Operation of the SWIFT CMT analysis system in Colombia and characteristic of seismicity in the complex subduction zones

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Colombia is located in the triple junction of the Nazca, Caribbean, and South American plate, and the complex plate subductions cause various seismicity pattern. The great earthquakes such as the 1906 Ecuador-Colombia earthquake (Mw8.8) and the 1979 Tumaco (south west of Colombia) earthquake (Mw8.2) occurred at the boundary between the subducting Nazca plate and the South American plate. There are no historical records of large earthquakes in the northern part of the boundary, and a potential for a future large earthquake is unresolved issue. An intermediate earthquake concentration known as the Bucaramanga nest is observed in the inland region. The 1967 M6.3 earthquake of the nest also caused much damage in Bucaramanga. However, most of nest earthquakes are not included in the global CMT catalog because of their small magnitude. Despite highly concentrated seismicity in the nest, the CMTs reported in the global CMT catalog also indicate various focal mechanism. This may causes difficulty in understanding the nature of the nest. To understand the nature of the nest activity and the complex plate interactions, it is very important to determine the focal mechanisms including small events.
The JST/JICA SATREPS project of "Research and development of disaster mitigation techniques of earthquake, tsunami, and volcano in Colombia" was started in 2015. We installed the SWIFT system (Nakano et al., 2008) in the Colombia Geological Survey and determined CMT solutions and source time functions of the Colombian regional earthquakes. We now carry out the following studies: 1) detection of very low frequency (VLF) earthquakes and tremors in Colombia, 2) determination of CMT solutions including small events which are not listed in the global CMT catalog. Although we have not been able to detect any VLF events until now, we obtained CMT solutions including small events by the SWIFT. The smallest magnitudes are Mw4.3 for shallow events and Mw4.6 for intermediate depth events. The global CMT catalog shows that the focal mechanisms in the Bucaramanga nest are highly variable, but our many CMT solutions show the mostly strike-slip faulting with some dip-slip components and SW-NE directions of P axis. Other events show focal mechanisms opposite to these mechanisms. Prieto et al. (2012) found repeating and "anti-repeating" earthquakes in the nest and suggested that the nest is not a volumetric but a planar seismic activity. Our results also support their idea, but we need more information of further past events. Toward understanding the nature of the nest and the complex subduction processes, we will also analyze the focal mechanisms of smaller events using P wave polarities.

Keywords: SWIFT, Colombia, seismicity

A dense seismic array observation across the central focal area of the 2015 Gorkha earthquake(Mw 7.8), Nepal

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On April 25, 2015, the Gorkha earthquake (Mw 7.8) struck central Nepal and resulted in nearly 9000 fatalities. This earthquake occurred in the India-Eurasia Plate Collision Zone. The focal mechanism showed a reverse fault with a compression axis in a NNE-SSW direction (USGS, 2015). The Himalayan seismogenic zone is located in a typical continental collision zone. Several geological cross sections through the central Himalaya have been proposed (e.g., Cattin and Avouac, 2000, JGR). However, little is known about the detailed geophysical structure of the India-Eurasia plate collision zone. Moreover, the 2015 Gorkha earthquake failed to rupture to the surface and hence a large earthquake appears to be inevitable (Bilham, 2015). Revealing the crustal structure of the India-Eurasia plate collision zone is important to constrain the process of earthquake occurrence and the crustal evolution process associated with the collision of the continents. To investigate aftershock distribution and crustal structure, we conducted a dense seismic array observation across the central focal area of the 2015 Gorkha earthquake. Thirty-five portable seismographs were deployed along a 90-km-long line between Shabru Besi and Hetauda. Each seismograph consisted of a 4.5 Hz 3-component seismometer and a digital data recorder (GSX-3). Waveforms were continuously recorded at a sampling rate of 250 Hz for one month. Recordings were started on August 15, 2015 and November 28, 2015. In this presentation, we present precise aftershock distribution and seismic velocity structure across the central focal area of the 2015 Gorkha earthquake.

Keywords: The 2015 Gorkha earthquake, India-Eurasia Plate Collision Zone, dense seismic array observation, aftershock distribution

Monitoring of Background Seismicity and Induced Earthquakes Associated with Enhanced Geothermal Systems in Ilan, Taiwan

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Hydro-fracturing stimulation is one of the key steps in the development of EGS. It aims to create a subsurface system full of cracks and fractures, thus providing an efficient water channel network to enhance the thermal energy extraction. Since small earthquakes are triggered by the occurrence of rock fracture, the distribution of hydro-fractures can be delineated by locations of these induced earthquakes. In this project, we have deployed 6 bore-hole seismometers to accurately capture the weak signals from these micro events. The influence on local seismicity from water-pumping is another important issue in this project. Preliminary analysis of data from our own borehole network indicates that many recorded local micro events are not reported in the CWB catalogue, thus, we need to rely on the borehole data to better evaluate the local background seismicity. We have also analyzed data during the stimulation experiments conducted in 11/09, 11/13 and 11/14, 2014. After various examinations, we noticed two major signals during the stimulations, the tremors, which are likely induced by water-pumping, and the free-oscillations of the water-filled cracks, which are obviously enhanced during the pumping period. However, probably because the energy from the induced rock failure is too weak, these signals were only recorded by the nearest borehole station, and there is no clear arrival time in the tremor signals. During the period from October 2014 to November 2015, 1313 local earthquakes were recorded by the bore-hole seismic network. We first determined the seismic velocity of the shallowest layer (depth < 500 m) with applying ambient noise technique on seismic records of local earthquakes, and inverted a minimum velocity model and preliminary locations of earthquakes by using the package VELEST developed by Kissling. We then relocated local earthquakes using “HYPODD” technique, and calculated local magnitude (ML) of these events. Most of these events are located at depth less than 5 km with rather small magnitudes (ML<1.0). Our results have well demonstrated that we are able to improve local micro-earthquake monitoring by using the bore-hole seismic network. During the stimulation experiments, no apparent variations of seismicity were noticed. Interestingly, the seismicity right beneath the injection well (2 –5 km) was clearly increased 3 days after the pumping, and such phenomena lasted for about 10 days. Besides the seismic swarm related to the stimulation experiments, we also identified several seismic swarms at shallow depth which imply relatively active geological structures in the study area.

Keywords: borehole seismometer, induced earthquakes, focal mechanism of micro-earthquake

Focal Mechanisms and Seismicity in the Region of Induced Earthquakes of Song Tranh Dam, Vietnam

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Vietnam is located in South East Asia and bounded by the Pacific and Mediterranean-Himalaya seismic belts on its eastern, western and southern sides, respectively. The dynamic tectonic processes in this region cause the territory of Vietnam and adjacent areas to have intensive differential movement, making the regional tectonic structure very complicated. The tectonics have led this territory to have moderate seismic activity and complicated geological structures, such as the Lai Chau-Dien Bien fault zone, Red River fault zone, and others. Southern Vietnam was considered to be a region with low seismicity, compared to the North. However, the sequence of earthquakes that occurred at Song Tranh Dam during the last several years surprised many scientists because the southern region of Vietnam was not expected to have major tectonic activity. This region where many induced earthquakes are now occurring is associated with the filling of a new reservoir. There have been four M4 earthquakes (maximum earthquake was 4.7 in November, 2012), so it is one of the most active induced earthquakes examples in the world. It is important to determine the strong motion attenuation relations for this area since damaging earthquakes may be expected in the near future. We collect and process data from 5 seismic stations around Song Tranh dam, include more than 300 events larger than 1.5 and more than 2000 seismic waveforms to determine arrival times and locate the earthquakes in the Song Tranh dam region. In this study we use time domain analyses to determine focal mechanisms. We use software of Dreger and Ford (2011) modified for the Song Tranh Dam region. Induced earthquakes processed by this software include events withmagnitudes larger than 3.5 and recorded on 4 or more stations.

We also compare our results with mechanisms for tectonic earthquakes in the region (Hung Nhuong Tavi and Tra Bong faults). The results show a difference in focal mechanism between tectonic earthquakes and induced earthquakes which may be related to the increased fluid pressure from filling of the reservoir. To confirm this result, we will need to process the many smaller events with magnitude less than 3.0, which have occurred around Song Tranh Dam.

We used a genetic algorithm method to estimate the local velocity structure. We applied this method to determine a layered model for the Song Tranh dam region. Our results obtained a new 1D model of 7-8 layers. The shallow P wave velocity of 4.6 km/s is slower than 5.9 km/s for previous studies in northern VietNam. For a deeper layers from 6 to 12 km, P wave velocity becomes larger, 5.4 km/s −5.9 km/s. The Vp/Vs shows relatively higher values of 1.75-1.77 for the depth around 12 km. When layer thickness changes from 21 km to 28 km, the P wave velocity increases and changes from 6.5 km/s to 7.3 km/s, however, Vp/Vs ratio decreases from 1.77 to 1.67. Finally, the depth of the Moho surface changes from 28 to 35 km and the P wave velocity changes from 7.8 to 8.2 km/s, with Vp/Vs value of about 1.78. Earthquakes still occur at Song Tranh dam (a recent M3.3 occurred on August,26th 2015), and more than a thousand earthquakes with magnitude less than 1.5 have not yet been processed. We continue to update the seismic analyses with information from smaller earthquakes to improve our results.

Keywords: Song Tranh Dam, Focal Mechanism, Velocity structure, induced earthquake

Detectability of temporal variation of b-value prior to two earthquakes (Mj6.3 in 2013, Mj5.1 in 2014) in Northern Tochigi Prefecture

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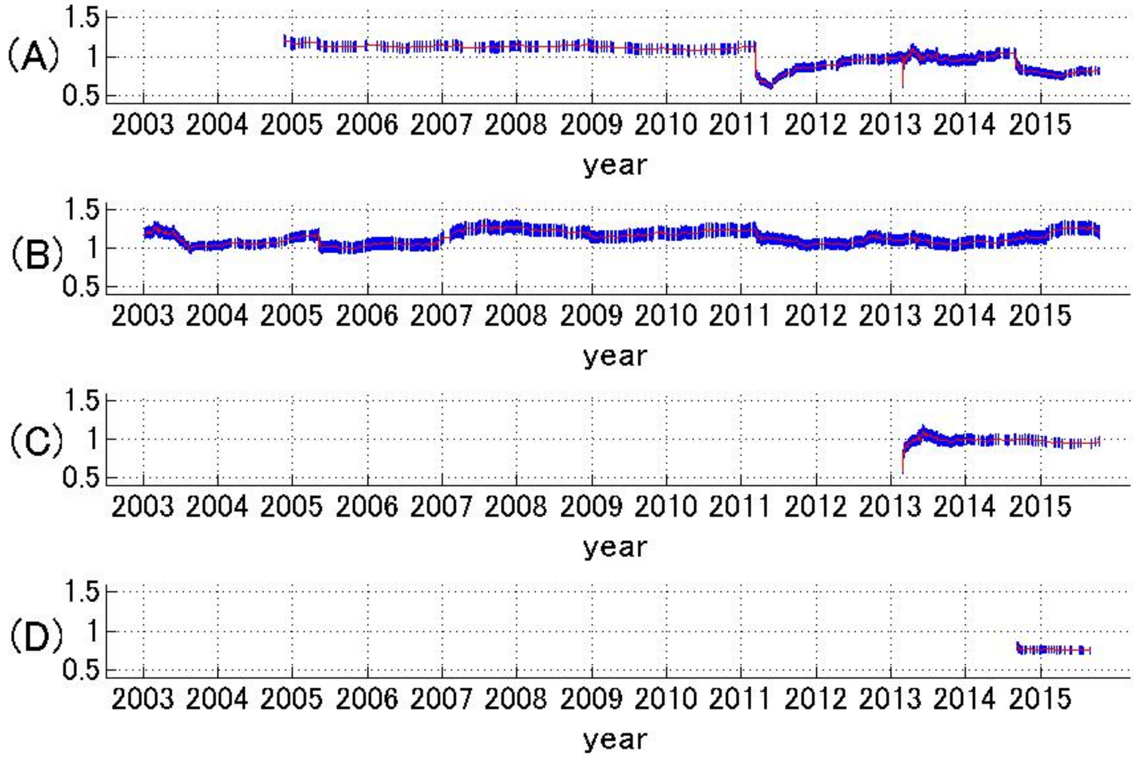
It has been reported that the b-value decreases prior to large earthquakes in nature (e.g., Imoto, 1991) and failure of a rok sample in laboratories (e.g., Scholz, 1968) . To discuss a temporal variation of the b-value, a sufficient number of earthquakes is required. In general, calculation of b-value prior to large earthquakes requires long-term data because seismic activity is not always high at that term. In other words, the temporal resolution of b-value variation before a large earthquake is usually low. Therefore, sufficiently high seismic activity before the large earthquake is required to evaluate the b-value variation precisely.

For example, two major earthquakes occurred in northern Tochigi Prefecture: Mj6.3 in 2013 and Mj5.1 in 2014. The two events followed the increase of seismic events. One possible cause of this increase is the Mw9.0 Tohoku earthquake in 2011 (e.g., Aketagawa, 2011).

In this study, we try to detect the temporal variation of the b-value in northern Tochigi Prefecture where a large number of earthquakes could be observed in a short period prior to the two major events. First, to increase the temporal resolution, we calculate the b-value for a circular region with 20km radius from the epicenter of the Mj6.3 event; the result is shown in Figure A. While the b-value was greater than 1.0 and stable before March 2011, it dramatically decreased to ~0.6 after the occurrence of the Tohoku earthquake in 2011 and recovered to around 1.0 almost within one year. After that, it decreased to ~0.7 again following the Mj6.3 event in 2013 and recovered to ~1.0 within a small period. Although it decreased to ~0.75 again following the Mj5.1 event in 2014, it did not recover but continued, at least, one year. Regarding these different variations in each sequence, we considered the seismic activity in northern Tochigi precisely. We consider regions 1, 2, and 3. The region 1 is located south of the source region of the Mj6.3 event and includes an active fault. The regions 2 and 3 include the source areas of the Mj6.3 and Mj5.1 events, respectively. The temporal variation of b-value for each region is shown in Figure B, C, and D. In region 1, constant seismic activity has continued for the whole term and the b-value was stable and greater than 1.0. The b-values are also stable but ~1.0 in region 2 and ~0.75 in region 3. On the basis of these results, we found that the temporal variation of the b-value of the entire region is affected by the temporarily activated one of the three regions. However, in regions 2 and 3, the numbers of events to calculate the b-value precisely are insufficient despite their activation. So we found that we cannot detect temporal variation of the b-value prior to the major events. This finding tells us that we need to consider the target region carefully when we research the temporal variation of the b-value.

Acknowledgments
In this study, we used the JMA unified hypocenter catalogue.

Keywords: b-value, Northern Tochigi Prefecture, seismic activity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Spatiotemporal variation of earthquake-tide correlations after the 2011 Tohoku earthquake

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We examined correlations between tides and earthquakes off the Pacific coast of eastern Japan for about five years after the 2011 Tohoku earthquake (Mw 9.1). A previous study by Tanaka (2015) using the earthquakes with Mw 5.0 or larger in the Global Centroid Moment Tensor (CMT) catalog after the Tohoku earthquake showed significant correlations on the northwest side of the large-slip area of the Tohoku mainshock, where large postseismic afterslip has been identified by geodetic measurements (Ozawa et al., 2012; Sun et al., 2014). In the present study, we extend this work to a larger catalog including smaller earthquakes, to more thoroughly explore the earthquake-tide correlations. In about ten years prior to the Tohoku earthquake, high correlations were observed in the northern part of the Tohoku source area where the mainshock rupture initiated (Tanaka, 2012); however, those correlations could not be seen with smaller earthquakes (Tanaka and Asano, 2012).

The data we used are the CMT solutions of 1068 interplate earthquakes with Mw 4.0 or larger from the Tohoku earthquake to December 2015, which were determined by the waveform inversion of seismograms from the NIED Hi-net and F-net stations (Asano et al., 2011). Based on tidal phase angles at the earthquake origin times derived from theoretically-calculated tidal Coulomb failure stresses with a friction coefficient of 0.2 (Tanaka et al., 2012), we evaluated the Shuster's p-value (Schuster, 1897), which represents the significance level to reject the null hypothesis that the earthquakes occur randomly irrespective of the tidal phase angle.

We examined the spatial distribution of p-value using the 200 km x 200 km moving windows for the period after the Tohoku earthquake. The results indicate significant correlations on the south side of the Tohoku large main-slip area. The smallest p-value of 0.52% was observed in the window located off Ibaraki prefecture. The temporal variation of p-value in this region shows the p-value was larger than 10% just after the Tohoku earthquake and gradually decreased with time. The p-value in the latest 700 days is 0.09%. When using only larger earthquakes, we found no significant correlation in this region; we can see p-values smaller than 5% with the earthquake magnitude cutoff smaller than 4.8.

On the other hand, with increasing the earthquake magnitude cutoff, we observed high correlations on the northwest side of the Tohoku large slip area. The highest correlation was seen when the magnitude cutoff was set to be 4.8, and the smallest p-value of 0.63% was obtained in the window located near the coast off Iwate prefecture. The area of high correlation is well correlated with the large afterslip area (Ozawa et al., 2012; Sun et al., 2014), as documented in the previous work (Tanaka, 2015). The temporal variation of p-value shows that the p-value was smallest (0.12%) just after the Tohoku earthquake and gradually increased with time. No significant correlation was found after 2014 in this region.

Keywords: the 2011 Tohoku earthquake, earth tides, earthquake triggering

Retrospectively forecasted seismicity in eastern Japan using spatio-temporal kernel smoothing

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The best and pervasive statistical model to describe seismicity is the ETAS (Epidemic Type Aftershock Sequence) model (Ogata, 1988) which is based on modified Omori law and explain secondary aftershocks together with background seismicity. The ETAS model better explains mainshock-aftershock sequence but does not always fit earthquake swarm. Helmstetter and Werner (2014) instead proposed a simple, nonparametric model using a spatio-temporal kernel smoothing, without using the modified Omori law.

We applied the smoothing kernel model not only to the mainshock-aftershock type sequences, such as the Tohoku-oki earthquake (2011.3.11 M9.0) and the Iwate-Miyagi Inland earthquake (2008.6.14 M7.2) but also to a significant earthquake swarm in the Izu Peninsula that occured in 2000 to compare with the ETAS model. As a result, our kernel model for the mainshock-aftershock type earthquake performed almost same accuracy as the ETAS model did, except the significant underestimate immediatery after mainshock. Furthermore, the case of Tohoku-oki earthquake that a large foreshock (2011.3.9 M7.3) was observed, the number of predicted earthquakes became several hundred times higher than the background rate during the time period between the foreshock and M9 mainshock. Although the probability gain was about several hundred times higher than the one in a few days after the Iwate-Miyagi Inland earthquake, probability gain was low in a few days after the Tohoku-oki earthquake compared to that for the Iwate-Miyagi Inland earthquake. Because we applied the two-dimentional model only using earthquakes shallower than 30 km, the prediction accuracy of the interplate earthquakes is lower than that of the inland earthquakes. In the case of the earthquake swarm occurred in the Izu Peninsula, our kernel model was able to better estimate the seimicity than the ones by the ETAS model.

Keywords: smoothing, aftershock, earthquake swarm

Quantification of the cross-correlation criteria for small foreshock detection

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Recently, small foreshocks have been frequently detected using a cross-correlation technique (e.g., Bouchon et al., 2011, Science). For inland earthquakes, foreshocks whose hypocenters were estimated to be adjacent to the mainshock hypocenter were detected from several tens of minutes before the main shock occurrence (Doi and Kawakata, 2012, GRL; 2013, EPS). Toyomoto et al. (2015, SSJ) tried to detect foreshocks of an M 5.4 earthquake in central Nagano prefecture on June 30, 2011, in a similar manner to Doi and Kawakata (2013). Using the continuous waveforms of the vertical component at N.MWDH (Hi-net) station (the epicentral distance of the mainshock is 4.5 km), they newly detected 14 foreshocks with a cross-correlation criterion of 0.6, in addition to 27 foreshocks listed in the JMA (Japan Meteorological Agency) unified hypocenter catalogs. To efficiently detect small foreshocks for other inland earthquakes, it is necessary to design how to set the cross-correlation detection criterion for foreshock detection.
In this study, we carried out foreshocks detection of the same earthquake in the same method as Toyomoto et al. (2015, SSJ) using the waveform record of N.MNYH (Hi-net) station (epicentral distance of main shock is 5.3km). In this case, the maximum correlation coefficients during one minute tended to be higher than those for records at N.MWDH station, and the result of detection strongly depends on a threshold employed in a cross-correlation method. This indicates that we should not use a universal threshold independent of data. One of alternative way is to use the standard deviation of cross-correlation coefficients. Then, we made a histogram of the cross-correlation coefficients of 1-day data. The histogram of N.MWDH data is Gaussian and the cross-correlation coefficients obey a normal distribution with the average of zero. Although the histogram of N.MNYH data is not Gaussian, so the cross-correlation coefficients have a large-deviation. In such a case, a criterion depending on the standard deviation is inadequate.
Acknowledgments:
We used continuous waveform records of NIED high-sensitivity seismograph network in Japan (Hi-net) and the JMA unified hypocenter catalogs.

Keywords: foreshock, cross-correlation, detection criteria

Improvement of determination of hypocenters by pop-up type ocean bottom seismographs near Ogasawara Islands

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There are only three permanent seismic stations in Ogasawara Islands, two Chichi-jima and one Haha-jima stations. Hypocenters, therefore, can be poorly determined in regard to locations of the east-west direction.

Meteorological Research Institute (MRI) deployed pop-up type Ocean Bottom Seismographs (OBSs) to investigate the more accurate locations of hypocenters than JMA catalogue in this area. The observation network covers the area of the range 26-29°N and 140-143°E. Observation period was from 15 Jul. to 10 Oct., 2015. We analyzed the eight continuous data at OBS stations and determined the hypocenters. We compared hypocenters determined by the OBS data with those of JMA catalogue. We extracted 31 events as the same events whose difference between the origin time by the OBS and the JMA are within three seconds. The hypocenters by the OBS tend to be shifted by 30′to 1°westward from those of the JMA. Its tendency is same as the result between hypocenters by the USGS and the JMA. It suggests that the locations of hypocenters can be improved by applying the results to the data of only permanent stations.

Keywords: Determination of hypocenters, Ocean Bottom Seismographs (OBSs), Ogasawara Islands

Determination of focal mechanism solution using simulated annealing

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Many seismologists have determined focal mechanism solutions using grid search (e.g. Nakamura and Mochizuki, 1988, QJS) or genetic algorithms (e.g. Kobayashi and Nakanishi, 1994, GRL). However, simulated annealing (SA) that is known as one of the efficient methods for global optimization has never been used to determination of this solution, although it allows for getting an optimal solution by jumping out of local minimum. In this study, we apply the SA to determination of focal mechanism solution. When we express the null, pressure and tension axes using a set of Euler angles (e.g. Nakamura and Mochizuki, 1988), the optimal set of Euler angles is determined by minimizing difference between synthetic and observed polarity of P-wave first motion. To investigate the feasibility of the application, we determine focal mechanism solution of the 14 March 2014 Iyo-Nada intermediate-depth earthquake (M_{JMA} 6.2). The computation of SA method is then about the 1278 time faster than the grid search method. Strike, dip and rake angles calculated by the optimal set of Euler angles is nearly identical to focal mechanism reported by the Japan Meteorological Agency (JMA).
Acknowledgements: We used JMA Unified Hypocenter Catalogs. We also used a computer program disclosed by CSIRO for simulated annealing.

Keywords: focal mechanism solution, simulated annealing, grid search

The 2011 M6.4 Shizuoka earthquake sequence: triggering process investigation

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Many inland areas in Japan were seismically activated following the 2011 M9.0 Tohoku-oki earthquake. The activation mechanism includes triggering by dynamic, static or fluid-induced stress changes (e.g., Toda et al., 2011; Miyazawa et al., 2011; Shimojo et al., 2014). In this study we aim to understand the triggering processes associated with the 2011 M6.4 Shizuoka earthquake sequence; the mainshock of the sequence occurred on March 15, close to Mt. Fuji.
To improve the detection of smaller earthquakes, we have applied the Matched Filter Technique (MFT; Peng and Zhao, 2009) for the time interval from the Tohoku-oki earthquake until seven hours after the Shizuoka earthquake. We used Hi-net (NIED) continuous waveform data and seismograms of 1126 template events with M >= 1.0, which occurred in the study area between 2001 and 2014. The total number of Hi-net stations used was 25, selected within a 40 km radius from the main shock.
No foreshock activity was detected prior to the March 15 Shizuoka earthquake, which contrasts with other similar inland seismicity activations following the Tohoku-oki earthquake (e.g., Kato et al., 2013; Shimojo et al., 2014). Since the co-seismic static stress change due to the Tohoku-oki earthquake on the Shizuoka fault plane was significant (~0.5 bar), we argue that this is likely the most significant triggering mechanism and the delay of this sequence could be explained by the rate-and-state friction law (Dieterich, 1994).
The aftershock detection for the first 7 hours following the M6.4 event was significantly improved. When looking at the space-time distribution of the MFT detections, we observe that the earliest aftershocks (first minutes after the Shizuoka earthquake) occur to the north, close to Mt. Fuji, likely due to a stress increase from the Shizuoka mainshock. Indeed, by comparing the locations of these events with the slip model of Shizuoka earthquake derived from strong-motion data (JMA, 2011), we observe that they occur at the tip of the mainshock rupture.
The largest earlier aftershocks (M >= 4.0) occur as well in the north region. Aftershock distribution and focal mechanism data suggest that the northernmost earthquakes may have occurred on a different fault segment.
We also detect a rather gradual expansion of the aftershock distribution to shallower depths; the delay of activation in the shallow part remains to be further explored.

Keywords: seismicity, 2011 Shizuoka earthquake, triggering

Re-evaluation of Hypocenter of the Sakurajima Earthquake on January 12,1914

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The hypocenter of the Sakurajima Earthquake on January 12,1914 is Kagoshima-Bay in general.
The 100th anniversary passes from 1914 Eruption of Sakurajima, we determine hypocenter of this earthquake by using selected S-P time data not only reported ones but also re-measured from smoked-paper seismograms. As a result, the hypocenter is revealed near by Kagoshima-city.
The direction of first motion of smoked-paper seismogram recorded at of the Kagoshima meteorological observatory shows the hypocenter being located SE from the Kagoshima meteorological observatory.

Keywords: The Sakurajima Earthquake on January 12,1914, smoked-paper seismogram record, first motion analysis, S-P time (Duration of Preliminary Tremor), hypocenter determination

Nucleation Process of the 2011 Mw6.2 Northern Nagano Earthquake

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Introduction. Previous research.

An Mw6.2 inland earthquake occurred in northern Nagano region, central Japan, about 13 hours after the Mw9.0 Tohoku-oki megathrust earthquake. The regional seismic activity recorded in the Japan Meteorological Agency (JMA) catalog in the first hours following the megathrust event was highly incomplete, thus not allowing a detailed analysis of triggering mechanisms. By applying a Matched Filter Technique (MFT) to the continuous Hi-net (NIED) waveform data, Shimojo et al. (2014) revealed an immediate post-Tohoku seismicity activation in an area located about 10 km south of the Mw6.2 Northern Nagano source region. They also detected a few foreshocks close to the hypocenter of the Mw6.2 mainshock, within one hour before the occurrence of the moderate-size event. However, the physical processes that led to the occurrence of the Mw6.2 earthquake remained unclear. In this study we take advantage of the data recorded by a dense temporary seismic network operated by NIED from 2008 to 2012 to reveal with an unprecedented resolution the nucleation process that culminated with the occurrence of the Northern Nagano earthquake.

Data and Method

We use the waveform data of the NIED “Hizumi” temporary network, with station spacing of about 5 km or less in the study area. The data recorded by the permanent Hi-net stations (spacing of about 20 km) complements that of the dense regional network. We have first picked P- and S-wave arrivals of earthquakes on the continuous seismograms and use the pick data to locate the events. The earthquakes were then relocated using the tomoDD software (Zhang and Thurber, 2003) and a 3D velocity structure in the region (Sekiguchi et al., 2013). The newly located earthquakes were further used as MFT templates to search for new events within the 13-hour time interval, in the hypocentral region of the Mw6.2 earthquake.

Results and Discussion

We have detected a total of 286 earthquakes in the source region of the Mw6.2 event. The earthquakes are relatively small, with magnitudes less than 3.0, and distribute within two spatially distinct clusters: one of these clusters was located close to the hypocenter of the Mw 6.2 event (“West” area), the other about 5 km to the east (“East” area).

In the “East” the seismicity starts within one hour after the Tohoku-oki earthquake. The events occur off the Mw6.2 fault and expand with time from shallow towards deep locations. In the “West” the seismicity starts immediately after the passage of surface waves excited by a moderate earthquake in the Tohoku-oki aftershock area, which occurred 21 minutes after the Mw9.0 megathrust; the majority of these events distribute along the fault line of the Mw6.2 mainshock. The seismicity (in the “West”) that occurred in the immediate vicinity of the Mw6.2 hypocenter was activated about 3 hours before the mainshock and continued until its occurrence.

In both “West” and “East” regions the seismicity activation pattern shows correlation with the amplitude of the low-frequency waveforms observed at a nearby Hi-net seismic station. Such a correlation may indicate that dynamic stress changes caused by the aftershocks of the Tohoku-oki megathrust event effect the seismicity in both areas. The triggering “sensitivity” might be enhanced by excitation and circulation of fluids, which are abundant both within the shallow thick sediment as well as the lower crust of the Nagano basin, as revealed by high-resolution tomography studies (Sekiguchi et al., 2013).

Keywords: the 2011 Northern Nagano earthquake, dense temporary regional network, Matched-Filter Technique, dynamic triggering, migration of pore-fluid

The 3-stage earthquake generation process observed during 3 months before the 2011 Tohoku earthquake

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1.none

1 Introduction

Various phenomena were observed before the 2011 Tohoku earthquake. As for the broad band seismic network; F-net, its availability degraded. The 1st degradation occurred from December 22, 2010 to January 18, 2011, then 2nd one occurred from February 16 to March 2, after the part of the first degradation recovered to normal status. The main shock occurred on March 11, after the part of the second degradation returned to normal again.

Remarkable improvement of such measuring instrument as GNSS in recent years gives useful information about movement of crusts. So, seismic activities and measuring results of GNSS etc. are added to further check the degraded situation of the F-net.

2 Analysis

It seems that the period of approximately 3 months before the earthquake was consisted of 3 stages indicated below.

First stage

Period: End of December, 2010 to End of January, 2011.

Analysis: Accumulation of strain in the continental plate reached maximum limit in the Tohoku and Chubu regions. Possibly as a result of such situation, the wide area in Japan showed vibration or slip. Then the Pacific ocean plate stopped its advancement. Since such movements are on several day-basis, this slipping is the one like Creep. They occurred in the area far from the epicenter, the epicenter have not been formed at this moment.

Second stage

Period: Middle of February to early March

Analysis: As a result of the first stage, restless increase of stresses by the Pacific ocean plate can not be accepted any more. Then, small breakage was formed near the initial rupture point of the earthquake.

Third stage

Period: Several days before to the day of the main shock on March 11.

Analysis: Slipping of the continental plate started, and it reached the main shock.

Observed phenomenon:

On March 8, eastward movement was recorded by GNSS.

The Sanriku-oki earthquake (M7.3) occurred on March 9. The earthquakes with magnitude of 6 followed.

On March 11, The main shock of the Tohoku earthquake occurred.

Keywords: 2011Tohoku earthquake, F-net, GNSS

	2010/Dec	2011/Jan	/Feb	/Mar 3/11
東北地方の動き (Move. of Tohoku area) **地震・火山活動** (EQ and Volcano)	―――――― （西へ移動） X 父島近海 地震 M7.4	――――――X （停止） X　（新燃岳 箱根直下 低周波地震	噴火）X――――X 震源域付近 M5 以上地震	―（東へ移動） XX 震源域付近 M7.3− M9 地震
GNSS（広域の動き）		X　X 南,上方　西,下方		X（前兆滑り）
F-net（欠測）	――――	―――― 三陸・北海道南部 及び能登・伊豆で欠測	―――― 三陸・北海道 南部で欠測	
解釈（Analysis）		**第一段階（1st stage）** 陸側プレートの広域で歪の蓄積が限界に到達。 陸側プレートは弾性を失い広域で動きを示した。	**第二段階（2nd stage）** 陸側プレートと太平洋プレートの境界に部分的な破壊箇所が生まれた。	**第三段階（3rd stage)** 部分的な破壊箇所が広域の破壊（本震）に発展した。

図１. 2011 年東北地方太平洋沖地震発生までの３段階の過程

Fig1. 3-stage process before the 2011 Tohoku earthquake