Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS27-01 Room:201B Time:May 22 09:00-09:15

High-frequency seismogram envelope synthesis of early aftershock sequences

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The detection of early aftershocks is challenging because their waveforms are hidden by the large amplitude of coda waves of the mainshock and are obscured due to the occurrence of a large number of events in a short time interval. The lack of early aftershocks in an earthquake catalog could bias the analysis and modeling of aftershock activity. In order to investigate the excitation of early aftershocks quantitatively, it is better to regard the early aftershock sequence as a continuous energy radiation process rather than discrete earthquake occurrence. In this study, we theoretically synthesize envelopes of 1-16 Hz seismograms by convolving the energy of coda waves excited by an impulsive source with the energy radiation function of an aftershock sequence. The radiative transfer theory, which accounts for the spatio-temporal distribution of the multiply scattered wave energy, is used to describe the coda excitation process. The scattering coefficient and the intrinsic absorption factor used in this theory are independently estimated from the coda wave of small earthquakes. The Omori-Utsu law, the Gutenberg-Richter law, and an omega-square source spectrum are used to describe the energy radiation function. The p- and c-values of the Omori-Utsu law and the b-value of the Gutenberg-Richter law are chosen based on results reported in the literature.

When the seismogram of an Mw7 mainshock is observed at hypocentral distances of 10-30 km, our theoretical modeling shows that the energy of scattered waves dominates over the energy excited by the early aftershocks in the first 30-100 s after the mainshock. At this lapse-time range, the envelope amplitude decays exponentially according to the functional form of the radiative transfer equation. The envelope amplitude increases as the dominant frequency decreases because the lower frequency energy is effectively excited for larger earthquakes and the attenuation of coda wave is slower at lower frequencies. On the other hand, the energy excited by early aftershocks becomes dominant after 30-100 s after the mainshock. At these later times, the envelope amplitude decays as a power-law due to the functional form of the Omori-Utsu law. Since smaller aftershocks occur more often than larger ones according to the Gutenberg-Richter law, the amount of the higher frequency component of the seismogram envelope with respect to the lower frequency counterpart increases at later times. These theoretical characteristics are confirmed by the analysis of the continuous waveforms of the 2008 Mw6.9 Iwate-Miyagi earthquake and its early aftershocks recorded by Hi-net stations.

Keywords: early aftershocks, seismogram envelope, high frequency, coda wave, Omori-Utsu law, Gutenberg-Richter law

SSS27-02 Room:201B Time:May 22 09:15-09:30

Detection of immediate aftershocks using seismogram envelopes as templates

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Hypoceneter location and its temporal variation of aftershocks are the source of information of mainshock rupture and stress perturbation around the fault. Since the number of aftershocks decays exponentially, study of immediate aftershocks is important to get the above information. However, the location of immediate aftershocks is difficult due to coda wave of mainshock and successive occurrence of afterrshocks.

Here we propose a new method of hypocenter location using seismogram envelopes as templates. There has been proposed some location methods using aftershock seismograms as templates. Our method employs envelope that are the logarithm of root-mean-squared (RMS) amplitude of band-pass filtered seismogram. The envelope is smoother and more stable than seismogram, and it changes absolute value with the earthquake magnitude but keeps its shape, which is the advantage of the use of envelope.

The proposed method composes of two processes. The first process is the calculation of cross-correlation coefficients between a continuous (target) envelope and template envelopes. Assuming an origin time, we set time windows in the target and templates to calculate the cross-correlation by referring to the arrival times of P-wave of template events. We define the average cross-correlation among the stations and three components as the cross-correlation for each template. We repeat this process by shifting the origin time to obtain a set of cross-correlation values for pairs of (origin time, template).

The second process is the event detection and location. First, we search for the maximum cross-correlation among all pairs of (origin time, template), which gives the origin time of the first event and corresponding template. At present, we simply regard template location as the location of the detected event. Magnitude of event is calculated by the amplitude ratio of target and template envelope. To avoid duplicate detection around this event, we set a dead time of detection around the origin time of the first event. Then we search for the second highest cross correlation value in a time window excluding the dead time. We repeat this procedure until the highest cross-correlation value falls below a threshold.

We applied this method to a data set of the 2004 Mid-Niigata Prefecture (Niigata-Chuetsu) Earthquake (M = 6.8) in central Japan. Aftershock activity of this earthquake is extensive with a number of aftershocks with magnitude greater than 6.0, and with a complex fault system that consists of two parallel westward-dipping faults and a conjugate fault plane. We tested the method by using target envelopes of two stations, 34 templates with a length of 8 s, both in a center frequency of 4 Hz. During a period of one-hour from the mainshock, we could detect 71 events, which are comparable to the number of the catalog events. The location of events are generally near the catalog location, however, the event magnitude is systematically larger than the catalog value. Of course the result depends on the above parameters and we should develop a method of suitable selection of parameters. In addition, we should improve the method of magnitude estimates and, most importantly, relative location of events against templates. Though we have much job to do, we conclude that the employment of envelopes as template works adequately even just after the mainshock of large inland earthquake.

Acknowledgement: We used hypocentral parameters and arrival time data of the JMA catalog that was prepared by the JMA and the Ministry of Education, Culture, Sports, Science and Technology in Japan. I thank the National Research Institute for Earth Science and Disaster Prevention (NIED) and the University of Tokyo for providing waveform data. This work was supported by JSPS KAKENHI Grant Number 23540487.

Keywords: aftershocks, hypocenter location, template, envelope, correlation, Chuetsu earthquake

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS27-03 Room:201B Time:May 22 09:30-09:45

Estimation of faulting types of small earthquakes using template events east off Tohoku

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In the northeastern Japan subduction zone, there are many earthquakes with various focal mechanisms. The most reliable focal mechanisms are those evaluated using CMT solutions, but it is difficult to estimate CMT of small earthquakes. However, it is essential to know focal mechanisms of small earthquakes to discuss earthquake generation process in detail.

In this study, we have developed a new method that classifies small earthquakes into several groups of faulting types. In the method, we used template events whose focal mechanisms are known. For pairs of target and template events, we evaluated the similarities of the waveforms for several stations. If the two events are located at the same location and have the same focal mechanism, they should show very similar waveforms at the same station. Thus if the cross-correlation coefficients are large for two events, we can consider the two events have similar focal mechanisms. As a first step, we examined relationship between the focal mechanism differences and the waveform cross-correlation coefficients whose focal mechanisms are known. Here, the differences in focal mechanisms were quantified by using minimum 3D rotation angle (Kagan, 1991). The P and S waves were separately analyzed by using 10 second time windows to reduce the effect of the separation distance between the two earthquakes. Although there were many event pairs with low cross-correlation coefficients for event pairs with small differences in the focal mechanisms, we found that event pairs with large cross-correlation coefficients (CC) always had small differences in focal mechanisms and small inter-event distances. According to the evaluation of the focal mechanism-known pairs, we adopted a threshold of $CC>=0.6$ to select events with similar focal mechanisms.

As a second step, we calculated CC of event pairs; in each event pair, the focal mechanism of one event (template event) is known but the other (target event) is not. We classified events using the threshold of $CC>=0.6$. Most events were classified as thrust faulting and some events were normal faulting.

Although we need more effort to optimize the method, our method based on template events has a potential of classifying large number of earthquakes into several fault types.

Keywords: focal mechanism, template event, subduction zone

Japan Geoscience Union Meeting 2013
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SSS27-04 Room:201B Time:May 22 09:45-10:00

Small repeating earthquakes after the 2011 off the Pacific coast of Tohoku earthquake (2)

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The 2011 off the Pacific coast of Tohoku earthquake (Mw9.0) was the largest earthquake in recorded history in Japan. For the stress changes by this earthquake, many aftershocks and induced earthquakes have occurred in and around the source regions. In this study, I show the space-time characteristics of the inter-plate aseismic slip from sequences of small repeating earthquakes in Japan after the 2011 Tohoku earthquake.

I have already detected many small repeating earthquakes occurred at the upper boundary of the subducting plates in Japan before the 2011 Tohoku earthquake. The inter-plate slip-rates estimated from these sequences were consistent to the space-time changes of the inter-plate coupling. I also identified aseismic slips following large inter-plate earthquakes occurred in 2003 to 2008 and quasi-static slips associated with foreshocks off Miyagi that started from 2011.

After the 2011 Tohoku earthquake, seismic activities of small repeating earthquakes become active around the source regions. They are particularly active in the northwestern deeper part of the 2011 main-shock and its large aftershocks. The cumulative slip is more than 4 m in the most frequent area and is consistent to the value estimated from GPS data analysis. Detected sequences also show post-seismic slips at the trench-side of the northern and southern part of the source region in the subducting Pacific plate and in the subducting Philippine Sea plate beneath the metropolitan district, which suggest induced inter-plate slips. In two years after the earthquake, the slip-rates are three to five times of the relative plate motion in the north and western part. On the other hand, they are almost decreasing to the rate before the 2011 main-shock in the southern part. I cannot detect small repeating earthquakes within coseismic slip areas of the 2011 main-shock and large aftershocks after the 2011 main-shock. Distributions of small repeating earthquakes probably outline their large slip areas. Therefore, I suggest that both coseismic slip areas and after-slip areas of large earthquakes can estimate from the space-time changes of small repeating earthquakes.

Some of small repeating earthquakes are burst-type sequences which occur only after the 2011 Tohoku earthquake. Observed seismograms may be distorted by the multiplicity of the seismic waves to come from various places, the seismic velocity changes at the propagation path or site, or changes of physical properties at the plate interface. Other repeating sequences, which classify in continuous type conventionally and are not detected after the 2011 main-shock, seem to be included in earthquake clusters influenced for the recurrence cycle of the larger earthquake. We should pay attention to future activities to investigate whether physical property at the plate interface has changed by the effect of inter-plate large slip and stress changes.

Keywords: The 2011 off the Pacific coast of Tohoku earthquake, small repeating earthquake

SSS27-05 Room:201B Time:May 22 10:00-10:15

The great 1933 Sanriku-oki outer-rise earthquake: Relocated aftershocks, recent seismicity and fault scarp morphology

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The 1933 Sanriku-oki earthquake is the largest earthquake that occurred outer trench-slope region of the northern Honshu, Japan. Recent observations and analyses on earthquakes, such as 2006 and 2007 Kuril earthquakes, 2004 Sumatra earthquake suggest the interactions between outer-rise and interplate thrust earthquakes. Thus it is important to examine the mechanisms of the aftershocks of the 1933 earthquake that encompass a wide area including the inner trench region according to the JMA location. In this study, we examined the data quality of the 1933 earthquake based on smoked paper records and relocated the earthquakes by using phase data from regional stations and modern relocation methods. Relocations by the double-difference method show about 170 km long aftershock area under the outer trench slope that is separated from the seismicity under the inner trench slope. The earthquakes under the inner trench slope were located where recent activity of interplate thrust earthquakes is high. Separation of aftershock activity between outer trench-slope and inner trench slope was also confirmed by a examination of recent earthquakes that are accurately located based on OBS data at the study area. Earthquakes under the inner trench slope immediately after the 1933 Sanriku-oki earthquake are consistent with earthquake location discrimination based on waveforms and S-P time data (Umino et al. 2007). These two regions of seismicity suggest stress triggering of interplate earthquakes by the deformation from the 1933 outer-rise earthquake. We also relocated pre March 11th, 2011 seismicity near the trench region. The result show the present seismicity at the outer trench-slope region of northern Honshu can be divided into several groups of earthquakes along the trench; one group roughly corresponds to the aftershock region of the 1933 earthquake. Comparison of the 1933 rupture dimension based on our relocations with the morphologies of fault scarps in the outer trench slope suggest that the rupture was limited by the region where fault scarps are trench parallel and cross cutting seafloor spreading fabric.

Acknowledgements: We thank R. Hino and K. Obana for providing relocated hypocenter of earthquakes based on OBS data, Y. Tamura for access to seismograms of the 1933 earthquake and its aftershocks recorded at the Mizusawa observatory and JMA for phase data of earthquakes.

Keywords: 1933 Sanriku-oki earthquake, outer-rise earthquake

Japan Geoscience Union Meeting 2013
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SSS27-06 Room:201B Time:May 22 10:15-10:30

An approximately-nine-year-period variation in seismicity and crustal deformation near the Japan Trench

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It is well known that the statistical probability of earthquake occurrences changes over the course of a day due to periodic variations in the tidal stress acting on faults. However, periodicity on a decadal scale has been studied by relatively few people. It has been reported that approximated ten-year periodicity is observed globally for the seismicity of M-8-class large earthquakes. However, the mechanism underlying this periodicity has not yet been revealed. In this study, decadal-scale periodicity of earthquakes along the Japan Trench is investigated. A new finding is presented that in northeast Japan, since 1923, the probability of the occurrence of earthquakes with an M >=5 has increased approximately every nine years. This increase in probability is also evident for historic events with an M>=6 that occurred during the past one thousand years, implying the presence of a periodic stress disturbance at an appreciably regular interval. Periodicity becomes even more apparent for large earthquakes with an M>7.5 and about half of the recorded 29 events intensively occurred within two successive years on a cycle of approximately nine years. The past strain and tilt observations conducted in Japan during the 1950s through the 1970s indicate that nation-wide gradual compression was repeating every 8–10 years in the direction of relative plate motion. These compression periods are in accordance with the periods of higher seismic activity discussed above. As a first step in investigating the origin of earthquake periodicity, periods associated with lunar motion are considered. It is shown that a long-term motion primarily governed by the period of the lunar perigee is synchronised with the cyclic variation in seismicity and crustal deformation described above. Decadal changes in tidal stress, as calculated using an ordinary theory of solid Earth tide, are too small to cause periodic variations in seismicity. Therefore, the conditions by which tidal stress is sufficiently amplified to trigger an earthquake are investigated. The results show that, if assuming that a tidal force acts on a spherically asymmetric block-like upper mantle beneath the Pacific Plate, the computed phase and amplitude can explain the observations. Otherwise, it is difficult to consider direct tidal force alone as the main source of periodic variations in seismicity. Other possibilities should be considered, such as unknown interactions between the plate boundary and the ocean/atmosphere with a period of around nine years or a resonance between the period of the tidal force and a recurrence period of slow slip events in the transition zone on the plate boundary. Apart from understanding the origin, the important fact confirmed in this study is that in some areas, the occurrence of large earthquakes, if considered as a group, appears to be strongly governed by a periodic stress disturbance rather than by completely random processes. Elucidating the wide-range approximated nine-year mode helps us narrow a range in occurrence time in a probabilistic mid-term prediction of large interplate earthquakes.

Keywords: crustal deformation, earthquake cycle, seismicity, tide, subduction zone

SSS27-07 Room:201B Time:May 22 10:30-10:45

Pseudo earthquake quiescence following the 2011 M9.0 Tohoku-Oki earthquake

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The large extensional stress perturbations associated with the 11 March 2011 Tohoku-Oki earthquake (magnitude (M) 9.0) [e.g., Ozawa et al., 2011] has boosted widespread increase in seismicity across NE and central Japan [e.g., Kato et al., 2011; Toda et al., 2011; Miyazawa, 2012]. In addition to the induced seismicity, several sequences of earthquake quiescence or sudden reductions of seismicity were reported after the Tohoku-Oki earthquake [e.g., Toda et al., 2011]. However, it has been argued that sudden rate reductions were potentially due to temporal changes in the completeness magnitude threshold of any earthquake catalogue following the immediate aftermath of large mainshock [e.g., Felzer and Brodsky, 2005; Peng and Zhao, 2009]. After the Tohoku mainshock, small magnitude earthquakes tended to be masked by overlapping arrivals of waves from immediately following numerous earthquakes occurred in not only the source region of the Tohoku mainshock but also inland regions.

For example, a seismic cluster broke out on 27 February 2011 in the Hida mountain range (near Norikura), where the present volcanic front is located, and its activity had continued until the Tohoku-Oki mainshock. The representative focal mechanisms are thrust and strike-slip faulting with the P-axis aligned WN-SE direction, which is a typical stress field in this region. Just following the Tohoku mainshock, the seismic activity reported in the JMA catalogue shows earthquake quiescence: one day later the seismicity gradually turned around its previous level. In order to investigate whether this earthquake quiescence is real or not, we applied a matched-filter technique to detect missing events with the use of continuous three-component velocity seismograms recorded by a dense network of continuous and highly-sensitive seismic stations.

In contrast to the JMA catalogue, the seismicity in the cluster has still continued even just after the Tohoku mainshock and seismic quiescence was not observed. We identified a total of several tens of events in the cluster during a time-window when the JMA has not reported any existence of seismic events. Our newly detected catalogue describes the temporal and spatial evolutions of seismicity more precisely. The newly constructed catalogue in the Hida Mountain range (near Norikura) shows that the seismicity increased in the immediate aftermath of the Tohoku mainshock. This rate increase is likely explained by a static-stress transfer model. Thus, the quiescence seen in the JMA catalogue following the Tohoku mainshock is artificial due to temporal increases in the completeness magnitude threshold of the catalogue.

SSS27-08 Room:201B Time:May 22 11:00-11:15

Characteristics of triggered tremor beneath the Yatsushiro Sea by the surface wave of a teleseismic event

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Chao and Obara(2012, SSJ) and Obara et al.(2012, SSJ) found tremors induced by the surface waves of the 2012 Mw8.6 Sumatra earthquake. One of the tremors occurred near the Yatsushiro Sea, the western part of the Kyushu Island. In this study, we reexamine the characteristics of the tremor by using data from the dense seismic network deployed around the sea.

We detected the locations and time evolution of tremors by a grid search method. Waveforms at the seismic stations are stacked with time shifts calculated from the location at a grid. The optimum location is determined at the grid where the power of the stacked waveform is largest among the spatially distributed. The time evolution is detected by checking the power for various origin times. We found that the tremors were located at the depth of around 20km. It corresponds to the lower limit of background seismicity.

Acknowledgement

We used the seismic data from Kyushu University, the Japan Meteorological Agency, the National Research Institute for Earth Science and Disaster Prevention and Kagoshima University.

Keywords: triggered tremor, the Yatsushiro Sea

Japan Geoscience Union Meeting 2013
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SSS27-09 Room:201B Time:May 22 11:15-11:30

Spatiotemporal stress change concerned with Tohoku-Oki Earthquake derived from the seismicity rate in off southern Tohok

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Using a method of Dieterich (1994), we estimated spatiotemporal evolution of Coulomb stress in and around the subducted Pacific (PAC) plate and Philippine Sea (PHS) plate in off southern Tohoku and Kanto district from the analysis of seismicity rate.

Our results show that the Tohoku-Oki Earthquake extensively perturbed Coulomb stress in the PAC and PHS plates. In a previous study, Uchida et al.,(2009) suggested that an interplate coupling between the PAC and PHS plate becomes weak in the southern part of northeastern edge of the PHS plate. In our results, however, large stress change was seen in this region during March 2011. We also found that such region showing large stress change have been moving southward for several months. After March 2011, M$>$5 earthquakes occurred near the region which had stress change in March 2011. Widespread large stress change are considered to be related to occurrence of M$>$5 earthquakes.

Next, we determined focal mechanisms of earthquakes which occurred in the study region. For some events after Tohoku-Oki Earthquake, P and T axes' direction of the focal mechanisms were different from those for the events before mainshock. The regions where mechanism trend varied before and after the Tohoku-Oki Earthquake seem to coincide with the regions where large stress change was observed.

Keywords: Tohoku earthquake, Sterss change, Aftershock

Japan Geoscience Union Meeting 2013
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SSS27-10 Room:201B Time:May 22 11:30-11:45

Seismicity and crustal structure in the focal area of the inland earthquakes induced by the 2011 Tohoku-Oki earthquake

Tomomi Okada[1*], Ryota Takagi[1], Keisuke Yoshida[1], Maki Yonekawa[1], takuya yamamura[1], Akira Hasegawa[1], Group for the aftershock observations of the 2011 Tohoku-Oki earthquake[1]

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After the occurrence of the 2011 Tohoku earthquake with a magnitude of 9, the seismicity in the overriding plate has changed. The seismicity seems to form the seismic belts. The earthquakes after the 2011 Tohoku earthquakes tend to be located at the edge of these seismic belts.

From the time-latitude distribution, we can see the change of seismicity in the occurrence of the 2011 Tohoku earthquake. Most of the earthquake clusters have activated just the 2011 Tohoku earthquake and decreased, although some of them activated gently. In some earthquake swarms, we can observe temporal expansion of the focal area. This temporal expansion can be explained by the fluid diffusion.

In the lower crust, we found seismic low velocity zone, which seems to be elongated along N-S or NE-SW, the strike of the island arc. These seismic low-velocity zones are located not only beneath the volcanic front but also beneath the fore-arc region. Seismic activity in the upper crust tends to be high above these low-velocity zones in the lower crust. Most of the shallow earthquakes after the occurrence of the 2011 Tohoku earthquake are also located above the seismic low-velocity zone. Normal fault earthquakes in northern Ibaraki and southeastern Fukushima are also located just above the seismic low-velocity zone.

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SSS27-11 Room:201B Time:May 22 11:45-12:00

Swarm Activity at the Southwestern Frank of Mt. Norikura, Gifu Prefecture, Central Japan, in February and March, 2011

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An intense swarm activity was observed around the south-western frank of the Mt. Norikura, Gifu Prefecture, Central Japan, in February and March 2011. Swarm activity took place at 2:18 JST, February 27, 2011 with a Mjma 5.0 earthquake followed by a Mjma 5.5 event at 5:38 JST, February 27, which is the largest event in this activity, The activity decreased until the end of March, with slight re-activation until the end of December 2011. Focal mechanism solutions derived from the first P-wave motion analyses exhibit the NNW-SSE compression stress field that indicates these earthquakes are located on the ENE extension of the Takayama-Oppara fault system which roughly run NE-SW direction in Hida district, Gifu Prefecture.

We applied the matched-filter technique to this seismic activity if we could detect the temporal evolution of such an intense activity quickly. We selected thirty (30) templates earthquakes recorded at surrounding nine (9) seismic stations for matched-filter detection. More than 4,800 events are detected during the period from February 27 to March 31, which is about three times as JMA located. Number of earthquakes we could locate is about one third of detected events, which is roughly same as the JMA located. Although we have to check the precision and accuracy of our located events for precise discussion, we could say this method is one of the powerful tools to investigate the temporal variations of swarm activities.

Keywords: swarm activity, Hida district, Gifu Prefecture, Mt. Norikura-dake, Takayama-Oppara Fault, matched-filter technique

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS27-12 Room:201B Time:May 22 12:00-12:15

The relationship between shallow seismicity and geologic structure in the Sambagawa belt, northwestern Kii Peninsula

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Background seismicity is significant in both Tamba and Wakayama regions, Kinki district, southwest Japan. Although Katao and Ando (1996) and others already pointed out that the geologic structure controls their hypocenter distributions, no detail study has been performed. Here we examine the spatial relationship between seismicity and geologic structure in the Wakayama region, northwestern Kii Peninsula, analyzing the hypocenter relocations by the hypoDD method, and seeking more fault plane solutions of microearthquakes. In addition, we perform a three-dimentional comparison between deep geologic structure estimated from the Bouguer gravity anomalies and the relocated hypocenter distribution.

As a result of the hypoDD relocations, E-W trending seismic clusters have become more visible. Other trends of linear seismic clusters are also discernible. Linear and elongated seismic clusters in the western Sambagawa metamorphic belt are unconcealed. Numerous fault plane solutions sought from smaller earthquakes using the Kyoto University SATARN system increase the ratio of strike-slip mechanisms to the reverse ones, which may associate with the visible EW-trending seismic clusters. Two 20-km-long, EW-trending high gravity anomaly zones, which are robust features (Kakuta et al, 2002, Komazawa et al, 1999), is characterized as aseismic zones. These zones, evidently corresponding to the Mikabu ultramafic rocks, hold higher density than those from schist and other sedimentary units. We interpret that significant difference in mineral compositions between the Mikabu zones and the other areas in the Sambagawa belt plays an important role to differentiate their brittle-ductile transition depths, thus the thickness and strength of the seismogenic layer.

Keywords: northwestern Kii Peninsula, Sambagawa belt, shallow seismicity