Occurrence probability and frequency of large (Mj6.8) earthquakes on active faults in Japan

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The 2016 Kumamoto earthquake (Mj 7.3; Japan Meteorological Agency magnitude) caused devastating damages and more than 180 casualties. It occurred in an active fault zone and surface ruptures appeared mostly along the previously mapped active faults (The Headquarters for Earthquake Research Promotion-HERP, 2016). The source fault was a part of the Futagawa fault zone that has been evaluated for long-term forecast of destructive earthquake occurrence in Japan (HERP, 2002; 2013). The Mj 7.3 earthquake was the first case, after the 1995 Kobe earthquake, that characteristic earthquake with surface rupture occurred on the major active fault zone evaluated by HERP. It coincides with the past estimation of the average occurrence interval of 10-20 years of an earthquake on those active faults in Japan (Secretariat of HERP, 2001). Meanwhile, the occurrence of large (Mj6.8) earthquakes on minor active faults has been more frequent in recent years.

Under these circumstances, we re-examined the frequency and probabilities of large (Mj6.8) earthquakes on active faults in the last 125 years. In order to classify the damaging earthquakes on active faults, we used the catalogue of damaging earthquakes in Japan (Usami et al., 2013) and previously evaluated reports by HERP.
In total, 28 large (Mj6.8) damaging crustal earthquakes occurred in the last 125 years, and 22 of them (80 %) are related with mapped active faults, and 6 (20 %) are not. The 22 earthquakes in 125 years yield the average recurrence interval of 5.7 years. Using the individual recurrence intervals, 4.6+/-3.7 years is obtained for all large (Mj6.8) damaging earthquakes and 6.0+/-5.5 years for those on active faults. These estimates clearly show shorter recurrence intervals than the previous estimation made in 2001.

We also examined the frequency distribution of recurrence intervals of all the large (Mj6.8) damaging earthquakes. The distribution shows a bimodal distribution consisting of two groups: one <6 years and another >8 years. The average recurrence interval of the former group is 2.9+/-1.5 years, which is extremely short in comparison with the average recurrence interval in the last 125 years. The longest interval in the latter group is 17 years between the 1978 Izu-Oshima-Kinkai earthquake and the 1995 Kobe earthquake. It is thus apparent that the occurrence of the Mj6.8 damaging earthquakes exhibits the temporal clustering and long quiescence periods.
Under the assumption of Poisson process, we then calculated the earthquake probability within the next 5, 10 and 30 years for entire Japan. We obtained 72%, 92%, 100% probabilities for all Mj6.8 damaging earthquakes, and 62%, 86%, 99.7% for active fault earthquakes, respectively. Assuming the present day is within a clustering period, the probability increases up to 68-97% within the next 5 years.

We further investigated the temporal clustering and the timing of mega-thrust earthquakes along the subduction zones. In northeastern Japan, 5 active fault earthquakes occurred within 5 years before and after the 2011 Tohoku earthquake. In southwestern Japan, 3 active fault earthquakes occurred within 5 years before and after the 1944 Tonankai and 1946 Nankai earthquakes. These frequencies are comparable with the average recurrence interval of 2.9+-1.5 years for the above-mentioned <6 years

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group. This result is in accord with the previously known idea that inland crustal earthquakes increase before and after the occurrence of mega-thrust earthquakes along the subduction zones, although the above probability is computed with the assumption of Poisson process, hence it is time-independent. We can reasonably expect the occurrence of a few active fault earthquakes before the upcoming Nankai earthquake, probably 3 to 5 active fault earthquakes. To forecast them more accurately, the earthquake probability based on the BPT model for individual active faults and time-dependent seismic hazard assessment are necessary.

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Application of the 3D geological structure analytical technique to sea section in the Hinagu Fault Zone

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Hinagu Fault Zone extends from the Aso volcano to the Yatsushiro-sea. In the Yatsushiro-sea, some seismic surveys were carried out so far, and clarified distribution of a number of submarine fault group (the fault group called Yatsushiro-sea Submarine Fault Group). The Headquarters for Earthquake Research Promotion (2013) estimated the probability (0-16%) of the Yatsushiro-sea Submarine Fault Group triggering an M7.3 earthquake within the next 30 years. However, the activities and amount of displacement (vertical and horizontal) are not understood well. Tokai University conducted, as part of MEXT 2010 nearshore active fault survey project, a high-resolution single-channel seismic survey using parametric sub-bottom profiler for confirm a deformation structures and distribution of them. We continued investigating it continuously after the project. In this study, we tried 3D geological structure analytical technique for detecting not only vertical displacement but also horizontal displacement.
We observed drag deformation which is suggests to the existence of strike-slip fault in seismic profile at Northeastern part of the fault group (tentatively as A area). We applied the technique using a lot of seismic profile (survey interval is 20-50m) to the A area. On surfaces which formed in about 20,000 y.B.P and about 13,000 y.B.P, we observed subsidence area located in Northwest side of main fault. The subsidence area is gradually slow down depth to the southeast like a stairs. The feature is similar to ground surface displacement which observed by GEONET and ALOS-2/PALSAR-2 interferometric SAR of the 2016 Kumamoto Earthquake. The scale is different but the feature similarity suggests Yatsushiro-sea Submarine Fault Group has strike-slip component. There are three valleys in the subsidence area extend NW to SE direction, and these are right laterally displaced. Based on the formation age of the surface, we estimate the mean laterally slip rate 2.1-4.5m/ky. However, the slip rate is higher than land fault (Hinagu Fault: slip rate 0.7m/ky). So, the slip rate is still under consideration

Keywords: Hinagu Fault Zone, Yatsushiro-sea Submarine Fault Group, Seismic Trenching, Strike-slip fault

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An outcrop showing recent cumulative slip on a normal fault co-ruptured with the Futagawa fault at the 2016 Kumamoto earthquake

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The 16 April 2016 Mw = 7.0 Kumamoto earthquake accompanied ˜31-km-long surface rupture along the NE part of the Hinagu fault and the Futagawa fault (Kumahara et al, 2016). The surface rupture zone along the Futagawa fault mostly exposed right-lateral strike slip up to 2 m. A unique feature of the 2016 surface rupture is an ˜10-km-long normal faulting surface rupture with a maximum of 2-m vertical separation mostly along the previously mapped Idenokuchi fault located 1-2 km south of and sub-paralleled to the Futagawa fault.
Here we report an outcrop at the normal faulting surface rupture at the riverbed of Kanayama river which runs through Shimojin, Mashiki City. The site is located 300-m south-east of the Futagawa fault and a 50-60 cm normal coseismic slip occurred at the 2016 Kumamoto earthquake. Although we only had a brief time to observe this outcrop due to levee wall construction, we observed a normal fault (f1) which was responsible for the 16 April earthquake and recent gravel units (Fig. 1). Along the f1 strand, the top of bedrock shows about 2.5 m of vertical separation that corresponds to roughly four or five times the amount of coseismic vertical separation. It allows us to infer that there have been several earthquakes that the normal fault have ruptured together with the Futagawa fault simultaneously.

Keywords: Active fault, Surface rupture, 2016 Kumamoto earthquake

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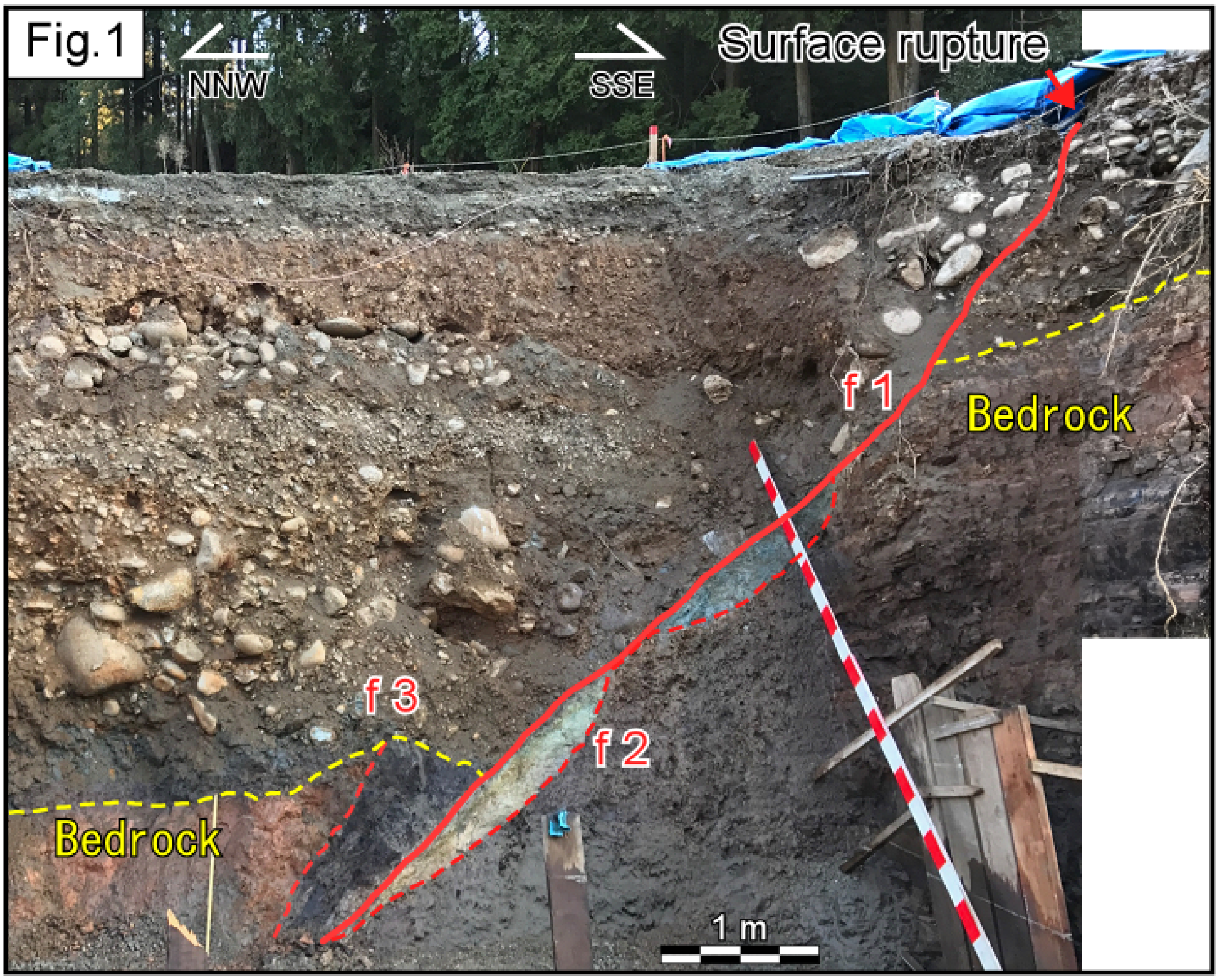

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The surface rapture of the 2014 Northern Nagano Earthquake detected by InSAR

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The DInSAR results (phase image and coherence image) derived from the sateraite images, displayed the visualization of large-scale fault motion and surface ruptures.
Since there is no blurring or terrain information interpreted on the image, it is difficult to extract the seismic surface ruptures and correct positioning of the surface rupture using only two images.
We developed a new surface rupture methodology by combining DInSAR result and the terrain representation image.
We applied the developed methodology by utilizing ALOS-2 data and created the DInSAR results for the past 2014 Northern Nagano Prefecture Earthquake and compared the extracted information with the local situation.
We confirmed intermittent surface ruptures from Shiroyama to Horinouchi in Hakuba village.
In Horinouchi, although broad flexural deformation appeared, the amount of deformation was small and mapping was difficult. The image was able to show this deformation area.
The present paper describes that the developed methodology could extract the seismic surface rupture over a wide area quickly, and demonstrated the potential mapping effectiveness as well.

Keywords: DInSAR, Surface rupture, 2014 Northern Nagano Prefecture Earthquake

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Postseismic deformation extracted by InSAR, after the 2014 Northern Nagano Prefecture Earthquake

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The 2014 Northern Nagano Prefecture Earthquake (Mj 6.7) occurred in November 22, 2014. The crustal deformation emerged in 30km*30km area by the InSAR analysis data after the earthquake (GSI, 2015). And, the surface ruptures occurred 9 kilometers from Shiojima Hakuba village to Higashisano along the Kamishiro fault (Okada et al., 2015). The relation between the appearance position of surface ruptures and the discontinuities of interference phase on the InSAR imagery was studied (Nakano, 2015).
We created InSAR phase image from ALOS-2 data after the 2014 Northern Nagano Prefecture Earthquake. The data is pair of 28 November 2014 and 26 June 2015. As a result of the analysis, the east side of surface rupture moved to the west or went to up. The amount of deformation is 3-4cm in the direction approaching a satellite.

Keywords: the 2014 Northern Nagano Prefecture Earthquake, InSAR, Postseismic deformation, Kamishiro fault, surface rupture, ALOS-2

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Historical earthquakes have altered age distributions of stone lanterns in temples and shrines in Japan

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Strong ground motion often topples stone lanterns, which are small stone objects standing in precincts of Japanese temples and shrines. For example, stone lanterns at Zenkoji Temple, Nagano, were severely damaged by the earthquake on 2014 Nov 22 in northern Nagano. Similar damage were recorded in historical documents, and seismologists use them to learn spatial distribution of shaking and to estimate the source fault. Date of dedication, or built, is often engraved on the column of stone lantern and we can determine ages of stone lanterns, and judging from the ages, older one were apparently survivors of past earthquakes. Stone lanterns are therefore records of historical earthquakes. How (or if) these earthquake are imprinted on groups of stone lanterns was not intensively investigated in the past. In this presentation we summarize our own surveys of stone lanterns at Kitano-Tenmangu Shrine, Kyoto, Iwashimizu-Hachimangu Shrine, Yawata, and Zenkoji Temple, Nagano, and argue whether stone lanterns literarily record historical earthquakes. These three sites are known for historical large earthquakes and a large numbers of stone lanterns in their small precincts. Age distributions of stone lanterns are mainly affected by anthropogenic or religious acts, and evaluation of these effects is necessary before we identify effects of earthquakes. We conclude that historical earthquakes likely have a weak but identifiable imprints on age distributions of stone lanterns. There are a few cases that large earthquakes apparently reset age distribution stone lanterns, suggesting large damages at the specific sites. Stone lanterns in the precincts apparently increases within 10 years of the earthquake, indicating the recovery stage of the community. On the other hand, it is hard to elucidate characteristics of historical ground motion solely from stone lanterns, and role of these items in studying historical earthquakes could be auxiliary to document records.

Keywords: historical earthquakes, storong ground motion

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Seismicity on Okinawa Island around 1858, estimated from observations by a French missionary

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In the middle of the 19th century, people from western countries visited the Ryukyu Islands to initiate trade with the Ryukyu Kingdom. Some of these visitors carried out weather and earthquake observations while staying on Okinawa Island, especially at Naha. Their records reveal details of historical earthquakes that were otherwise poorly recorded in the Ryukyu Kingdom era. Louis Furet, a French Missionary, visited Naha from 1857 to 1860, and undertook weather and earthquake observations at Naha during this period. The records were in French, and have now been published by Demarée et al. (2016). Using these records, we analyzed the seismicity in Naha from 1857 to 1860.
The occurrence times and intensities of earthquakes were recorded, and the intensity categorized according to the severity of the shaking as "la secousse", "légère secousse", "forte secousse", "violente secousse", and "secousse assez forte". In one event, the shaking was recorded as "Secousse assez forte" and was so strong that cracks appeared in the houses. In this case, we estimated the seismic intensity as 5 (Japanese seismic intensity scale). When the shaking was recorded as "Secousse assez forte" but the damage was not recorded, we set the seismic intensity to 4. Then we set "violente secousse", "forte secousse", "la secousse", and "légère secousse" to seismic intensities of 3, 2, 1, and 1, respectively.
Next we estimated the epicentral distances and magnitudes of the earthquakes, using the durations of the shaking and the seismic intensity. The recorded durations of 6 events ranged from approximately 60 s to 120 s. The theoretical seismic intensity was calculated using the equation by Si & Midorikawa (1999). The duration of the ground shaking was calculated using the equation by Nojima (2014), which uses the magnitude of the event and the epicentral distance, and calculates the timespan within the seismic intensity was above the specified threshold.
The results show that seven earthquakes with seismic intensities greater than 3 were observed in 1858. In the observations by the Okinawa Meteorological Observatory at Naha, since 1923, there have been only 4 occasions when seismic intensities over 3 were observed 3 times or more within a year. Moreover, there were no years in which seismic intensities of 3 or more were recorded 7 times in a year. This suggests that the seismic activity in 1858 was very high compared with that during the last 90 years.
Moreover, for three earthquakes that occurred from September 22, 1858, to November 7, 1858, we estimated the epicentral distances and magnitudes to be 50-100 km and 5.5-6.5, respectively. These suggest that the swarm activity from September to December accompanied the maximum magnitude of class 5-6 earthquakes, which occurred far from Okinawa Island when Furet was staying at Naha.

Keywords: Okinawa, seismicity, earthquake swarm

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Seismic reflection profiling survey across the eastern foot of Tsugaru Mountains

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Fault segmentation is an important issue in predicting the magnitude of an earthquake. To address the issue, we are conducting a comprehensive research in the Tsugaru Mountains and surrounding areas at the northernmost of Honshu. The Tsugaru Peninsula consists of the NS˜NNW-SSE extending Tsugaru Mountains (about 50 km-long, 10 -15 km-wide) and the hills and lowlands. As a fault zone related to the formation of the Tsugaru Mountains, there are the Tsugaru fault, the Aomoriwan-Seigan Fault zone, the Tsugaru-Sanchi-Seien Fault zone. It is considered that asymmetric shape of the Tsugaru Mountains was formed due to uplift and shortening accompanying these fault activities. However, compared with the scale of the mountainous area, the range where the active fault is recognized is short, there is also the possibility of extending further north. On the other hand, on the southern side of the Tairadate Mountains, hills with constant height spread to Sotogahama and Yomogita. The Negishi-Seihou Fault existing eastern portion of Tairadate Mountains may also be continuous to the south (including the marine area). Thus, although there are few known active faults in Yomogita Town to Sotogahama Town in the eastern foot of the Tsugaru Mountains, considering the possibility that the active structure may be blind in the vicinity of Yomogita. Therefore, we conducted a seismic reflection profiling along the Amida River in Yomogita Town, about 7.6 km-long, to define the subsurface structure of the area. In seismic lines, the vibrator truck (IVI ENVIRO VIBE) is used as the seismic source. Source and geophone spacing are 10-m. Seismic reflection data was processed by using the standard CMP stacking method. In this presentation we demonstrate the subsurface structure revealed by the seismic reflection survey

Keywords: Tsugaru Mountains, seismic reflection profiling, subsurface structure, blind thrust

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Segmentation of the Kitakami Lowland western marginal fault zone, northeast Honshu, Japan

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The western marginal faults of the Kitakami Lowland constitute an active fault zone extending almost north to south from the west side of Yahaba to the south of Isawa in Iwate Prefecture consists of various faults such as Uwandaira fault and Detana faults. They have been believed to originate from normal faults caused by E-W extensional stress field during middle Miocene, and to activate as reverse faults under E-W compressional stress field since Pliocene. Several researches have been done so far, but it is not yet clear how the underground geological structure continues. We have inferred a two dimensional subsurface density structures by gravity survey, and have proposed interpreted geological structure along several survey lines, in and around the Kitakami Lowland western marginal fault zone. In this paper, we attempt to clarify the structural continuity of the zone by synthesized these data.
The gravity surveys were conducted along four survey lines trending E-W, which are named from the south to the north, Isawa(59 km long), Kanegasaki(12 km long), Geto(9 km long), Waga(12 km long). In the ‘Mizusawa survey line’, we use Lacoste-Ronberg type gravimeter owned by Earth Science Research Institute, and in other lines, we conducted gravity survey with a Sintrex gravity meter CG-5. The typical interval of observation sites is 200 m. The elevation of the observation sites was surveyed with RTK-GPS. We assumed that the density for Bouguer and terrain corrections were 2.2 g/cm^3.
For the Mizusawa, Waga, and Kanagasaki survey lines, a density structure model was created in consideration of the reflection seismic section. For all line, three layers with different densities were assumed, and the density of the third layer corresponding to the basement rock was 2.7 g / cm^3. As a result of comparison under the above conditions, the inferred geological sections along the Geto and Waga lines, and those along the Kanegasaki and Mizusawa lines showed continuity. In the former areas, there are two half-grabens whose boundary fault in the eastern margins are inverted to reactivate as thrusts. In each of the latter, areas there is one half graben, with a reactivated boundary fault. Therefore we conclude that there is the segment boundary of the Kitakami Lowland western marginal fault zone between Geto-Waga and the Kanegasaki-Mizusawa area.

Keywords: the Kitakami Lowland western marginal fault zone

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Tectonic geomorphology of the northeastern Musashino Upland, central Japan

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We present geomorphic evidence for active faulting and folding found in the northeastern Musashino Upland to define locations, distributions, and recent activity of underlying blind thrust faults. In this region, we recognized geomorphic evidence including pairs of east-facing fold scarps that deform middle to late Pleistocene fluvial terrace deposits. At several locations, these geomorphic scarps are underlain by west-dipping blind thrust faults.

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Fault geometry of the Nodera fault of the Ouchigata fault zone in the southern part of Noto Peninsula, central Japan.

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The Ochigata fault zone is a reverse fault type active fault zone showing NE trending located in central Ishikawa Prefecture (The Headquarters For Earthquake Research Promotion, 2005). Although the main fault zone is continuously distributed along the northwest margin of the Houdatsu Hills, in the southwestern region of the Ouchigata fault zone, the fault shows a distribution that branches and runs parallel from the plain to the hills.Among them, the Nodera fault and the Tsuboyama - Yano fault which constitute the hill side have been shown to have different postures and elevation directions of the fault plane, but the factors have not been clarified, and examples of structural geological studies poor. In this study, field survey, sample analysis and fault analysis were conducted with the purpose of elucidating the morphology and fault geometry of Nodera fault and fault of the estimated inside hills.
The geology of this research area is widely distributed in the Jurassic granitic rocks called the Houdatsusan granitic body, and partly covered in the quaternary.
In this study, the outcrop of the fracture zone was found at the side extension of the Nodera fault. In addition, we found a fracture zone running parallel from the hills of the west side of the Nodera fault. These fracture zone outcrops generally show NNE - SSW trend, the outer edge fault gouge shows oblique deviation sense from lateral displacement, while the fault gouge at the center axis shows reverse fault sense including left lateral deflection component. In addition, in this research area, many faults showing lateral sense are distributed from oblique deviation of NNW - SSE trend, and faults of some NNW - SSE and NW - SE trend faults are distributed.
Stress analysis by multiple inverse method (Yamaji, 2000) was carried out using data obtained from these fault planes. As a result, stress 1 indicating NNE-SSW compression and stress 2 indicating WNW-ESE compression were obtained. Stress 1 corresponds to fault gouge data showing oblique deviation sense from lateral displacement of fault of NNE - SSW trend and fault gouge data showing reverse fault sense of NW - SE trend. These are considered to be formed before the stress 2 because they are cut into the fault plane corresponding to the stress 2. The data obtained from the central axis of the fault of NNE - SSW and NNW - SSE trend showing reverse fault sense corresponded to stress 2. This stress is consistent with the current maximum horizontal compressive stress direction by Tsukahara and Ikeda (1991) and CMT (Centroid Moment Tensor) solution of 2007 Noto Peninsula earthquake.
X - ray diffraction analysis was performed on the fault gouge of the fracture zone of the main NNE trend. As a result, the sample at the outer edge of the fracture zone contained a lot of illite and the sample at the center axis contained much smectite. From this, it is considered that the outer edge of the same fracture zone and the central gouge are formed in different environments.
In the previous study (Misaki, 1980), the Nodera fault was regarded as a pure reverse fault sense, but data obtained at the outcrop of the fracture zone may be associated with left lateral deflection component. This is in harmony with the surrounding tectonic relief. In addition, based on the results of stress analysis and X-ray diffraction analysis, it is considered that the faults running along the Nodera fault and the inside of the hills are currently active by reusing previously formed faults.

Keywords: active fault, Ouchigata fault zone, Nodera fault, fault rocks

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Comparative study of the active fault zone and the fault zone terminated its activity by the Late Pliocene –examples of the Atera Fault and the Median Tectonic Line in Nara Prefecture

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The activity assessment of the active faults basically needs younger sediments. To understand the fault activity in the area with no younger sediments, it is desired that the new method is developed to study the fault activity from the fault rocks in the basement rocks. For this purpose, both characteristics of the active and inactive fault zones should be clarified. The Atera Fault zone and the Median Tectonic Line (MTL) in Nara Prefecture have studied to understand the above characteristics.
The studied exposure of the Atera Fault is located at Tase, Tsukechi, Nakatsuawa in Gifu Prefecture. In this exposure, the fault is a boundary between the Quaternary sedimentary layers and the Cretaceous granite. The fault is divided into two in the upper part of the exposure. Upper and lower faults are located in the granite and at the boundary of the sediments and granite, respectively. Toda *et al*. (1994) have clarified that the three seismic events are detected from the exposure and that the upper fault have displaced in recent two seismic events.
The studied exposure of the MTL is at Hataya, Ohyodo in Nara Prefecture. In this exposure, the MTL is a boundary between the Quaternary Shobudani Formation and the conglomerate of the Cretaceous Izumi Group. The upper Shobudani Formation with the age ranging from 1.2 Ma to 0.12 Ma have been displaced by the MTL, as shown by Matsumoto (2001). Okada and Togo (2000) reported that the MTL in this area terminated its activity by 0.3 Ma. These suggest that the MTL in this area was active at 1.2 Ma and inactive at 0.3 Ma. The top of the fault exposure had buried in 10 m depth estimated from the distribution of the terrace plain (Samgawa, 1976).
The powder X-ray diffraction (XRD) and the X-ray fluorescence analysis (XRF) were performed using the samples collected from these fault exposures. The XRD results show that smectite appears in the old fault gouge of the Atera Fault, and that plagioclase decreases toward upward in the fault gouge of the MTL. Kaolinite is detected in almost all samples, and smectite appears only the lower part of the fault gouge in the MTL. The XRF results show that MnO extremely increases in the latest slip plane of the Atera Fault, and that the content of MnO in the fault gouge of the MTL is lower than those in the Izumi Group and the Shobudani Formation. Na_2O decreases toward upward in the Izumi Group and the fault gouge of the MTL. The concentration of MnO in the Atera Fault would result from the oxidization of the fault zone near the ground surface. In the MTL, no concentration of MnO is recognized. This is supposed that manganese was concentrated in the past and it was disappeared due to the surface erosion. The distribution of kaolinite and smectite and the decrease Na_2O toward upward suggest that the fault zone of the MTL have suffered surface weathering. The surface erosion of the MTL in the studied site is estimated to be quite low from the distribution of the terrace plain. This indicates that the velocity of the surface weathering have been faster than that of the surface erosion. In the Atera Fault, the granite is uplifted due to the fault displacement, and the fault gouge is presumed to be difficult to suffer the strong weathering. Therefore, the surface weathering of the fault zone is considered to be a possible marker of the recent fault activity.

Keywords: active fault, fault zone, Atera Fault, Median Tectonic Line

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Paleoseismic and topographic evidence for latest Pleistocene to Holocene repeated surface-rupturing earthquakes on the Sone Hills fault zone, central Japan

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Our paleoseismic trenching and detailed topographic analyses and surveying reveal evidence for multiple large earthquakes accompanied with distinct surface ruptures during the latest Pleistocene to Holocene on the Sone Hills fault zone, central Japan. The ENE-striking Sone Hills fault zone, extending for 32 km, lies southern margin of the Kofu basin which hosts over 200,000 population. Although this fault zone is proximal to well-studied Itoigawa-Shizuoka Tectonic Line active fault zone, its recent rupture history and deformation style are less understood. For properly evaluating the future probability of earthquake occurrence and potential magnitude of ground displacement, paleoseismic information is vital. In order to derive paleoearthquake history we excavated three trenches across the two sub-parallel small scarps on the southern slope of a series of ENE-trending narrow ridges developed at leading edge of the fault zone at Otsuka, Ichikawa-Misato Town, western part of the fault zone. Furthermore, to measure the amount of vertical offset associated with each of possible last two faulting events, we performed detailed topographic analysis of faulted fluvial terraces at Kokubun, Fuefuki City, central part of the fault zone. Trench walls at Otsuka exposed the mid-Pleistocene to Holocene sediments, which are deformed significantly by numerous faults with both the reverse and normal slip components. Such coexisting of reverse and normal slip faults may suggest that the fault zone has a substantial strike-slip component. Based on sedimentary and structural features such as truncation and capping of faulted strata and angular unconformity combined with age controls using radiocarbon dating and tephrochronology, we identified and constrained timing of multiple event horizons, of which two events occurred since the Holocene. Analysis of lidar derived high-resolution DEMs and in-situ topographic surveying using a total station at Kokubun shows that two levels of fluvial terrace surfaces with ca. 10 ka old for its higher one exhibit a ENE-trending linear scarp. The vertical offset of the higher terrace is estimated to be ca. 2.5 m, while that of the lower terrace is less than 1.5 m, suggesting that multiple events occurred during the Holocene period at Kokubun, which is consistent with the results from trenches at Otsuka, and that the vertical offset of the lower terrace shows slip during the last event. This research was carried out as a commissioned research project by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

Keywords: Sone Hills fault zone, Paleoseismology, Trenching, Tectonic landform

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Tectonic geomorphology and paleoseismology of the northern Neodani fault around Mt. Nogo-Hakusan, central Japan

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In the 1891 Nobi earthquake (Mw 7.5), central Japan, three left-lateral active faults, the Nukumi, Neodani, and Umehara faults ruptured simultaneously, resulting in enormous disaster. Although many studies have been conducted after the earthquake along the central and southern Neodani fault, the fault activity and paleoseismic history of the northern section is poorly known principally due to mountainous environment. In order to clarify the activity and earthquake history of the northern part of Neodani fault, we conducted detailed geomorphological interpretation using the airborne LiDAR data and field geological mapping as well as trench excavation at the uppermost Nukumi-Shiratani Valley, southwest of Mt. Nogo-Hakusan, where previous studies reported presence of a fresh fault scarp.
Four fluvial terrace surfaces occur in our study area: NS-I to NS-IV surfaces in descending order. A clear uphill-facing fault scarp cuts across the NS-II surface with a vertical displacement of 3.0 -/+ 0.1 m. In addition, a tributary valley dissecting the surface shows a left-lateral offset of 28 -/+ 5 m, where a fault cutting the NS-II gravels against conglomerate bedrock is exposed on the valley wall.
We excavated a ~5.5-m-long, ~1-m-wide and ~1.5-m-deep trench across the fault scarp. The sediments exposed on the trench walls are topsoil, black peat, lacustrine gray clay, eolian yellowish-brown silt, and gravel layer. The boundary between the yellowish-brown silt and gray clay is very clear, suggesting a drastic change in sedimentary environment. In addition, the gray clay layer bends up towards the fault, which is unconformably overlain by the black peat layer. The organic-rich horizons in the black peat layer are further deformed toward the fault. Based on stratigraphic and structural evidences including those mentioned above, we identified four paleoseismic events after deposition of the NS-II gravels. Our tephra analysis revealed that three of them occurred after the K-Ah tephra fall (~7.3 ka), the latest one possibly correlating to the 1891 Nobi earthquake. Since abandonment of the NS-II surface predates the K-Ah tephra fall but postdates the AT tephra fall (~30 ka), we estimated the left-lateral slip late of this section of the Neodani fault to be at least 2.6 -/+ 1.9mm/yr based on the amount of the stream offset mentioned above.
Our results suggest that the slip rate of the northern Neodani fault is comparable to or even higher than that of the central main section. Of particular interest is that despite presence of such a high slip-rate fault, there are few recognizable tectonic landforms along this section of the Neodani fault except for our study site. This is probably due to high erosion rate in high-relief mountains, suggesting that high slip-rate faults elsewhere may not accompany clear tectonic landforms in high-relief mountainous environment. Tectonic landforms are locally preserved at our study site probably because they are located in the uppermost Nukumi-Shiratani Valley above a clear knickpoint, where severe postglacial erosion has not reached yet.

Keywords: active fault, paleoseismology, LiDAR, Nobi earthquake

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Paleoseismology of the Kurozu fault, Nobi active fault system, central Japan: its role in multiple fault rupture

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During the 1891 Nobi earthquake, a well-known example of a multiple-fault rupture, three active left-lateral faults, the Nukumi, Neodani, and Umehara faults, ruptured simultaneously. Previous paleoseismic studies revealed that timing of surface-faulting events on these faults were not always synchronous, suggesting that a multiple-fault rupture as occurred in 1891 is a sort of exception rather than a rule. The Kurozu fault is a ~8-km-long short active left-lateral fault located in between the Nukumi and Neodani faults and is known to have ruptured in 1891 together with these two faults. Although the fault may play a certain role in rupture propagation from the Nukumi fault onto the Neodani fault, very little has been known on its recent fault activity.
At one location, the Kurozu fault cuts across a fluvial terrace surface on the left bank of the Neo-Nishitani River, forming a clear uphill-facing scarp. Our pit excavations into eolian deposits that overlay the terrace surface revealed a horizon of Aira-Tanzawa (AT, ~30 ka) volcanic glass concentration immediately above the terrace gravels. This suggests that the terrace is correlated to a surface downstream that was abandoned 30–40 ka. Our coring and penetration tests on the downthrown side of the fault scarp also suggest that the terrace surface is vertically displaced by ~5.5 m, yielding a vertical slip rate of 0.14–0.18 m/kyr on the Kurozu fault.
We also hand-excavated a trench across the fault scarp, exposing a fault zone that defines a clear boundary between terrace gravels on the upthrown side and peaty and lacustrine dammed-up sediments on the downthrown side. From displacement and deformation of the dammed-up sediments, we were able to identify evidence of only two surface-faulting events after abandonment of the terrace surface at 30–40 ka, including the 1891 Nobi earthquake. This is consistent with a coseismic vertical displacement of ~3 m at the time of the Nobi earthquake, which is about half the ~5.5 m cumulative vertical displacement of the terrace surface.
Our results suggest that a rupture interval of the Kurozu fault is on the order of as long as 10,000 years. This is a good contrast to those of the Nukumi and Neodani faults that are reportedly 2,000–5,000 years. Given that timing of surface-faulting events on these faults were not always synchronous, and also given that the Kurozu fault ruptured in 1891 together with these two faults, we infer that the Kurozu fault plays a critical “relaying” role in rupture propagation across the Nukumi and Neodani faults. Our static coulomb stress modelling also suggests that rupture of the Kurozu fault significantly promotes rupture propagation across these two faults.

Keywords: Nobi earthquake, active fault, trench, slip rate, paleoseismic history

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Active faults and their tectonic implication around northern margin of the Sanuki Range, Shikoku region, Japan

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The Sanuki Range is located in the northeast Shikoku region, and shows elongated shape trending east to west. Southern margin of the Sanuki Range is bounded by the Median Tectonic Line active fault system (MTL), and shows very linear form. Although the Nagao fault is developed along the central part of the northern margin of the Sanuki Range, its distribution is restricted to the central part of the Sanuki Range, and existence of active faults has not been known in the eastern and western extension of the Nagao fault. Based on detailed investigation of aerial photograph and stereoscopic images delivered from 5 m –10 m DEM, we found active faults in the east and west extension of the previous reported active faults. In this presentation, we reported the distribution and characteristics of these active faults, and discuss tectonic implications of these active faults. In the eastern extent of the Nagao fault, left lateral slip fault trending NW-SE and right lateral slip faults trending NE-SW are newly mapped. In one fault, north-side-up displacement is estimated. In the western extent of the Nagao fault, flexure scarps on terrace surfaces trending east-west are newly mapped over several kilometers. In the western side of above mentioned faults, a north-side-up fault known as Kamihogunji fault is distributed. This fault is extended to the east several kilometers by our survey. In the western part of the northern margin of the Sanuki Range, many strike slip faults are newly mapped. Right lateral slips are recognized at NE-SW trending faults, and left lateral slip are recognized at the NW-SE trending faults, respectively. All of these faults are short in length (less than several kilometers), and are distributed intermittently in hilly areas along the northern edge of the Sanuki Range.

Keywords: Sanuki Range, Nagao fault, Median Tectonic Line, active fault

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Seismic attenuation profiling for imaging active faults within poorly reflective oceanic crust in Nankai Trough

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We tested applicability of seismic attenuation profiling (SAP) method as an indicator to understand present fault activity within poorly-reflective incoming oceanic crust in the Nankai Trough. Seismic reflection surveys are usually conducted to investigate fault activities in sedimentary basins, where faults can be specified by offsets of seismic reflections from formation boundaries. However, it is almost impossible to analyze the activities within oceanic crust because seismic reflections are inherently invisible there. Seismic attenuation profiling was, therefore, applied to image faults and investigate their activities within the oceanic crust seaward from the trough axis of Nankai Trough.

The Nankai Trough is the northern margin of the subducting Philippine Sea Plate, where large earthquakes with Mw > 8 have occurred with a recurrence interval of 100 to 200 years. Seismic reflection studies have been carried out in order to figure out geologic structures of the seismogenic plate boundary and splay faults. On the other hand, only a few seismic reflection studies have been applied to investigate intracrustal faults within the incoming oceanic crust, because it is very difficult to observe seismic reflections.

In 2005, high resolution seismic reflection survey was conducted by R/V Kairei of Japan Agency for Marine-Earth Science and Technology (JAMSTEC) on a seismic line NT501H, which was designed along the axis of the Nankai Trough, southwest Japan. Through the surveys, a total of ca 552 km of high-resolution seismic reflection data were collected with two GI-Guns (a total of 12 liter) and a 5100 m streamer cable. Shot interval, receiver interval and CDP interval are 50 m, 25 m and 12.5 m, respectively. The GI-Guns and the streamer cable were towed at 5 m and 8 m depths, respectively. Those towing depths are shallower than ones of conventional Kairei seismic reflection survey (10 and 15m), providing broader frequency bandwidth due to higher ghost-notch frequencies. The broader frequency bandwidth has advantage in estimation of seismic attenuation in frequency domain, such as spectral ratio method.

In order to visualize fault activities in the incoming oceanic crust, we applied SAP that maps seismic attenuation property instead of seismic reflectivity. Spectral ratio method was used to calculate seismic attenuation from multichannel seismic reflection data, because the method is one of the most general methods to estimate Q. In the present study, average Q was calculated only for depths of the oceanic crust as well as the uppermost mantle, in order to avoid influences from sediments and see spatial variation in attenuation property within the igneous oceanic crust. Based on amplitude decay curve analysis, the method is applicable to approximately 10 km depth below the sediments.

Combining the seismic reflection profile and the seismic attenuation profile enables us to understand a whole picture of fault activity. The former clearly shows active and fossil faults in the sedimentary layers. The latter shows active faults within the igneous oceanic crust as high-attenuation anomalies, which extend immediately beneath the active faults that were specified by the seismic reflections. On the other hand, the fossil fault zone was discriminated as low-attenuation zone from the active fault zone, within the oceanic crust.

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Keywords: seismic attenuation, fault, oceanic crust

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Application of high density CSAMT exploration for active fault investigation by using multi-channel electromagnetic survey system

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High density CSAMT exploration using the newly developed multi-channel electromagnetic survey system was applied to the study area where active structures may be blind. GeodeEM3D, the survey system can measure six components of electric and magnetic field. Each device allows to establish distributed network by LAN cable of up to 40 EM units. The combination of electric field (E) and magnetic field (H) in one unit can be set variously, such as 4E / 2H, 2E / 3H, 3E / 1H. In addition, it can be used not only for CSAMT using controlled source but also for AMT using natural source. The measurable frequency band is 0.1 Hz to 10 kHz. It is possible to efficiently carry out the high density CSAMT exploration which is capable the small measuring point intervals and dense point distribution. The high-density CSAMT exploration was conducted in the study area where the active structure may be blind (along the Amida River in the vicinity of Yomogita town in the northern part of the Aomoriwan-Seigan fault zone). The length of the measurement line is 4km, the interval of the measurement point is 50m, and the measurement frequency is 0.5Hz to 8192Hz. The geological investigation and the reflection seismic exploration are carried out at this site (Kagohara et al., 2017). The result of resistivity section clearly presents a step with low resistivity zone. Interpretation was made along with the overlapping part with the result of seismic reflection exploration. As a result, we revealed the subsurface structure related to the active fault.

Keywords: Multi-channel electromagnetic survey system, high density CSAMT exploration, seismic reflection exploration, Tsugaru Mountains, subsurface structure, blind thrus

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Active tectonics around an ongoing rapid surface deformation area in southern Taiwan by integrating geodesy and field investigation

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Mudstone areas in southern Taiwan are located at the frontal fold-thrust belt of the Western Foothills. They are one of the areas with the most active surface movement and rapid topographic evolution in Taiwan. In the past century, there were more than ten disaster earthquakes in southwestern Taiwan. The M 6.6 Meinong earthquake occurred on February 5, 2016 and generated surface rupture along two lineaments near the town of Guanmiao. However, these two structures were neither well documented before nor included in structural models. In addition, the Lungchi area right east of the two lineaments shows both rapid preseismic and coseismic deformation, raising a question if this area is sensitive to stress change or the deformation is just transient. Therefore, this study aims to create a new active structural fault model in this region. We integrate observations from PS-InSAR and GPS to constrain short-term active tectonic patterns and the interseismic deformation rates. Moreover, we map river terraces based on field investigations along the upstream of Erren River to estimate long-term deformation patterns and rates. Thus, we can provide a new model of active tectonic and seismic potential in this area.

Keywords: PS-InSAR, Interseismic deformation, Meinong earthquake

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Tectonic features of active faults and seismicity in the Tehran basin, Iran

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Tehran, capital of Iran, is located at the pediment zone block area of the Alborz Mountains chain, (which form part of the Alps-Himalayan Orogenic Zone) at the abrupt topographic boundary between the mountain range and the northern border of the central Kavir Desert. The urban area of this megacity is located near seismically active faults in the north, (Tchalenko et al., 1974). The presence of diverse faults with evidence of internal post-Pleistocene deformation in this zone confirms its vulnerability to further destructive earthquakes, because the Tehran region has not experienced any major destructive earthquakes at least since 1830, therefore it is necessary to study the active tectonics and evaluating fault seismicity to detect the active faults. The border between the Alborz Mountain and the Tehran’s piedmont (northern part of Tehran City) is marked by the North Tehran Fault dividing the Eocene rock formation from the alluvial units of different ages (Early Pleistocene to the recent alluvium).
In this study, we focus on the deformation features of active faults developed in the Tehran basin, based on the deformation features of active faults developed in the Tehran basin, based on the interpretations of aerial photographs, perspective view of DEM, Google Earth and satellite imageries, geomorphic indices, seismic data and field investigations. Field investigations guided by the interpreted results of images and analysis of geophysical data reveal that the active faults are mainly developed along the topographical boundary between the mountains and basin, which are characterized by the deformational feature of oblique thrusts with horizontal displacement component. The faults mainly strike E–W to ENE–WSW (?) and dip to north with varied angles between ˜25° and 85°. Locally, the faults are characterized by left-lateral strike-slip topographical features, with systematic left lateral offset or deflection of valleys and streams. The faults cut the terrace risers and alluvial fans which are inferred to be formed in the late Quaternary and Holocene, indicating the current activity of these faults. Seismic data also show that the many historical earthquakes and many micro-earthquakes occurred in the study region, consistent with our results. Our results show that the active faults in the Tehran region are the potential source of large earthquakes and may require further more study for accessing the seismic hazard in the densely populated urban regions around the Tehran city, Iran.

Keywords: Tehran, Alborz Mountains chain, Kavir Desert, geomorphic indices, index of relative active tectonics (IRAT)

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