FULL PAPER

Open Access

Characteristics of the foreshock occurrence for M$_j$3.0 to 7.2 shallow onshore earthquakes in Japan

Hong Peng[*] and James Mori

Abstract

We use the Japan Meteorological Agency (JMA) earthquake catalogue from January, 2001 to February, 2021 to investigate the spatiotemporal foreshock occurrence for shallow (within 30 km depth) onshore earthquakes (M$_j$3.0 to 7.2). We find clear peaks for the numbers of small earthquakes within 10 days and 3 km prior to the larger earthquakes, which are considered as our definition of foreshocks. After removing the aftershocks, earthquake swarms and possible triggered earthquakes by the 2011 M$_w$9.0 Tohoku-oki earthquake, we find that for the 2066 earthquakes (mainshocks), 783 (38%) have one or more foreshocks. There is a decreasing trend of foreshock occurrence rate with mainshock depth. Also, normal faulting earthquakes have higher foreshock occurrence rate than reverse faulting earthquakes. We calculate the earthquake occurrence rate as a function of the magnitudes of foreshocks and mainshocks, and we have found no clear trend between the magnitudes of foreshocks and mainshocks.

Keywords: Japan, Foreshocks, Statistical seismology

Graphical Abstract
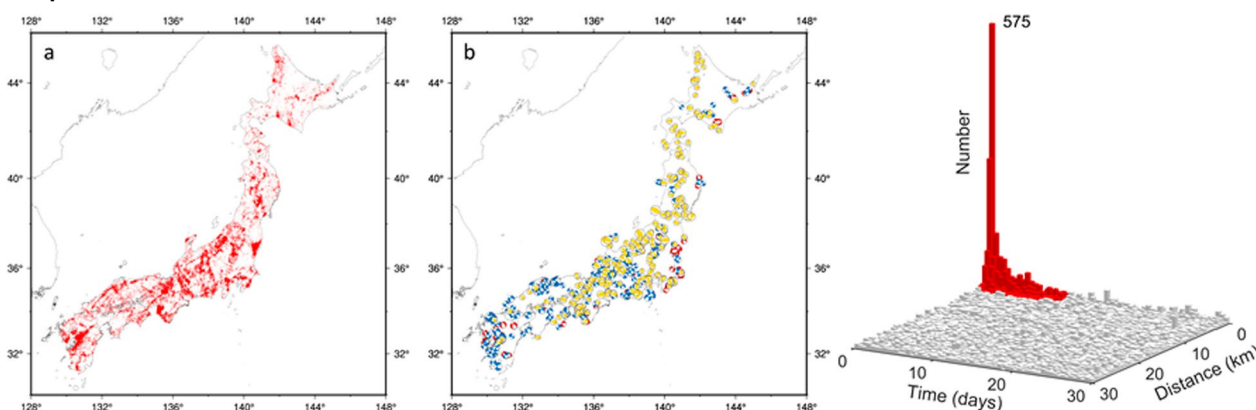
Key points

1. We analysis the foreshock occurrence for shallow (within 30 km depth) onshore earthquakes (M$_j$3.0 to 7.2) in Japan from January, 2001 to February, 2021,

*Correspondence: peng.hong.62a@st.kyoto-u.ac.jp
Earthquake Hazards Division, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

2. Around 38% of the shallow onshore earthquakes have foreshocks, and this is generally consistent with the reports of foreshock occurrence rate in other regions (e.g., California and Italy).

3. The foreshock occurrence rate depends on depth and type of mainshock focal mechanism, but not on mainshock magnitude.

4. These results can be used to estimate the probability of a mainshock following a potential foreshock. However, it is difficult to predict the mainshock magnitude.

Introduction

Foreshocks are one or more smaller earthquakes that occur prior to a larger earthquake (Mogi 1963), and are regarded as possible precursors for an impending earthquake. For decades, there has been numerous studies about foreshock occurrence for various regions of the world. However, there is not yet agreement on some basic characteristics of the foreshocks such as the foreshock occurrence rate. Depending on the definition of foreshocks, there is a wide range of foreshock occurrence rate from about 10% to 70% that have been reported in the western US (Jones 1985; Abercrombie and Mori 1996; Chen and Shearer 2015; Trugman and Ross 2019; van den Ende and Ampuero 2020; Moutote et al. 2021), Japan (Yoshida 1990; Maeda 1996) and Italy (Console et al. 1993). There were also some well recorded larger earthquakes without any foreshocks. For example, the 2004 M_w6.0 Parkfield earthquake did not show foreshocks, while the 1934 and 1966 Parkfield earthquakes had clear foreshocks (Bakun and McEvily 1979).

There has been a long history of studying the foreshocks in Japan. Studies of individual large earthquakes have explained the precursory activity before large earthquakes in terms of mechanisms such as, increased stress that decreases b-values (Enescu and Ito 2001; Nanjo et al. 2010) and precursory slip (Ohnaka 1993; Kato et al. 2012, 2016). Less is known about the numerous small earthquakes which also have foreshocks, and characterizing the properties that are common to many earthquakes should contribute to a better understanding of the mechanisms that control foreshock occurrence.
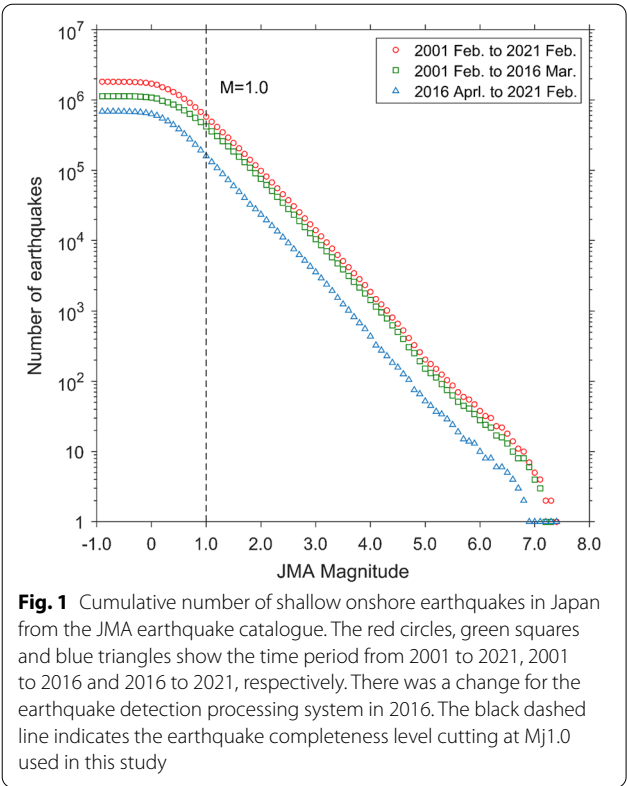
The purpose of this study is to look at numerous shallow onshore earthquakes in Japan to summarize the characteristics of foreshock occurrence. Most previous studies in Japan and other regions of the world investigated only around 50 to 100 mainshocks. Here, we search for the foreshocks of over 2000 M_j3.0 to 7.2 shallow onshore earthquakes in Japan in the last 20 years to characterize the foreshock properties. Tamaribuchi et al. (2018) also examined foreshock activity for the JMA earthquake catalogue using a cluster analysis. Our study differs in that we focus on shallow onshore earthquakes which have a better earthquake completeness at smaller magnitudes.

Data

Japan is one of the most seismically active regions of the world, and benefits from having some of the best seismic observation networks. After the 1995 M_j7.3 Hyogoken-nanbu (Kobe) earthquake, the National Research Institute for Earthquake Science and Disaster Resilience (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) recordings for the earthquakes in Japan, and when combined with the seismic stations operated by the Japan Meteorological Agency (JMA), universities and other organizations, they contribute to the JMA earthquake catalogue with a very good earthquake completeness level.

We use the hypocentral information of earthquakes in the JMA earthquake catalogue from January, 2001 to February, 2021. Since the seismic stations are mostly located on land, we only search for the foreshocks of shallow onshore earthquakes (within 30 km depth) to ensure a good earthquake completeness level. The earthquake completeness level for our dataset can be seen by looking at the plots of cumulative number of earthquakes as a function of magnitudes (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 to 2021, 2001 to 2016 and 2016 to 2021), the earthquake catalogues appear to be complete to a magnitude of less than 1.0. There are many factors that contribute to the earthquake detection ability (such as station distribution, station noise level and regional geology), and these effects vary with time and region. Tamaribuchi (2018) presented a detailed study of the 3-dimensional distribution of the earthquake completeness level in Japan, and his results showed that the earthquake completeness level for onshore earthquakes is about 0.3 to 1.0. Thus, a reasonably conservative threshold earthquake completeness level of M_j1.0 is chosen for this study.

Fig. 1 Cumulative number of shallow onshore earthquakes in Japan from the JMA earthquake catalogue. The red circles, green squares and blue triangles show the time period from 2001 to 2021, 2001 to 2016 and 2016 to 2021, respectively. There was a change for the earthquake detection processing system in 2016. The black dashed line indicates the earthquake completeness level cutting at Mj1.0 used in this study

Catalogue declustering

To evaluate the foreshock occurrence under normal ambient stress conditions, we attempt to remove aftershocks, earthquake swarms and possible triggered earthquakes by the 2011 M_w 9.0 Tohoku-oki earthquake. For the aftershocks, we decluster the JMA earthquake catalogue based on the aftershock time–space identification windows shown in Table 1 from Gardner and Knopoff (1974), which is commonly used for declustering earthquake catalogue (Zhuang et al. 2002). Figure 2 shows the yearly numbers of earthquakes before (blue) and after (red) the declustering. Earthquake swarm is a sequence during which sometimes hundreds of earthquakes occur in a narrow time–space window, and has patterns different from a typical foreshock-mainshock sequence. Figure 3 shows an example of earthquake swarm on December 18, 2009. Here, about 277 earlier earthquakes occurred within 1 day
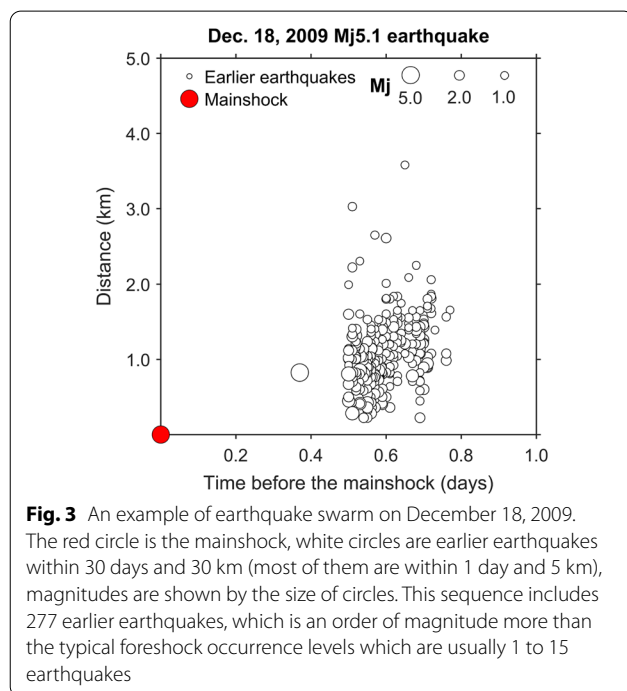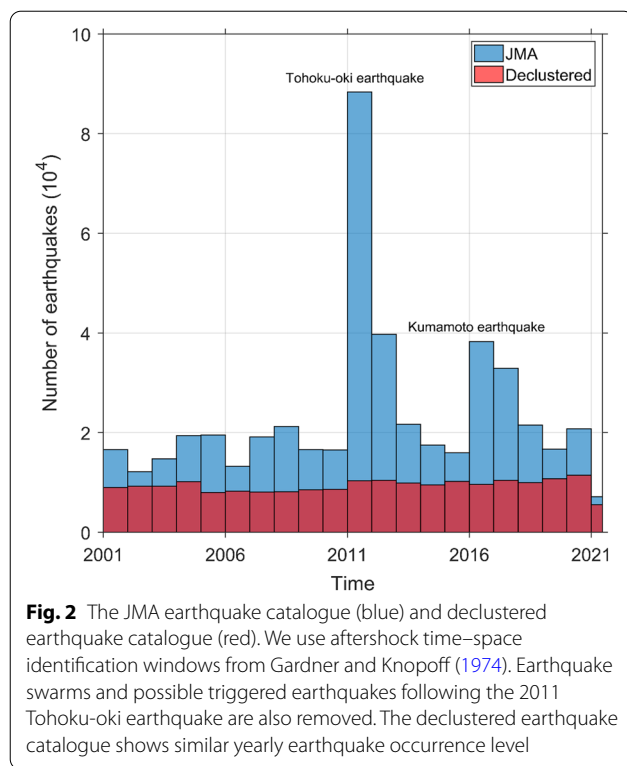
and 4 km prior to the mainshock, which is much higher than the earlier earthquake level of any other mainshocks. In this study, we define an earthquake swarm as a sequence that have more than 150 earlier earthquakes occurring within 30 days and 30 km before the subsequent mainshock, which is over 10 times higher than the level of activity in the typical foreshock-mainshock sequence. With this criterion, we exclude 29 mainshocks associated with earthquake swarm from our dataset. This number is relatively small in comparison with identified mainshocks and it does not significantly affect the statistical analyses.

The 2011 M_w9.0 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 are considered to be the triggered earthquakes related to the widespread effects of the 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 (Miyazawa 2011). To minimize the effects of these possible triggered earthquakes, we remove 822 earthquakes in 5 years from March, 2011 to March, 2016 across the country. Earthquakes which are considered to be the aftershocks of the Tohoku-oki earthquake are still occurring in the Tohoku offshore regions even 10 years after the mainshock (e.g., the 2021 M_j7.3 Fukushima earthquake). However, the onshore seismicity appears to return to the level 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 M_j3.0 to 7.2 mainshocks for the analysis of foreshock occurrence. The declustered catalogue down to M_j1.0 has 195,158 earthquakes (Fig. 4a). Mainshock focal mechanisms are available for 594 earthquakes (Fig. 4b), with 86 normal (rake 225°–315°), 236 strike-slip (rake 315°–45° and 135°–225°) and 272 reverse (rake 45°–135°) earthquakes. This dataset of mainshocks is considered to reflect the shallow onshore seismicity in Japan during the period for January, 2001 to February, 2021 under normal ambient regional stress conditions.

Table 1 Aftershock time–space identification windows (Gardner and Knopoff 1974)

JMA Magnitude	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	> =7.0
Distance (km)	19.5	22.5	26	30	35	40	47	54	61	70
Time (days)	6	11.5	22	42	83	155	290	510	790	915

Fig. 2 The JMA earthquake catalogue (blue) and declustered earthquake catalogue (red). We use aftershock time–space identification windows from Gardner and Knopoff (1974). Earthquake swarms and possible triggered earthquakes following the 2011 Tohoku-oki earthquake are also removed. The declustered earthquake catalogue shows similar yearly earthquake occurrence level

Fig. 3 An example of earthquake swarm on December 18, 2009. The red circle is the mainshock, white circles are earlier earthquakes within 30 days and 30 km (most of them are within 1 day and 5 km), magnitudes are shown by the size of circles. This sequence includes 277 earlier earthquakes, which is an order of magnitude more than the typical foreshock occurrence levels which are usually 1 to 15 earthquakes
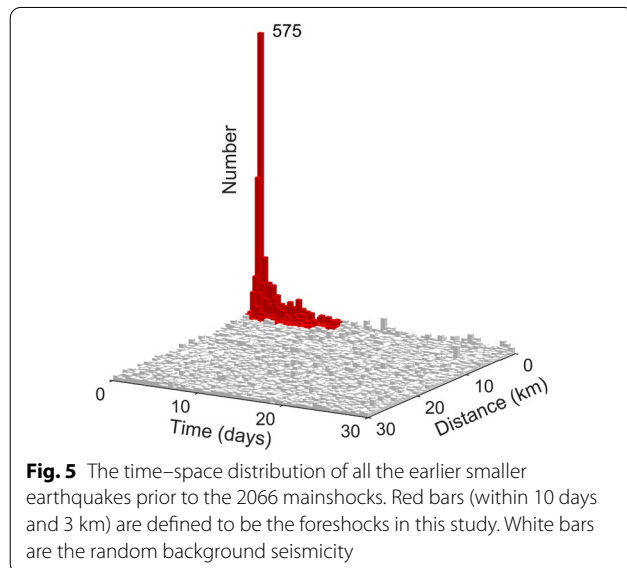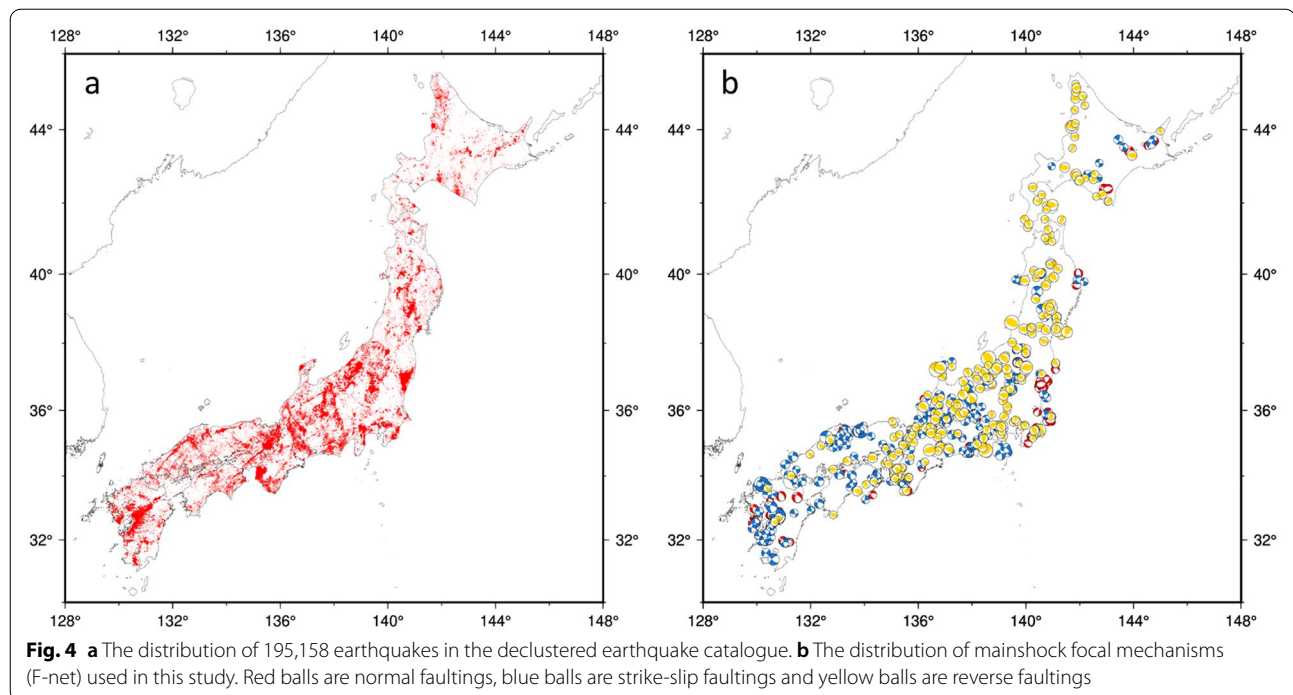
Definition of foreshocks

To define the foreshocks in this study, we investigate the time–space distribution of every pair of earthquakes when a larger earthquake follows smaller earthquakes. We use time of 0 to 30 days and distances of 0 to 30 km as the time–space window to search for the earlier earthquakes. Figure 5 shows the time–space distributions of earlier earthquakes for a total of 31,382 earthquake pairs. There are several strong peaks within a few days and kilometers of epicentral distance prior to the mainshocks. We use epicentral distance instead of hypocentral distance, since the location uncertainties are much larger in vertical compared to the horizontal. The red bars show values that are greater than the average background value, which is calculated for time longer than 15 days and distance farther 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 and at epicentral distance closer than 3 km. The other earthquakes at longer times and farther distances (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 time of less than 5 days and distances of less than 10 km. By applying the above definition for foreshocks, a mainshock can be a foreshock to a subsequent larger earthquake. Also, one earthquake may be a foreshock for more than one mainshock.

There may be some 'foreshocks' (small earlier earthquakes that are physically related to the mainshock) at longer time and farther distances beyond our definition. For example, studies in southern California included 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 those possible foreshocks from the background seismicity. We also checked if the earlier earthquake distributions within the select time–space window depends on earthquake magnitudes, but we could not see any clear difference as a function of earthquake size in this dataset, thus we use the same time–space window for all sizes of earthquakes.

It has been proposed that there are two types of foreshocks, those that occur within 1 h (e.g., Bouchon et al. 2011; Doi and Kawakata 2012) and those that migrate with distance over a longer time (Kato et al. 2012, 2016). In our dataset, we cannot see any differences for the foreshocks that occur within 1 h compared to longer times, all foreshocks would be treated in the same way.
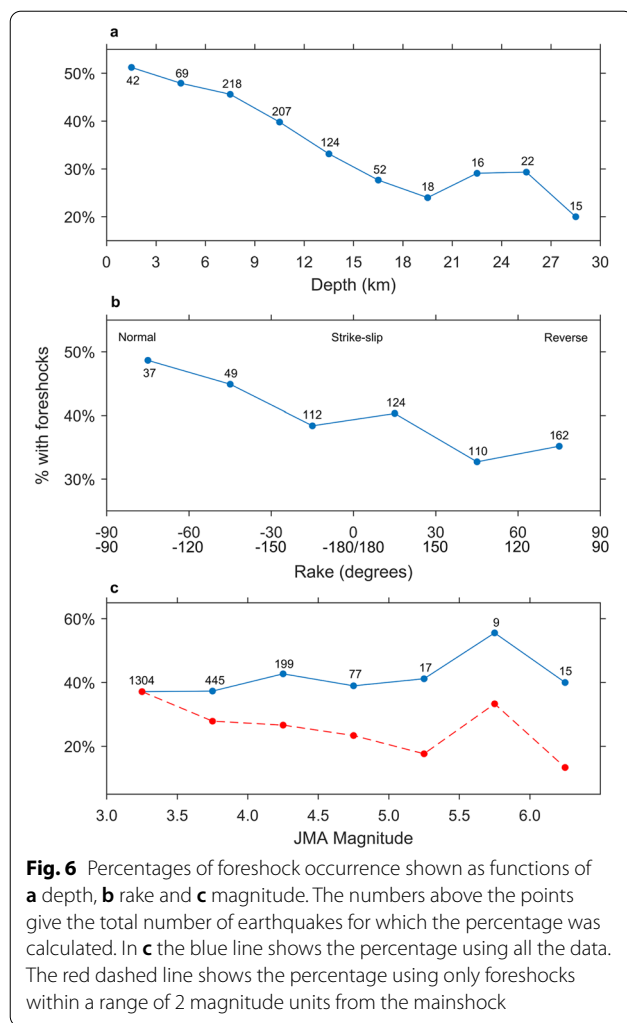
Fig. 4 **a** The distribution of 195,158 earthquakes in the declustered earthquake catalogue. **b** The distribution of mainshock focal mechanisms (F-net) used in this study. Red balls are normal faultings, blue balls are strike-slip faultings and yellow balls are reverse faultings

Fig. 5 The time–space distribution of all the earlier smaller earthquakes prior to the 2066 mainshocks. Red bars (within 10 days and 3 km) are defined to be the foreshocks in this study. White bars are the random background seismicity

Results

After searching for the foreshocks in our dataset for the 2066 mainshocks, we find 783 (38%) earthquakes have one or more foreshocks ($M_j \geq 1.0$), as defined by our criteria of 10 days and 3 km. The value is similar to the rate of 37% reported by Yoshida (1990) for 110 shallow mainshocks ($M \geq 5.0$) in Japan during 1961 to 1988, although he used larger windows of 30 days and about 30 km for searching the foreshocks. Tamaribuchi et al. (2018)

also reported that foreshock occurrence rate in Japan is around 30% to 40% for a wide range of magnitudes by analyzing the foreshock-mainshock sequences of clusters.

Characteristics of the foreshock occurrence rate are summarized in Fig. 6. Looking at Fig. 6a, which shows the percentage of earthquakes with foreshocks as a function of mainshock depth, we can observe a clear decrease of foreshock occurrence rate with depth. We have checked the earthquake completeness level as a function of depth to ensure that this result is not caused by incomplete recording at the greater depths. Figure 6b plots the relations between foreshock occurrence rate and mainshock focal mechanism using the rake angle. The mainshock focal mechanisms are from the Broadband Seismograph Network (F-net) and usually available for earthquakes of $M_j \geq 5.0$. 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, pure strike-slip or pure normal faulting. The equation for calculating this average rake is shown in the supplementary material. We can see that there is a decreasing trend of the percentage for earthquakes with foreshocks from the normal, through strike-slip to reverse faulting. We can also separate the dataset into various subsets which confirm these trends. If we look at the depth dependence for normal, strike-slip and reverse earthquakes, we see the same decrease of foreshock occurrence rate with depth (Additional file 1: Fig.

Fig. 6 Percentages of foreshock occurrence shown as functions of **a** depth, **b** rake and **c** magnitude. The numbers above the points give the total number of earthquakes for which the percentage was calculated. In **c** 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

S1). If we look at the rake dependence for different depth ranges, depths of 0 to 10 km and 10 to 20 km, there is a decrease of foreshock occurrence rate for strike-slip compared to normal earthquakes. For the 20 to 30 km range, it is difficult to see the trend since there are fewer earthquakes (Additional file 1: Fig. S2).

Figure 6c shows the foreshock occurrence rate as a function of mainshock magnitudes. It has been reported that foreshocks also follow b-values statistics (Console et al. 1993; Reasenberg and Jones 1989; Maeda 1996), thus counting different size ranges of foreshocks before different size of mainshocks may contribute to a bias. Two curves are shown in this plot, the blue curve shows the foreshock occurrence rate 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 rate for different size of mainshocks. The results in Fig. 6c do not show any clear relation between the foreshock occurrence rate and mainshock magnitudes.

Related to Fig. 6c, we calculate the foreshock occurrence rate through counting the number of times that an earthquake 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). For each sequence we only use the largest foreshock because smaller foreshocks are often considered to be the possible 'aftershocks' of the largest foreshock. The results are shown in Fig. 7 and Table 2 as a function of both foreshock and mainshock magnitudes. For example, if a M_j1.0 potential foreshock occurs, we would like to know what is the probability (occurrence rate) that a M_j3.0
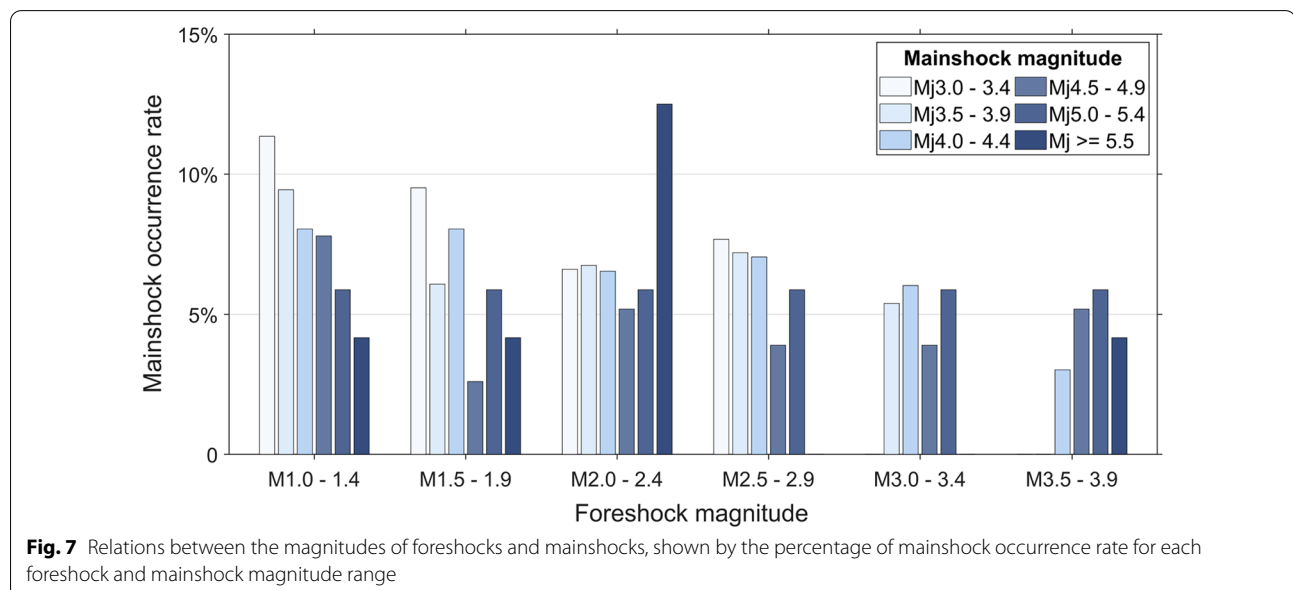

Fig. 7 Relations between the magnitudes of foreshocks and mainshocks, shown by the percentage of mainshock occurrence rate for each foreshock and mainshock magnitude range

Table 2 Mainshock occurrence rate 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%

Table 3 Percentage of earthquakes that have foreshocks using various time–space windows

	Time (days)			
	5	10	15	20
Distance (km)				
3	31.51%	37.90%	41.58%	44.48%
6	39.06%	48.06%	53.58%	57.70%
9	45.45%	56.10%	61.86%	66.17%

mainshock will subsequently occur. This result is given by the left, uppermost value in the Table 2, 11.35%. Looking at the Fig. 7 and values in Table 2, there are no clear trends as a function of foreshock or mainshock magnitudes. For example, for all values of foreshock magnitude from M_j1.0 to 3.9, there is approximately the same occurrence rate (about 6%) of M_j5.0 to 5.4 mainshocks. This implies that the size of the foreshock is not related to the size of the subsequent mainshock.

Discussion

Our result that 38% for the foreshock occurrence rate is somewhat dependent on the choice of the 10 days and 3 km time–space window. However, looking at the distributions in Fig. 5, there are very peaked distributions within several days and several kilometers. Thus, if the time–space windows include these peaks, the results are roughly similar. Table 3 shows the values for the foreshock occurrence rate using various time–space windows. This is probably one reason why the foreshock occurrence rate is often similar in different studies that use different space–time windows (e.g., Yoshida 1990; Tamaribuchi et al. 2018). The foreshock occurrence rate for longer time (20 days) and farther distances (9 km) contain many earthquakes which we consider to be the background seismicity, and are likely too high.

The results of the foreshock occurrence rate as a function of depth and mainshock focal mechanism are quite

similar to the trends in the western United States using a smaller dataset (Abercrombie and Mori 1996), despite having a difference in tectonic settings. The western United States 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 rate for shallow depth compared to greater depth, and higher foreshock occurrence rate for normal faulting compared to reverse faulting. Abercrombie and Mori (1996) suggested that these trends in depth and mainshock focal mechanism may result from variations in normal stress with depth and in mechanism from normal to reverse faulting, which indicates that higher normal stress may inhibit the foreshock occurrence.

The results for the depth dependence of foreshock occurrence rate are quite robust. Using slightly different parameters of time–space window or different subsets of the earthquake catalogue for foreshock definition does not significantly change the trend or percentages (Additional file 1: Fig. S2). Since normal faulting earthquakes are relatively few in Japan, the dependence on mainshock focal mechanism is not as clear. There were hundreds of triggered earthquakes following the Tohoku-oki earthquake with normal fault mechanisms. Thus, deleting or including these earthquakes during the 5 years following the mainshock may cause some differences in the results. Additional file 1: Fig. S1 shows the foreshock occurrence rate as a function of mainshock focal mechanisms for various combinations of parameters. There are some differences in the percentages, but there remains an overall consistent trend of foreshock occurrence rate decreasing for normal to reverse earthquakes.

Two end member models are often used to explain the foreshock occurrence and how it 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 and 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 et al. 2012). 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 United States (Abercrombie and Mori 1996).

A useful application of foreshock statistical analysis is evaluating the hazard levels for subsequent large earthquakes (Reasenberg and Jones 1989; Maeda 1996). Reasenberg and Jones (1989) assumed 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 the occurrence rate, which can be interpreted as probabilities for given magnitudes of foreshocks and mainshocks (Fig. 7 and Table 2). 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 rate of 2% to 12%. Other statistical models such as the Epidemic Type Aftershock-Sequences (ETAS) which uses background earthquake rates to calculate probabilities of larger earthquakes also give values that are 1% to 10% (the average is 3.7%) for different regions in Japan (Ogata and Katsura 2012).

Conclusions

We use a dataset of 2066 M_j3.0 to 7.2 shallow onshore earthquakes in Japan, with aftershocks, earthquake swarms and possible triggered earthquakes removed, to study the foreshock occurrence down to M_j1.0. Slightly over one third (38%) of the mainshocks have one or more foreshocks. We confirm a trend of decreasing foreshock occurrence rate with mainshock depth. Also, normal faulting earthquakes are more likely to have foreshocks compared to reverse faulting earthquakes. There is not a clear relation between the magnitudes of the foreshocks and mainshocks. The observed foreshock occurrence rate of mainshocks in this study, provide good statistics for seismic hazard evaluations and calculating probabilities of earthquake occurrence following possible foreshocks.

References
Abercrombie RE, Mori J (1996) Occurrence patterns of foreshocks to large earthquakes in the western United States. Nature 381(6580):303–307. https://doi.org/10.1038/381303a0

Bakun WH, McEvilly TV (1979) Earthquakes near Parkfield, California: comparing the 1934 and 1966 sequences. Science 205(4413):1375–1377. https://doi.org/10.1126/science.205.4413.1375

Bouchon M, Karabulut H, Aktar M, Özalaybey S, Schmittbuhl J, Bouin M-P (2011) Extended nucleation of the 1999 Mw 7.6 Izmit earthquake. Science 331(6019):877–880. https://doi.org/10.1126/science.1197341

Chen X, Shearer PM (2015) Analysis of foreshock sequences in California and implications for earthquake triggering. Pure Appl Geophys 173:133–152. https://doi.org/10.1007/s00024-015-1103-0

Console R, Murru M, Alessandrini B (1993) Foreshock statistics and their possible relationship to earthquake prediction in the Italian region. Bull Seismol Soc Am 83(4):1248–1263. https://doi.org/10.1785/BSSA0830041248

Dodge DA, Beroza GC, Ellsworth WL (1996) Detailed observations of California foreshock sequences: implications for the earthquake initiation process. J Geophys Res Solid Earth 101(B10):22371–22392. https://doi.org/10.1029/96JB02269

Doi I, Kawakata H (2012) A non-accelerating foreshock sequence followed by a short period of quiescence for a large inland earthquake. Geophys Res Lett. https://doi.org/10.1029/2012GL051779

Enescu E, Ito K (2001) Some premonitory phenomena of the 1995 Hyogo-Ken Nanbu (Kobe) earthquake: seismicity, b-value and fractal dimension. Tectonophysics 338(3–4):297–314. https://doi.org/10.1016/S0040-1951(01)00085-3

Gardner JK, Knopoff L (1974) Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull Seismol Soc Am 64(5):1363–1367. https://doi.org/10.1785/BSSA0640051363

Helmstetter A, Sornette D (2003) Foreshocks explained by cascades of triggered seismicity. J Geophys Res Solid Earth. https://doi.org/10.1029/2003JB002409

Jones LM (1985) Foreshocks and time-dependent earthquake hazard assessment in Southern California. Bull Seismol Soc Am 75(6):1669–1679

Kato A, Obara K, Igarashi T, Tsuruoka H, Nakagawa S, Hirata N (2012) Propagation of slow slip leading up to the 2011Mw 9.0 Tohoku-Oki Earthquake. Science 335(6069):705–708. https://doi.org/10.1126/science.1215141

Kato A, Fukuda J, Nakagawa S, Obara K (2016) Foreshock migration preceding the 2016 Mw 7.0 Kumamoto earthquake, Japan. Geophys Res Lett 43(17):8945–8953. https://doi.org/10.1002/2016GL070079

Maeda K (1996) The use of foreshocks in probabilistic prediction along the Japan and Kuril trenches. Bull Seismol Soc Am 86(1A):242–254. https://doi.org/10.1785/BSSA08601A0242

Miyazawa M (2011) Propagation of an earthquake triggering front from the 2011 Tohoku-Oki earthquake. Geophys Res Lett. https://doi.org/10.1029/2011gl049795

Mogi K (1963) Some discussions on aftershocks, foreshocks and earthquake swarms: the fracture of a semi-infinite body caused by inner stress origin and its relation to the earthquake phenomena (3rd Paper). Bull Earthq Res Inst Univ Tokyo 41:615–658

Moutote L, Marsan D, Lengliné O, Duputel Z (2021) Rare occurrences of non-cascading foreshock activity in Southern California. Geophys Res Lett. https://doi.org/10.1029/2020GL091757

Nanjo KZ, Ishibe T, Tsuruoka H, Schorlemmer D, Ishigaki Y, Hirata N (2010) Analysis of the completeness magnitude and seismic network coverage of Japan. Bull Seismol Soc Am 100(6):3261–3268. https://doi.org/10.1785/0120100077

Obara K, Kasahara K, Hori S, Okada Y (2005) A densely distributed high-sensitivity seismograph network in Japan: Hi-net by National Research Institute for Earth Science and Disaster Prevention. Rev Sci Instrum 76(2):021301. https://doi.org/10.1063/1.1854197

Ogata Y, Katsura K (2012) Prospective foreshock forecast experiment during the last 17 years. Geophys J Int 191(3):1237–1244. https://doi.org/10.1111/j.1365-246X.2012.05645.x

Ohnaka M (1993) Critical size of the nucleation zone of earthquake rupture inferred from immediate foreshock activity. J Phys Earth 41(1):45–56. https://doi.org/10.4294/jpe1952.41.45

Okada Y, Kasahara K, Hori S, Obara K, Sekiguchi S, Fujiwara H, Yamamoto A (2004) Recent progress of seismic observation networks in Japan -Hi-net, F-net, K-NET and KiK-net. Earth Planets Space. https://doi.org/10.1186/bf03353076

Papazachos BC (1975) Foreshocks and earthquake prediction. Tectonophysics 28(4):213–226. https://doi.org/10.1016/0040-1951(75)90038-4

Reasenberg PA, Jones LM (1989) Earthquake hazard after a mainshock in California. Science 243(4895):1173–1176. https://doi.org/10.1126/science.243.4895.1173

Tamaribuchi K (2018) Evaluation of automatic hypocenter determination in the JMA unified catalog. Earth Planets Space 70:141. https://doi.org/10.1186/s40623-018-0915-4

Tamaribuchi K, Yagi Y, Enescu B, Hirano S (2018) Characteristics of foreshock activity inferred from the JMA earthquake catalog. Earth Planets Space 70:90. https://doi.org/10.1186/s40623-018-0866-9

Trugman DT, Ross ZE (2019) Pervasive foreshock activity across Southern California. Geophys Res Lett 46(15):8772–8781. https://doi.org/10.1029/2019GL083725

Van den Ende MPA, Ampuero JP (2020) On the statistical significance of foreshock sequences in Southern California. Geophys Res Lett. https://doi.org/10.1029/2019GL086224

Yoshida A (1990) Characteristics of foreshock activities associated with large shallow intraplate earthquakes in the Japanese Islands. Papers Meteorol Geophys 4(1):15–32. https://doi.org/10.2467/mripapers.41.15

Zhuang JC, Ogata Y, Vere-Jones D (2002) Stochastic declustering of space-time earthquake occurrences. J Am Stat Assoc 97(458):369–380. https://doi.org/10.1198/016214502760046925

Publisher's Note