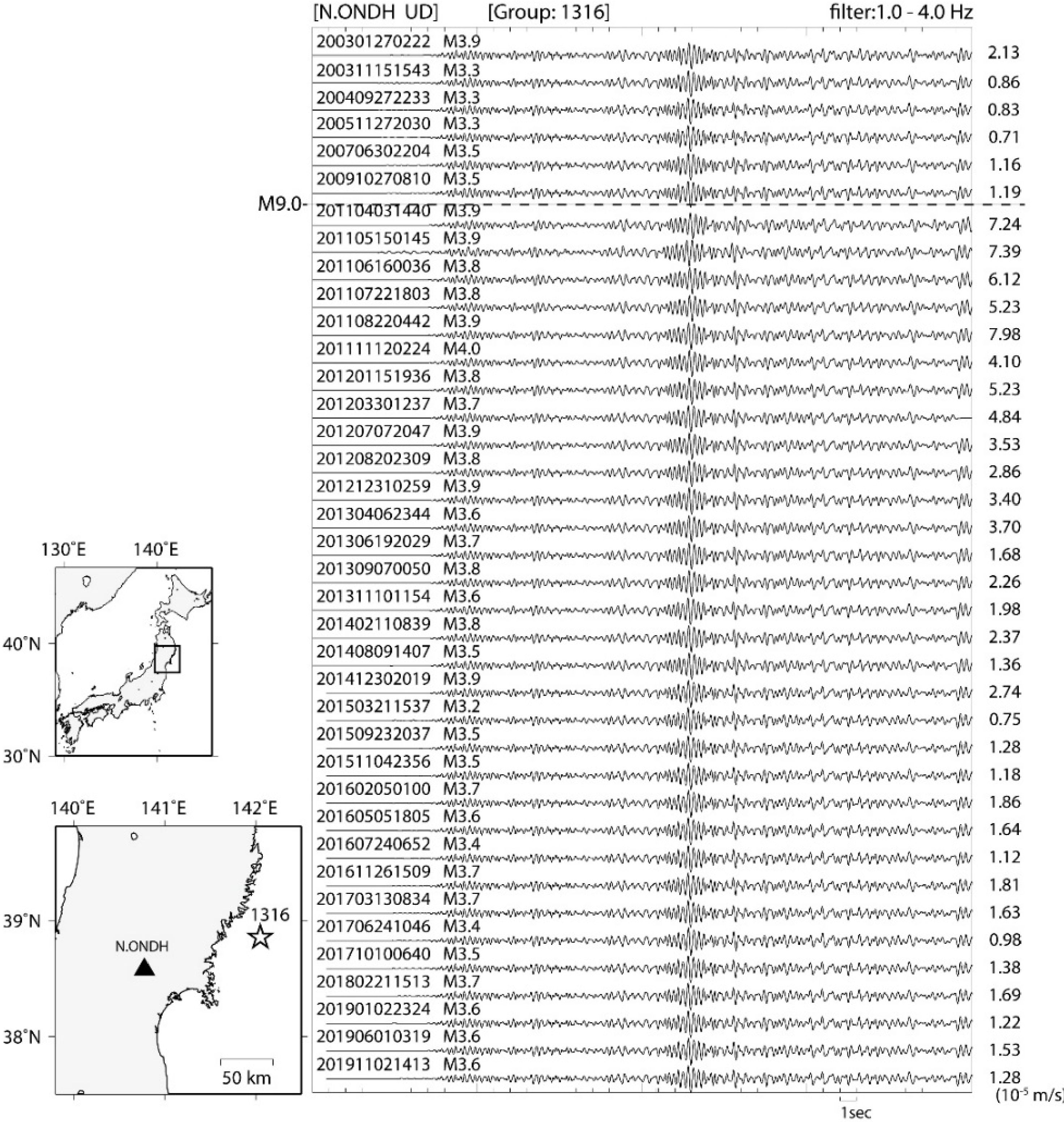

Figure 1

Example of vertical component waveforms for a small repeating earthquake sequence. The 1–4 Hz bandpass-filtered waveforms are shown. The onset (YYYMMDDHHMMSS format) and JMA magnitude of each earthquake are listed on the left side of each trace. Each trace is normalized by the maximum amplitude, which is shown at right. The timing of the 2011 Mw 9.0 Tohoku-Oki Earthquake is indicated by the dashed line. The inset map shows the locations of the repeating earthquake sequence (Group 1316; star) and the seismic station that recorded the waveforms (N.ONDH; triangle).

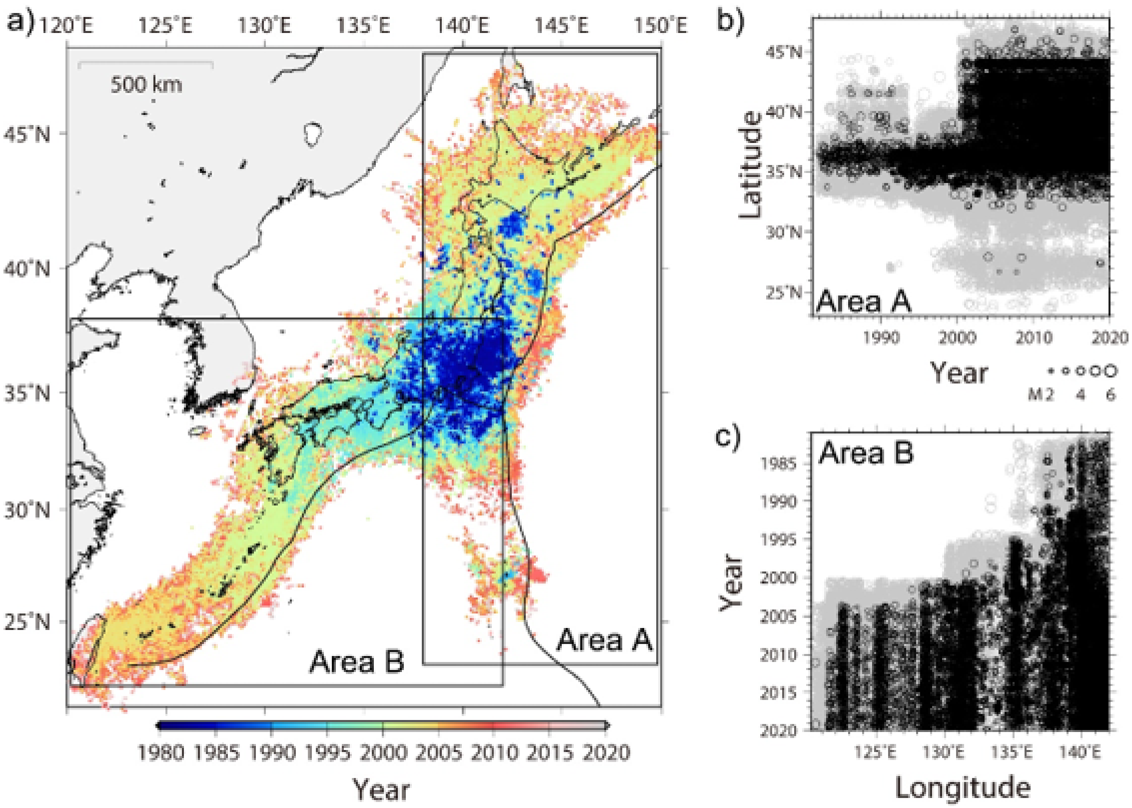

Figure 2

a) Timing of the first analyzed events across the study region. b) Latitude–time diagram for Area A. c) Longitude–time diagram for Area B. Black and gray symbols denote the similar earthquakes and analyzed earthquakes, respectively.

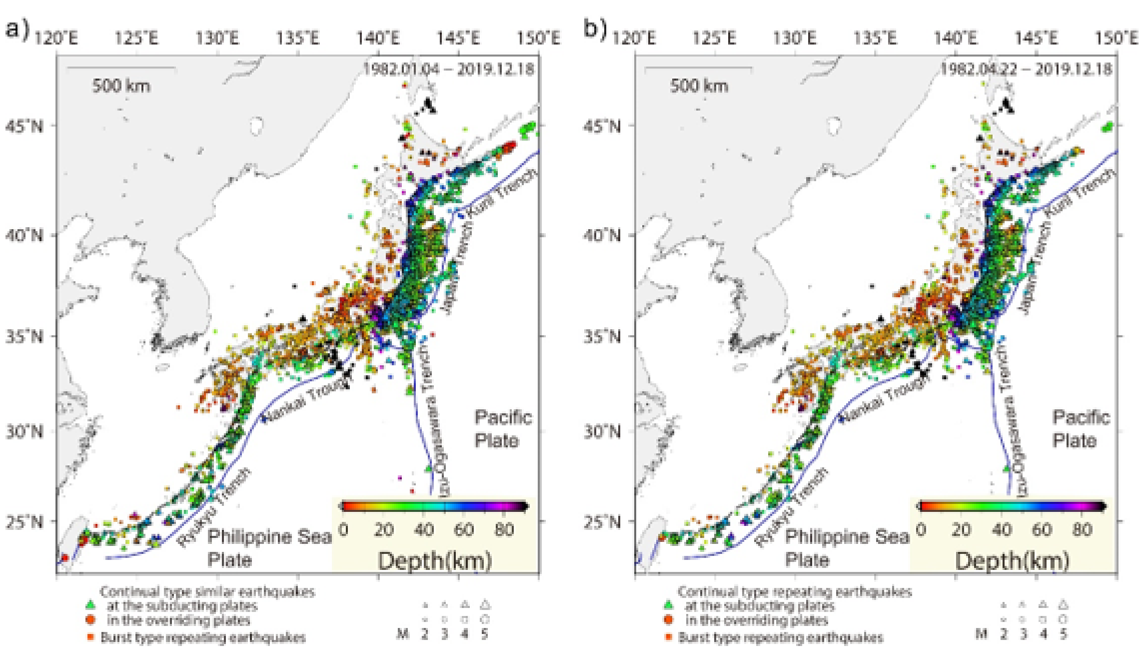

Figure 3

Spatial distributions of a) similar earthquakes and b) small repeating earthquakes in Japan. Dashed lines indicate the downdip limit of interplate coupling (Igarashi et al., 2001).

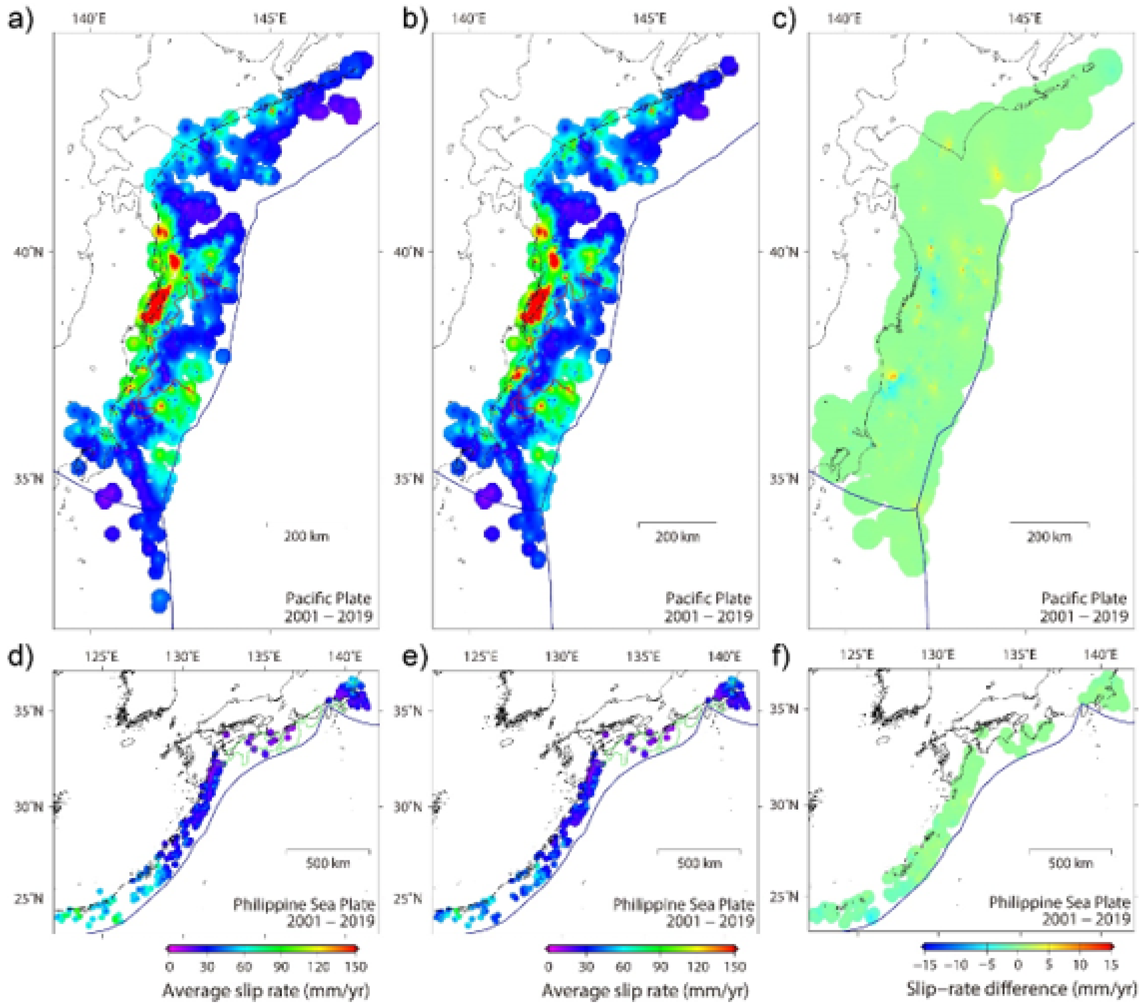

Figure 4

Average slip rates estimated from similar and repeating earthquakes during the 2001–2019 period, and their differences. a) and d) Average slip rates estimated from similar earthquakes. b) and e) Average slip rates estimated from repeating earthquakes. c) and f) Slip-rate differences. a)–c) are for the subducting Pacific Plate, and d)–f) are for the subducting Philippine Sea Plate. The dashed lines indicate the deepest limit of interplate coupling (Igarashi et al., 2001). Blue lines indicate plate boundaries. The red line in a) and b) denotes the outer edge of the large slip zone during the 2011 Tohoku-Oki Earthquake rupture (Kato and Igarashi, 2011). Green lines in d) and e) indicate the asperities of large interplate earthquakes on the subducting Philippine Sea Plate (Baba and Cummins, 2005; Sato et al., 2005) and the potential source region of the anticipated Tokai Earthquake (Central Disaster Management Council, 2001).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SimilarEarthquake.xlsx
- RepeatingEarthquake.xlsx