Characteristics of Foreshocks Occurrence of Onshore Earthquakes In Japan For Mj3.0 To 7.2 Mainshocks

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Abstract

We use the Japan Meteorological Agency (JMA) earthquake catalogue from 2001 to 2021 to investigate the spatiotemporal distribution of foreshocks for shallow mainshocks (Mj3.0–7.2) that are located onshore of Japan. We find clear peaks for the earlier small earthquakes within 10 days and 3 km prior to the mainshocks, which are considered as our definition of foreshocks. After removing the aftershocks, earthquake swarms and possible earthquakes triggered by the 2011 Mw9.0 Tohoku-oki earthquake, we find that for the 2,066 independent earthquakes, 783 (37.9%) have one or more foreshocks. There is a decreasing trend of foreshock occurrence with mainshock depth. Also, normal faulting earthquakes have higher foreshock occurrence than reverse faulting earthquakes. We calculate the rates of foreshock occurrence as a function of the magnitudes of foreshocks and mainshocks, and we have found no clear trend between the magnitudes of foreshocks and mainshocks.

Key Points

1. We analysis the foreshocks of shallow onshore earthquakes in Japan from 2001 to 2021, which are recorded by Japan Meteorological Agency (JMA) earthquake catalogue.
2. Basically, about 37.9% shallow onshore earthquakes have foreshocks, and this is consistent with the reports of foreshocks in other regions (e.g., Italy and California).
3. The foreshocks occurrence may depend on the type of mainshock focal mechanism, but they are random in magnitudes.
4. A rupture-controlled model or cascade model can interpret the foreshocks occurrence of onshore shallow earthquakes in Japan.

Introduction

An earthquake (mainshock) may be preceded closely in time and space by one or more smaller earthquakes which are known as foreshocks (Mogi, 1963). There have been numerous studies of foreshocks for various regions, and a wide range of reported rates of foreshock occurrence from about 10% to 70% in the western US (Jones, 1985; Abercrombie and Mori, 1996; Chen and Shearer, 2015; Trugman and Ross, 2019; van den Ende and Ampuero, 2019; Moutote et al., 2021), Japan (Yoshida, 1990; Maeda, 1996) and Italy (Console et al., 1993). There were also some well recorded larger earthquakes without foreshocks. For example, the 2004 M6.0 Parkfield earthquake did not have foreshocks while the 1934 and 1966 Parkfield earthquakes had clear foreshocks (Bakun and McEvily, 1979). In order to help clarify the rates of foreshock occurrence, we summarize the characteristics for a relatively large dataset of over 2000 mainshocks with magnitudes from Mj3.0 to 7.2 that have been recorded onshore of Japan over the last 20 years. In contrast, previous regional studies of foreshocks examined only about 50 to 100 mainshocks.

Data

Japan is one of the most seismically active regions of the world, and benefits from having some of the best observation networks. After the 1995 Mj7.3 Hyogoken-nanbu (Kobe) earthquake, the National Research Institute for Earthquake Science and Disaster Prevention (NIED) installed the High Sensitivity Seismograph Network Japan (Hi-net), which currently is composed of about 800 borehole seismic stations spaced uniformly across Japan at intervals of 20 to 30 km (Okada et al., 2004; Obara et al., 2005). These stations provide high signal to noise (SNR) recording of the earthquakes and contribute to the Japan Meteorological Agency (JMA) earthquake catalogue with a very good level of completeness.

We use hypocentral information from the JMA earthquake catalogue from January 1, 2001 to February 28, 2021. We only consider the shallow (depth <= 30 km) mainshocks which were located onshore to ensure a good level of event completeness in searching for the foreshocks. The level of completeness for our dataset is determined by looking at the plots of cumulative number of earthquakes as a function of magnitude (Fig. 1). There are several time periods shown in the figure since the processing system for earthquake detection was changed in 2016 to include more automatically detected earthquakes with magnitude less than 1.0 (Tamaribuchi, 2018). For all the three time periods (2001 – 2021, 2001 – 2016 and 2016 – 2021), the earthquake catalogues appear to be complete to a magnitude of less than 1.0. Thus, a threshold level of Mj >= 1.0 is chosen for this study.

Catalogue Declustering

In order to evaluate the foreshocks under normal ambient stress conditions, we attempt to remove aftershocks, earthquake swarms and possible triggered earthquakes from the 2011 Tohoku-oki earthquake. For the aftershocks, we decluster the earthquake catalogue based on the aftershock time-space windows from Gardner and Knopoff (1974), which are commonly used for declustered earthquake catalogues. Figure 2 shows the yearly number of earthquakes before (blue) and after (red) the aftershock removal. Earthquake swarms are sequences during which sometimes hundreds of earthquakes occur in a short time, and have patterns different from typical foreshock-mainshock sequences. Figure 3 is an example of an earthquake swarm on December 18, 2009. For this earthquake, about 277 earlier earthquakes occurred within about 4 km and 1 day prior to the mainshock. In this study, we define earthquake swarms as sequences that have more than 150 earlier earthquakes that occur within 30 days and 30 km before the subsequent mainshock(s), which is over 10 times higher than the earthquake level prior to most of the independent earthquakes. We exclude 29 mainshocks associated with swarms from our earthquake catalogue. This number is about 1% of all the identified independent earthquakes and it does not significantly affect the statistics.

The 2011 Mw9.0 Tohoku-oki earthquake presented a special problem since there was increased seismicity following the mainshock in eastern Japan, and even farther distances throughout much of the country (Miyazawa, 2011). These earthquakes are normally not classified as aftershocks, but were considered to be the triggered earthquakes related to the widespread effects of the great Tohoku-oki earthquake. The triggered earthquakes should be removed because inferred foreshocks (identified by the time-space window) may not be directly related to the subsequent nearby mainshocks, but instead caused by the larger scale regional stress changes from the Tohoku-oki earthquake. For minimizing the effects of these possible triggered earthquakes, we remove 822 earthquakes (Mj3.0 to 7.0) for 5 years from March 2011 to March 2016 across the entire country. Earthquakes which are considered to be aftershocks are still occurring in the offshore Tohoku region 10 years after the mainshock (e.g., the 2021 Mj7.3 Fukushima earthquake). However, the levels of seismicity onshore appear to return to normal levels before the Tohoku-oki earthquake in about 5 years (Fig. 2).

After the aftershocks, earthquake swarms and possible triggered earthquakes following the Tohoku-oki earthquake are removed, we have 2066 independent earthquakes (Mj3.0 – 7.2) for the analysis of foreshock occurrence. The earthquakes are distributed relatively evenly across the entire country (Fig. 4). Focal mechanisms are available for 593 independent earthquakes, with 86 normal (rake 225° – 315°), 235 strike-slip (rake 315° – 45° and 135° – 225°) and 272 reverse (rake 45° – 135°) earthquakes. This dataset of mainshocks can be the representative of the onshore Japan seismicity during the period for 2001 to 2021 under normal ambient regional stress conditions.

Definition of foreshocks

To define the foreshocks in this study, we investigate the time and space distribution of every pair of earthquakes when a larger earthquake follows a smaller earthquake. We use times of 0 to 30 days and distances of 0 to 30 km as the time-space window to search for earlier earthquakes. Figure 5 shows the time and space distribution of the earlier earthquakes for a total of 31,382 earthquake pairs. There are several obvious peaks within a few days and few kilometers of epicentral distance prior to the mainshocks. We use epicentral distance instead of hypocentral distance, since the location uncertainties are larger in the vertical compared to the horizontal. The red bars show values that are greater than the average background value, which is calculated for times longer than 15 days and distance greater than 10 km. Therefore, the definition of foreshocks used in this study are earthquakes smaller in magnitude than the mainshock that occur within 10 days prior to the mainshock at epicentral distances closer than 3 km. The other earthquakes at longer time and farther distance (white bars) are considered to be the random background seismicity. Figure 5 is similar to a figure presented by Jones (1985), which shows that foreshocks in California mostly occur at times of less than 5 days and distances of less than 10 km.

There may be some ‘foreshocks’ (small earlier earthquakes that are physically related to the mainshock) at longer time and farther distance than our definition. For example, studies in southern California include earthquakes up to several months before the mainshock as foreshocks (Trugman and Ross, 2019, Van den Ende and Ampuero, 2020, Moutote et al, 2021). However, in this study we cannot distinguish such possible foreshocks from the background seismicity.

Results

After searching for the foreshocks in our earthquake catalogue for the 2,066 independent earthquakes (Mj 3.0–7.2), we find 783 (37.9%) earthquakes have one or more foreshocks (Mj > = 1.0), as defined by our criteria of 10 days and 3 km. The value is very similar to the rate of 37% reported by Yoshida (1990) for

110 shallow mainshocks in Japan M > = 5.0 during 1961 to 1988. Characteristics of the foreshock occurrence are summarized in Fig. 6. We look at the foreshock occurrence as a function of depth in Fig. 6a, which shows the percentage of earthquakes with foreshocks as a function of mainshock depth. We observe a clear decrease of foreshock occurrence with depth. Figure 6b plots the relations between foreshock occurrence and mainshock focal mechanism by using the rake angle. The mainshock focal mechanisms are from the Broadband Seismograph Network (F-net) and usually available for earthquakes of Mj > = 3.5. Since the fault plane is not known for most of the smaller earthquakes, the rake values on the two nodal planes are averaged. This is not a simple average of the rake angles, but an average of the angle difference from pure reverse or pure normal faulting. Using this method, the difference between the rake angles of the two nodal planes is usually small. We can see that there is a decreasing trend of the percentage of earthquakes with foreshocks from the normal, through strike-slip to reverse faulting.

Figure 6c shows the foreshock occurrence as a function of mainshock magnitude. It has been reported that foreshocks also follow b-values statistics (Console, 1993, Reasenberg and Jones, 1989, Maeda, 1993), so counting a different size range of foreshocks before different size mainshocks may contribute to a bias. Therefore, two curves are shown in the plot. The blue curve shows the occurrence rates using the data for all magnitude foreshocks. The red curve uses only foreshocks that are within 2 magnitude units of the mainshock. The second curve should be a more consistent measure of foreshock occurrence for different size mainshocks. The results in Fig. 6c do not show any clear relation between foreshock and mainshock magnitudes.

Related to Fig. 6c, we calculate the rates of foreshock occurrence by counting the number of times a foreshock of given size is followed by a mainshock (as compared to the number of times that an earthquake of the same size is not followed by a mainshock) using our defined time-space window of 10 days and 3 km. For each foreshock sequence we use only the largest foreshock because smaller foreshocks are often considered to be the possible ‘aftershocks’ of the largest foreshock. The results are shown in Table 1 and Fig. 7 as a function of both foreshock and mainshock magnitudes. For example, looking at the first row in Table 1, for the Mj1.0 to 1.4 foreshocks about 11.35% of the events are followed by Mj3.0 to 3.4 mainshocks, and 9.44% are followed by Mj3.5 to 3.9 mainshocks. Looking at the values plotted in Fig. 7, there are no clear trends as a function of foreshock or mainshock magnitude. For example, for all values of foreshock magnitude from Mj1.0 to 3.9 foreshocks, there is approximately the same rate of the occurrence (about 6%) of Mj5.0 to 5.4 mainshocks. This implies that the size of the foreshock is not related to the size of the subsequent mainshock.

Table 1
Occurrence rates for different magnitudes of mainshocks as a function of foreshock magnitude.

	Mainshock magnitude						
		3.0–3.4	3.5–3.9	4.0–4.4	4.5–4.9	5.0–5.4	>= 5.5
Foreshock magnitude	1.0–1.4	11.35%	9.44%	8.04%	7.79%	5.88%	4.17%
	1.5–1.9	9.51%	6.07%	8.04%	2.60%	5.88%	4.17%
	2.0–2.4	6.60%	6.74%	6.53%	5.19%	5.88%	12.5%
	2.5–2.9	7.67%	7.19%	7.04%	3.90%	5.88%	0
	3.0–3.4	-	5.39%	6.03%	3.90%	5.88%	0
	3.5–3.9	-	-	3.02%	5.19%	5.88%	4.17%

Discussion

The results of the foreshock occurrence as a function of depth and focal mechanism are quite similar to the trends in the western United States using a smaller data set (Abercrombie and Mori, 1996), despite having a difference in tectonic settings. The western US is dominated by normal and strike-slip faulting while reverse faulting is more common in most regions of Japan. Both regions show higher foreshock occurrence for shallow depth compared to greater depths, and higher foreshock occurrence for normal faulting compared to reverse faulting. Abercrombie and Mori (1996) suggested that these trends in depth and focal mechanism may be the result of variations in normal stress with depth and in mechanism from normal to reverse faulting, which indicates that higher normal stress may inhibit foreshock occurrence.

The results for the depth dependence of foreshock occurrence are quite robust. Using slightly different definitions for the foreshock time-space window or different subsets of the catalogue does not significantly change the trend or percentages (Fig. S1). Since normal faulting earthquakes are relatively few in Japan, the dependence on focal mechanism is not as clear. There were a number of triggered earthquakes following the Tohoku-oki earthquake with normal fault mechanisms. Thus, deleting or including these earthquakes during the 5 to 10 years following the mainshock causes some differences in the results. Figure S1 shows the foreshock occurrence as a function of mechanism for various combinations of parameters. There are some differences in the percentages, but there remains an overall consistent trend of foreshock occurrence decreasing for normal to reverse earthquakes.

Two end member models are often used to explain the foreshocks and how they can be related to the mainshocks. A rupture-controlled or ‘cascade model’ interprets foreshocks as a part of a series of triggered earthquakes that result in the mainshock (e.g., Helmstetter and Sornette 2003). The process is rather random with no clear scaling of the size and location of the triggering foreshocks. At the other end of the spectrum, the nucleation-controlled model interprets the foreshocks as a part of an initiation process across the area. This may include possible slow slip or other precursory mechanisms (e.g., Dodge et al., 1996, Kato and Ben-Zion, 2021). Various models infer that the size of the initiation process scales with the size of the mainshock. In our results, there does not seem to be a scaling between the magnitudes of the foreshocks and mainshocks, which would be more consistent with the rupture-controlled model. The independence of the foreshock magnitude compared to the mainshock magnitude was also reported in Greece by Papazachos (1975) and the western US (Abercrombie and Mori, 1996).

A useful application of foreshock statistics is for evaluating hazard levels for subsequent large earthquakes (Reasenberg and Jones (1989), Maeda 1996). Reasenberg and Jones (1989) assume a b-value distribution for the foreshock-mainshock sequences and calculate probabilities for larger earthquakes following small earthquakes that may be potential foreshocks. We also calculated occurrence rates, which can be interpreted as probabilities for given magnitudes of foreshocks and mainshocks (Fig. 7 and Table 1). Using the 'generic model' of Reasenberg and Jones (1989), which is considered to appropriate for many regions, they show that the probability of a larger earthquake following a smaller earthquake is always from 2 to 10%. These values are generally consistent with our results in Fig. 7 which show occurrence rates of 2 to 12%. Other statistical models such as the Epidemic Type Aftershock Sequence (ETAS) which uses background seismicity rates to calculate probabilities of larger earthquakes also give values that are 1 to 10% (average is 3.7%) for different regions in Japan (Ogata and Katsura, 2012).

Conclusions

We use a dataset of 2066 shallow independent earthquakes (Mj3.0–7.2) for onshore Japan, with aftershocks, earthquake swarms and possible triggered earthquakes removed, to study the occurrence of foreshocks down to Mj1.0. Slightly over one third (37.9%) of the mainshocks have one or more foreshocks. We confirm a trend of decreasing foreshock occurrence with mainshock depth. Also, normal faulting earthquakes are more likely to have foreshocks compared to reverse earthquakes. There is not a clear relation between the magnitudes of the foreshocks and mainshocks. The observed rates of foreshocks and mainshocks in this study, provide good statistics for seismic hazard evaluations and calculating probabilities of earthquake occurrence following possible foreshocks.

Declarations

Availability of data and materials:

All the data are available online by Japan Meteorological Agency (JMA) and National Research Institute for Earth Science and Disaster Prevention (NIED) (hinet.bosai.go.jp, fnet.bosai.go.jp).

Competing interests: Not applicable.

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Authors' Contributions:

Hong Peng writes the code based on mathematical equations to analysis the data, gets the main results, and writes the original manuscript.

James Mori provides the concept and methods for this research, and he edits the text of the paper before submission.

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Figures

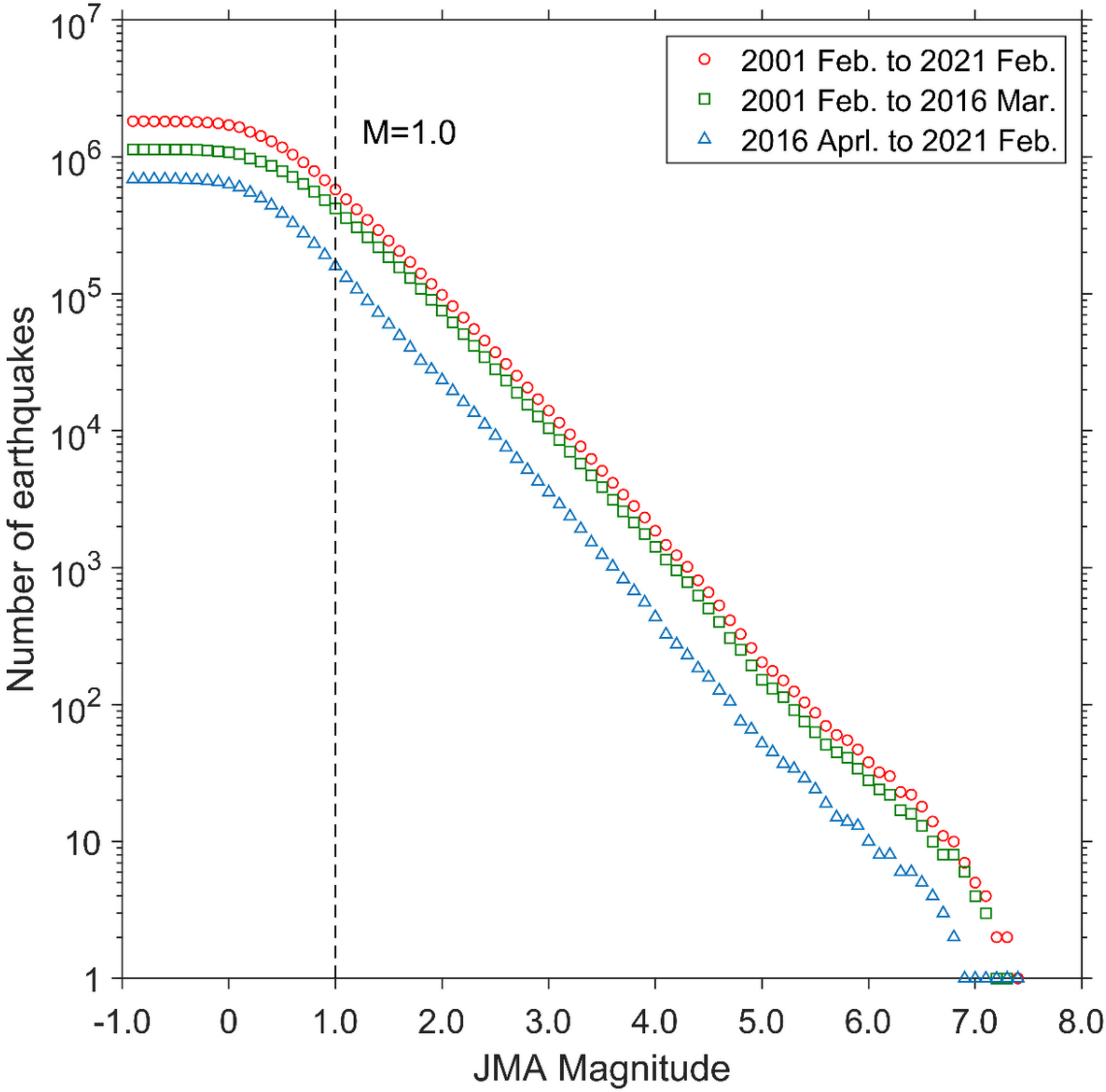

Figure 1

Cumulative number of onshore earthquakes in Japan from the JMA earthquake catalogue. The red circles show the time period from 2001 to 2021, the green squares are for 2001 to 2016 and the blue triangles are for 2016 to 2021. There was a change in the earthquake detection processing system in 2016. The dash line indicates the level of earthquake completeness at Mj1.0 used in this study.

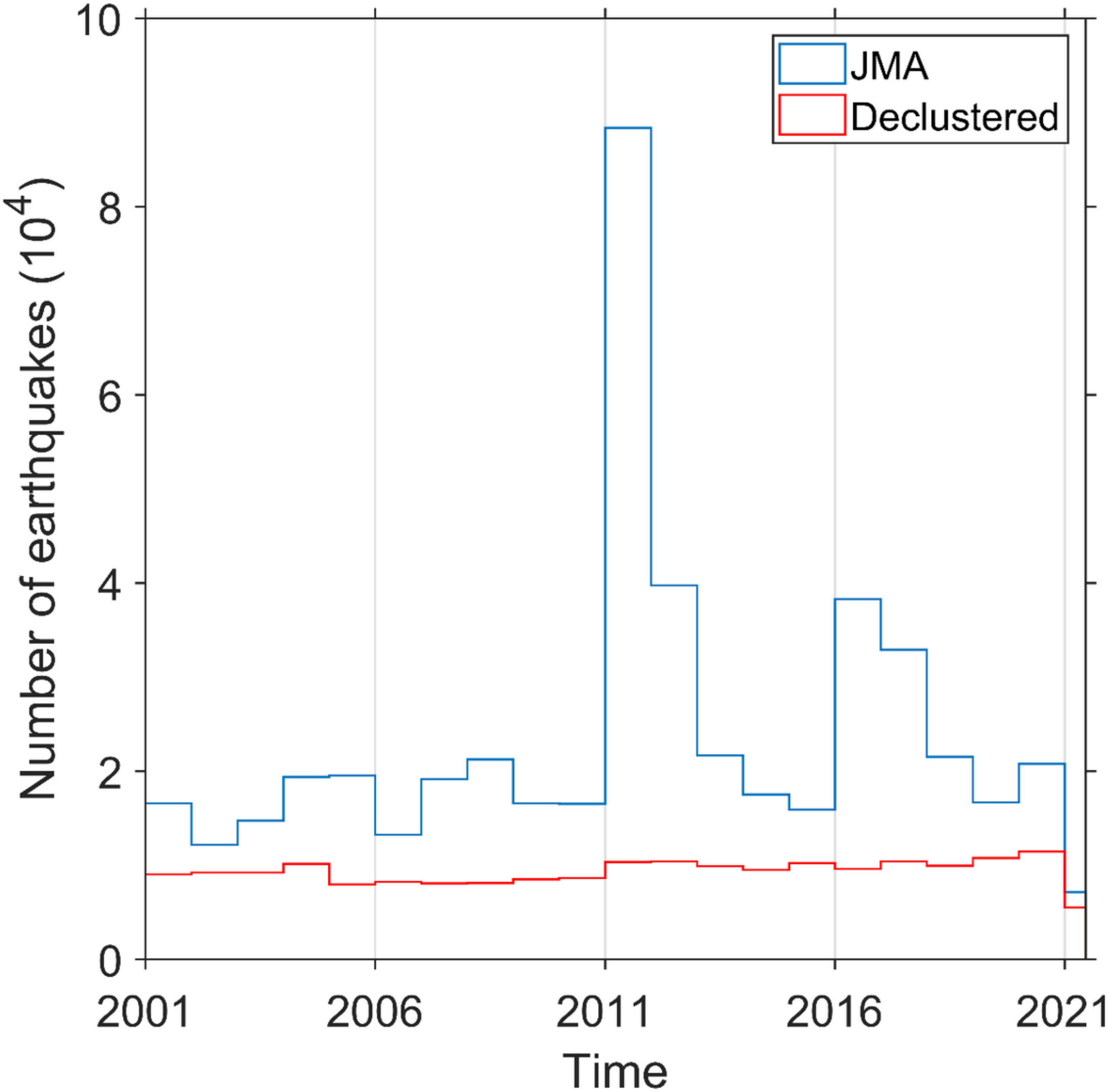

Figure 2

JMA earthquake catalogue (blue) and declustered earthquake catalogue (red). We use aftershock identification windows from Gardner and Knopoff (1974). Earthquake swarms and possible triggered events following the 2011 Tohoku-oki earthquake are also removed. The declustered earthquake catalogue shows similar level of yearly earthquake occurrences.

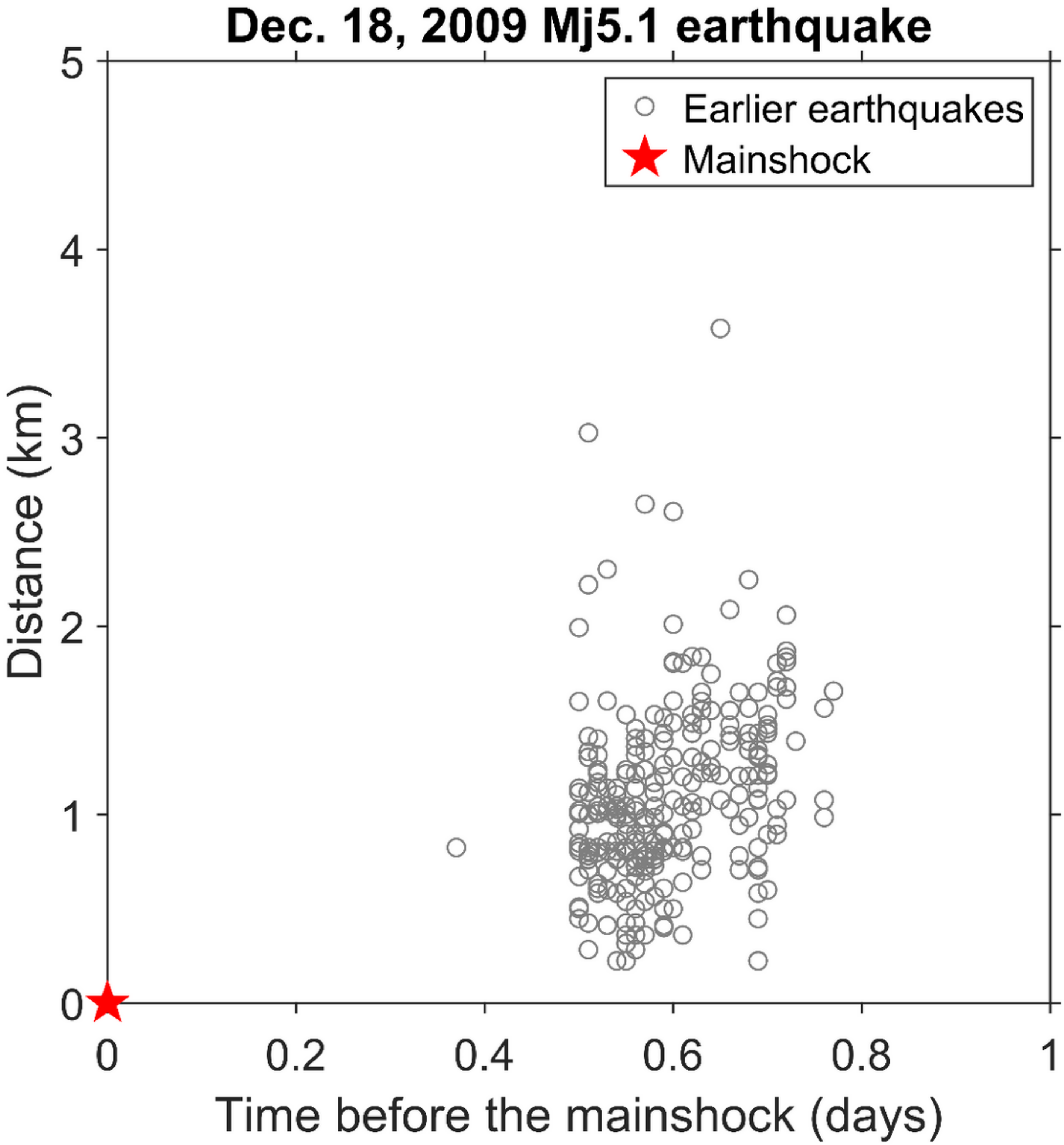

Figure 3

Example of earthquake swarms on December 18, 2009. The red star is the mainshock, white dots are earlier earthquakes within 30 days and 30 km (most of them are within 1 day and 5 km). This earthquake includes 277 earlier earthquakes, which is 10 times more than the average level for an independent earthquake.

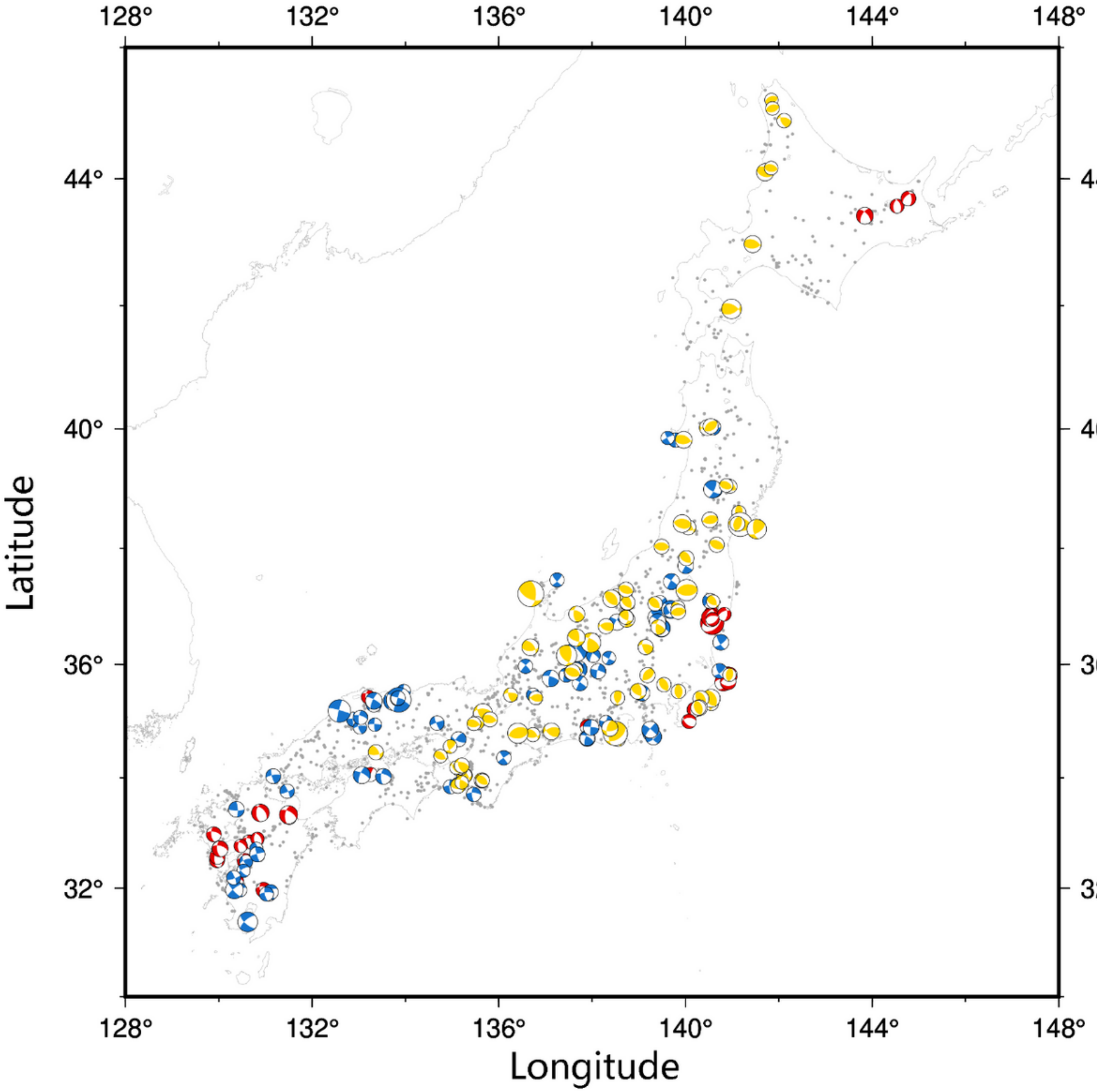

Figure 4

Distribution of mainshocks with focal mechanisms (F-net) used in this study. Red are normal faults, blue are strike-slip faults and yellow are reverse faults. There are 2,066 independent earthquakes shown by the focal mechanisms plus the small grey dots.

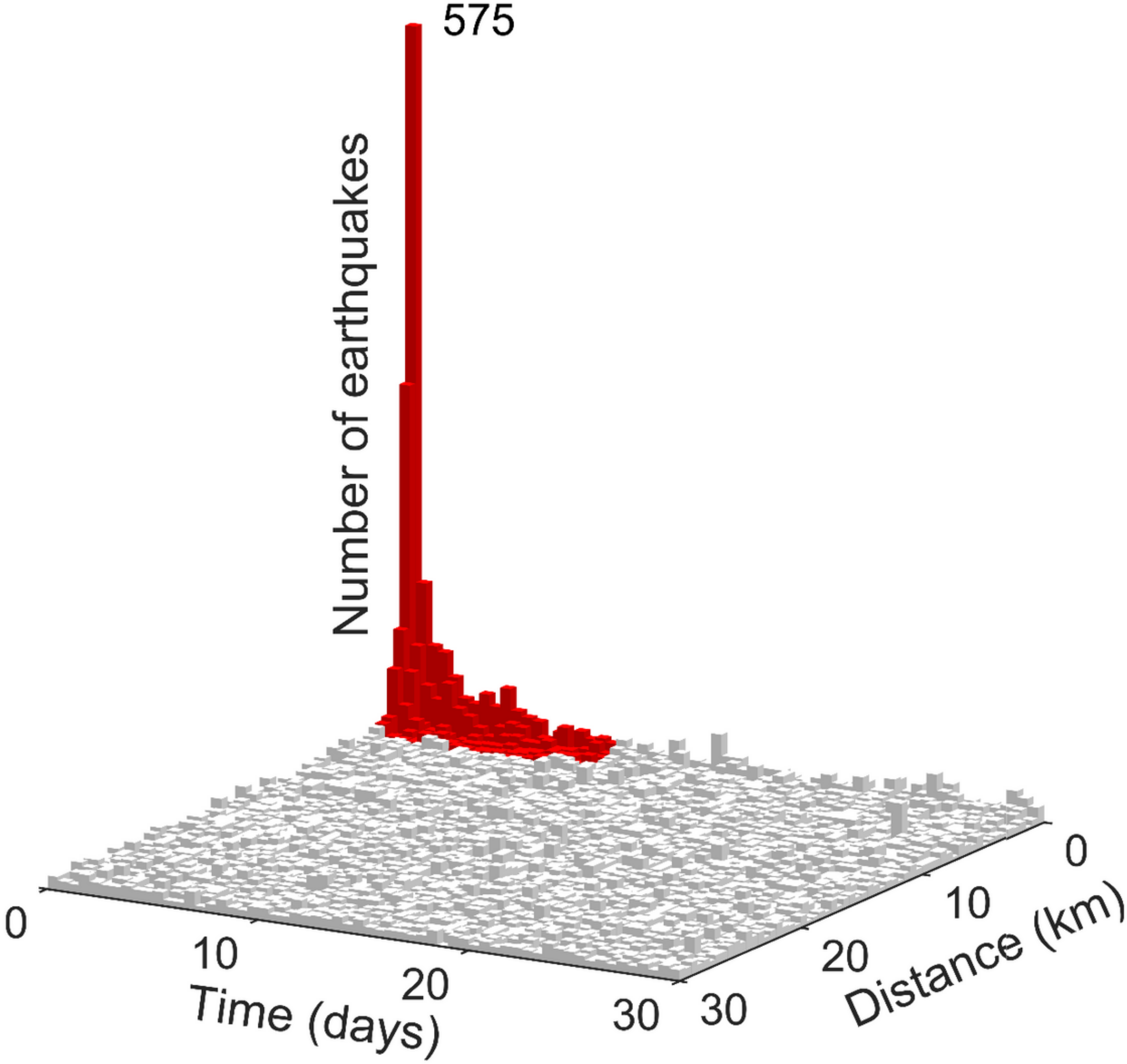

Figure 5

The time-space distribution of all earlier smaller events prior to the 2066 independent earthquakes. Red bars (within 10 days and 3 km) are defined to be the foreshocks in this study. White bars are the random background seismicity level.

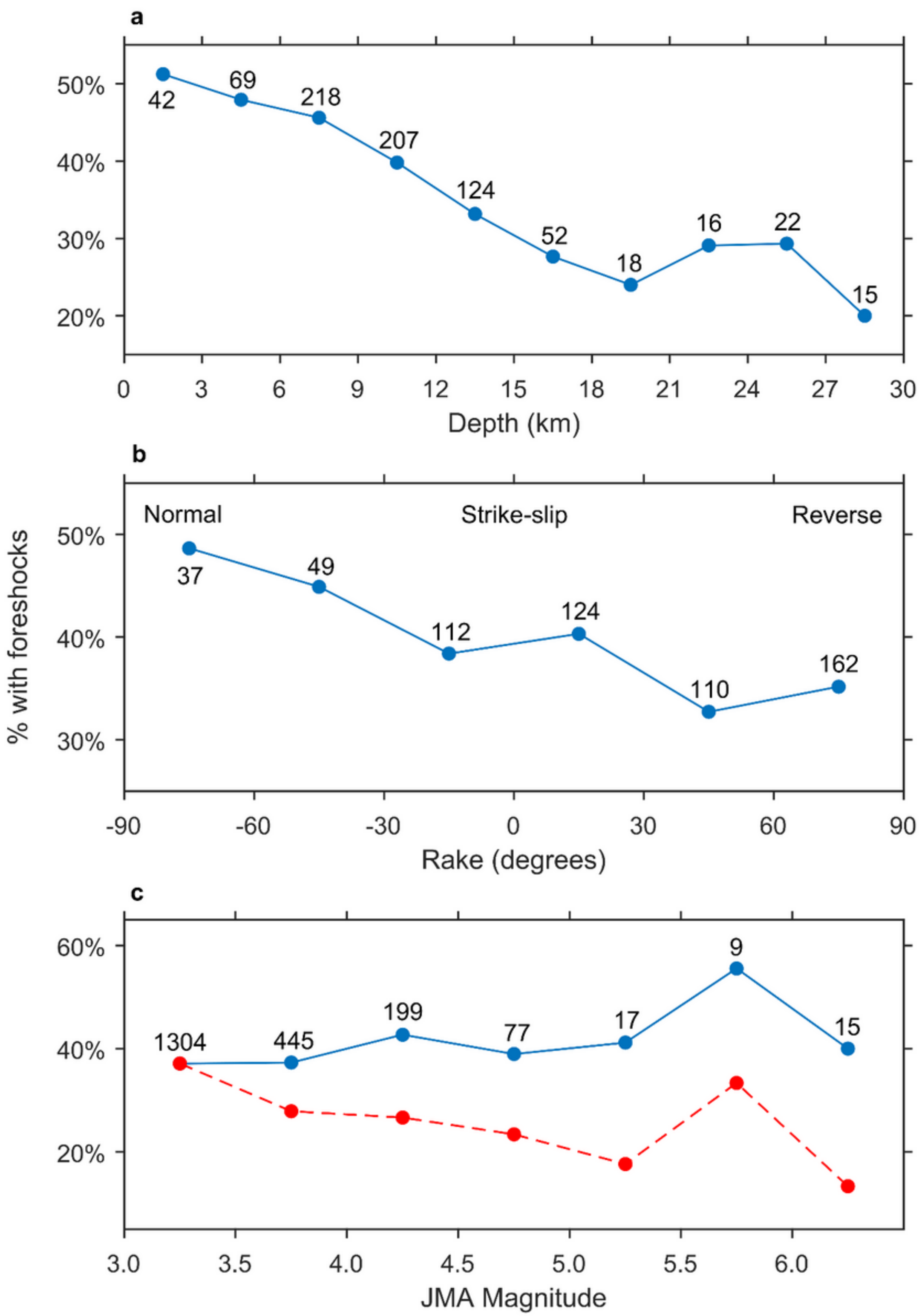

Figure 6

Percentages of foreshock occurrence shown as function of (a) depth, (b) rake and (c) magnitude. The numbers above the points give the total number of events for which the percentage was calculated. In 6c, the blue line shows the percentage using all the data. The red dashed line shows the percentage using only foreshocks within a range of 2 magnitude units from the mainshock.

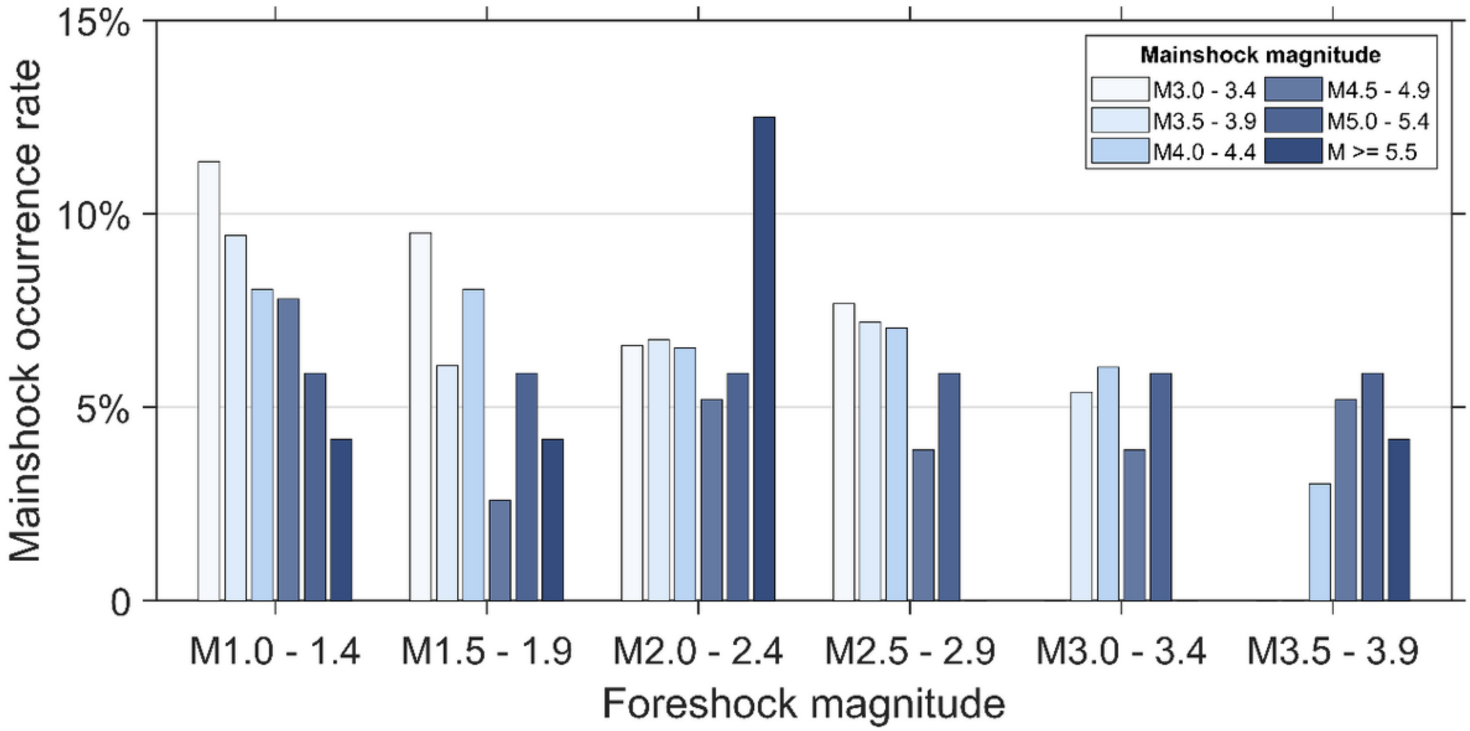

Figure 7

Relations between the magnitudes of foreshocks and mainshocks, shown by the percentage of mainshock occurrence for each foreshock and mainshock magnitude range.

Supplementary Files

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