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ESTIMATION OF CRUSTAL STRUCTURE IN HORONOBE AREA, HOKKAIDO, JAPAN, BY USING MULTIPLET-CLUSTERING ANALYSIS

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ABSTRACT

Hypocenter locations of shallow earthquakes in Horonobe area, northern Hokkaido, Japan, which is near the convergent boundary between Okhotsk and Amuria plates, were determined to reveal the subsurface structure and the mechanisms of earthquake occurrence. The absolute source locations of 211 earthquakes which occurred in the period from December 2002 to September 2005 were determined; then, those earthquakes with similar waveforms were identified, and the source locations of 26 multiplet groups were relocated by using cross-spectrum and clustering analyses. The relocated hypocenters allowed two seismically active areas to be identified, at 10–20 km and 25–30 km depth. The earthquake locations indicate structures trending nearly N-S direction, and the structures causing repeated stick-slips at asperities, thus generating similar earthquakes. The relationships between magnitude and the distance to the next event, and between magnitude and the time interval of event occurrences were investigated. The relationships between them suggest that earthquake swarms would be induced by continuous strain accumulation at asperities along faults and its subsequent release as a result of plate tectonic movements. A cutoff line could be also seen in the relationship between magnitude and the distance to the next event, suggesting that the distance between the source locations depends on the event magnitude. These results have given us the knowledge that the asperities on the delineated faults intermittently release strain energy as similar earthquakes with magnitudes of less than about 3.0.

KEY WORDS

Subsurface measurement, Multiplet-clustering analysis, Repeating similar earthquake

INTRODUCTION

The eastern edge of the Japan Sea approximately coincides with the convergent boundary between Okhotsk plate and Amurian plates[1], and earthquakes are probably associated with stress accumulation and its release by the fault system in the crust owing to the movement of the plates. GPS and microearthquake data suggest that the plate boundary lies under the land surface in northern Hokkaido, although it is difficult to trace the plate boundary. The Hokkaido Nansei-Oki earthquake (M7.8), which occurred inside the mobile belt, suggests a complicated fault structure, in which the fault planes incline to the east in its northern part and to the west in its southern part. Therefore, it is reasonable to suppose the existence of multiple boundaries in a wide fault zone [e.g. 2].

On the other hand, Horonobe area, northern Hokkaido, is in an area that a recently installed seismic network has shown to be characterized by high seismicity [3]. Although the location accuracy in depth is not still confident, the estimated source depth of the earthquakes is usually shallower than 25 km, and the earthquakes are considered to occur along hidden faults in a stress-concentrated zone. Knowledge of the structures causing these seismic clusters and understanding of their mechanisms are expected to provide information on the stability of the crust and the relationships between plate tectonics and earthquakes in this region.

Similar earthquake events and high-resolution mapping techniques can be used to reveal these structures and earthquake mechanisms [4, 5, 6, 7, 8, 9, 10, 11, 12]. In this study, similar earthquakes in Horonobe area were relocated by using a multiplet-clustering analysis, and the subsurface structures and the mechanisms of seismic clusters were evaluated.

EARTHQUAKE DATA COLLECTION

The earthquake events studied in this research were collected by the Hi-net system of the National Research Institute for Earth Science and Disaster Prevention (NIED) and the seismic network of the Japan Atomic Energy Agency (JAEA) from 20 December 2002 to 30 September 2005 (Figure 1). Most of the events had magnitudes of less than 3.0. Among the total of 4217 events located by Hi-net, we searched for those events whose P- and S-wave arrival times were detected at more than two seismic stations in the JAEA system (the JAEA system consists of four stations). A total of 221 events were selected for analysis in this study. Similar earthquakes were identified within the selected earthquakes for application of multiplet-clustering analysis (MCA) (Figure 2) [13]. Our aim was to investigate whether seismic clusters and structures could be identified after improvement of the location accuracy. The vertical component signal at the JAEA downhole station, –97 m below sea level, was used to identify similar waveforms, because the P-wave waveforms at this station were clearer than those at other stations. The waveforms of all events were inspected by eye, and finally, 188 similar events were classified into 26 groups.

RELOCATION OF SIMILAR EARTHQUAKES USING MULTIPLET-CLUSTERING ANALYSIS

First, the absolute source locations of the selected similar earthquakes were determined using the hypocenter determination software Hypomh, based on a three-layered velocity structure, where the focal mechanism were also estimated [3, 14, 15] (Figures 3 and 4). The source locations were widely dispersed because of location errors of more than 1 km, and no structures could be identified.

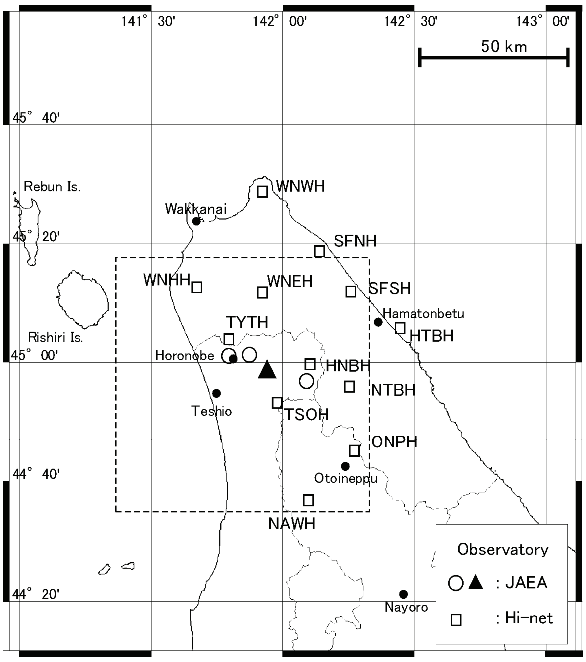


Figure 1. Locations of seismic stations around Horonobe, showing both those of JAEA and Hi-net. The dotted box denotes the area of the source locations shown in Figure 3.

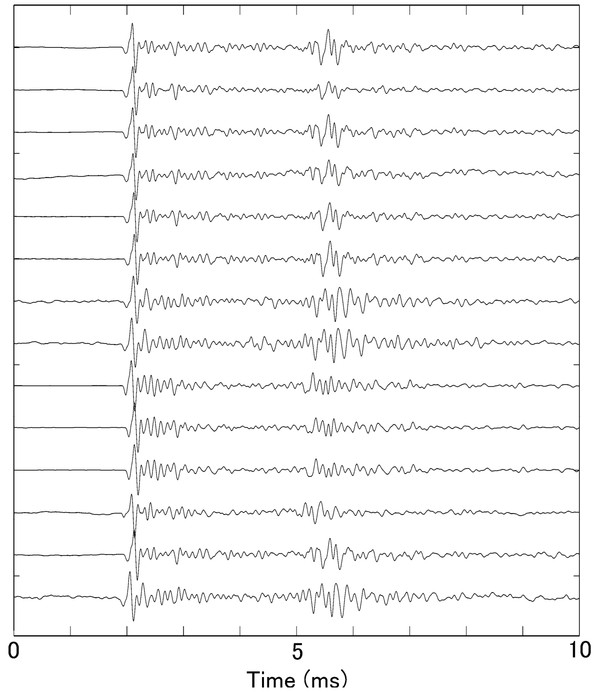


Figure 2. Example of the waveforms of a multiplet.

After determination of the absolute source locations, MCA was applied to relocate the source locations [8, 13]. In MCA, the source locations of events in each group are first determined relative to a master event in the group by a cross-spectrum analysis. The time-window length for the cross-spectrum estimation was 1 s and that for the Fast Fourier transform was 2.56 s, where the frequency resolution was 0.039 Hz. The frequency range for the time-delay estimation was 5–15 Hz, and the mean value of the time delays estimated for 10 different moving time windows was used to estimate differential times. After the relocation of the events in each group, typical events were selected from each group, and the similarity of the waveforms was evaluated within the selected representative events. Events with similar waveforms, but with insufficient similarity to have been classified into the same group by the initial classification, were selected, and a clustering analysis was applied to determine the relative positions of the clusters.

DISCUSSION

According to the estimated source locations, the depths are less than 30 km (Figure 2), and two seismically active areas (areas A and B) were identified. The seismic sources in area A were located at around 30 km depth, and those in area B were shallower, at 10–25 km depth.

Tamura et al. (2003) [3] imply the existence of earthquakes deeper than 20 km. However, we think that the absolute source location, especially the depth, should not be discussed in figure 2, because the station correction is not considered and the coverage of seismic network is not enough to determine the confident velocity structure for the event locations. We doubted the low-frequency events for the reason of deep events. We have checked the source locations of low-frequency events, which are observed since 2000 and recorded on Japan Meteorological Agency (JMA) earthquake catalogue in this area, and confirmed that the analyzed events in this study are different from the low-frequency events. On the other hand, the result of MCA is confident because the source location is the relative locations, and the influence of velocity structure in determination of source locations is smaller. The average of RMS in the relative locations is from 0.16 ms to 0.09 ms, and which corresponds to 0.8 km and 0.45 km in distance if the wave velocity is assumed to be 5 km/s. Therefore, we do not discuss the absolute location of the sources and the structures.

Because similar events were observed, there must exist unstable structures with asperities causing repeated stick-slips and continuous stress loading enforcing the repeated slips. The nodal planes (Figure 4) suggest steeply inclined structures oriented NNW to NNE, and the P-axes are oriented nearly NNW-SSE and NNE-SSW. These results indicate that compressive stresses oriented nearly E-W are acting on faults with steep inclinations. Considering that Horonobe area is at the convergent boundary between the North American and Eurasian plates, we infer that the district is under continuous stress loading in a nearly West to East direction, and strain energy accumulates on the fault planes as a result of the loading. This interpretation is supported by movements of the land surface detected by GPS [e.g. 16]. Therefore, it is reasonable to infer that the groups of similar earthquakes are expressions of the release of strain energy at faults oriented nearly N-S, and that the faults are subjected to compressive stress in an E-W direction.

The relationship between the magnitude of each event and the distance to next event (Figure 5) shows a cutoff magnitude (shown by a broken line), although the range of magnitude is limited (0 to 3.0). The distance to the next source location of similar earthquakes is more than several hundreds of meters, and the distance between event locations is larger than the expected source radius of the earthquakes, suggesting that the distance between source locations depends on the event magnitudes and that the source areas of similar earthquakes do not overlap. It is remarkable that a similar phenomenon has been observed along faults in California, where multiplets have been observed and streaks of earthquakes identified [6]. In the case of creeping faults, lock and release at asperities generates repeated earthquakes. Our results suggest that asperities release strain energy, and no more shear slip is induced at the same asperities. This means that strain energy accumulates at several asperities distributed along the fault because of the regional stress loading, and that the strain energy is released at the different asperities one after the other.

Figure 6 shows the relationship between magnitude and the time interval between the occurrence of similar events for the earthquakes in areas A and B. In area A, the maximum magnitude was nearly 2.0, and it did not vary in relation to time intervals of more than 10 hours. On the other hand, in area B, the maximum magnitude increased with the time interval up to magnitude 3.0.

These results suggest that the maximum values of the strain energy release rate and magnitude are limited in area A, where the size of asperities and the frictional strength of asperities are limited. On the other hand, the asperities in area B seem to have different size of asperities or different frictional strength, and the range of released energy is extensive than that of the asperities in area A.

This difference between the two areas could not be definitively explained, but is assumed to be related to size and strength of asperities and also conditions around the faults such as temperature and rock properties changing with depth. These results give us the key knowledge that the asperities on the delineated faults intermittently release strain energy as similar earthquakes, and that the feature of similar earthquake occurrence such as relationship between magnitude and time interval is different depending on the seismic clusters.

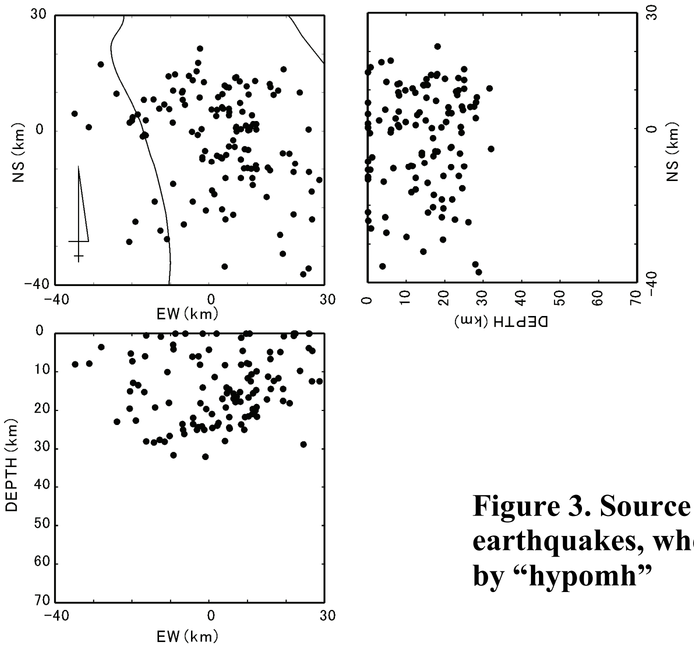


Figure 3. Source locations of analyzed earthquakes, where the locations are determined by "hypomh"

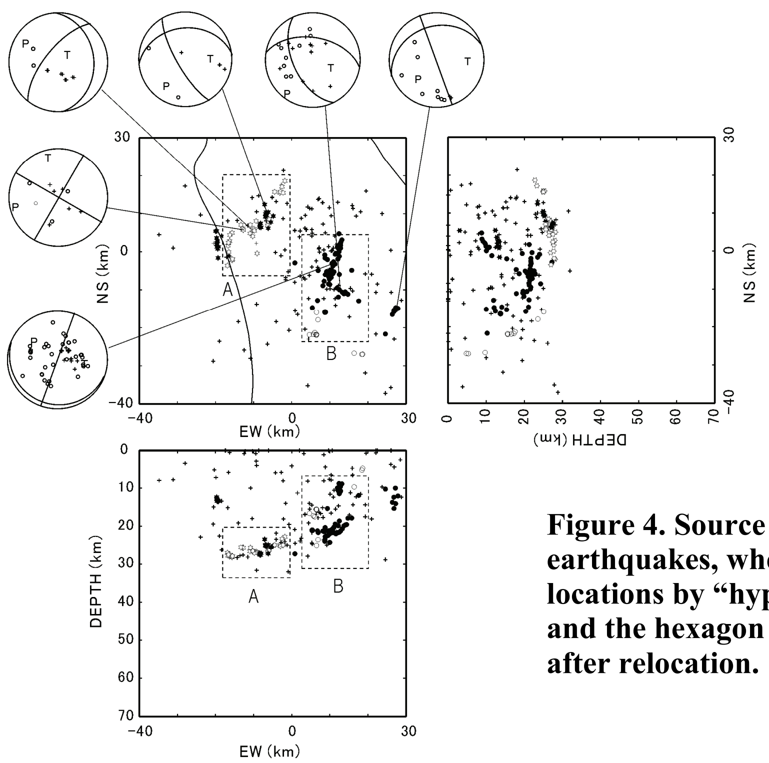


Figure 4. Source locations of analyzed earthquakes, where the cross denotes the locations by "hypomh" and the closed circle and the hexagon denote the source locations after relocation.

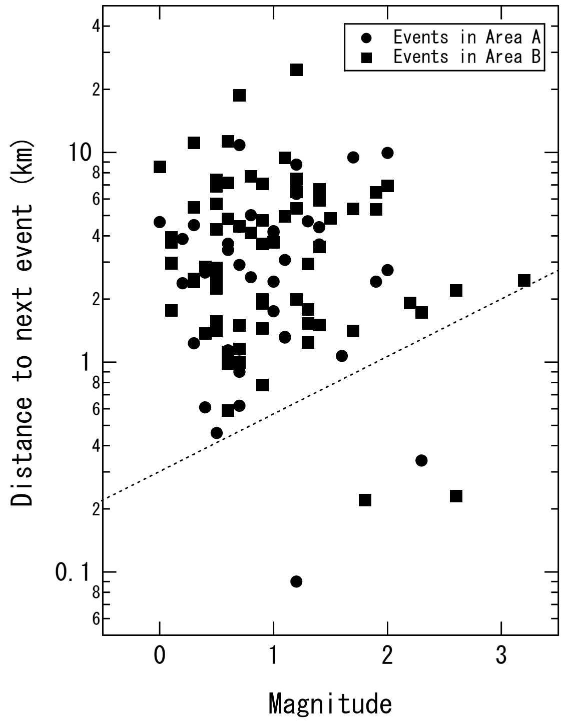
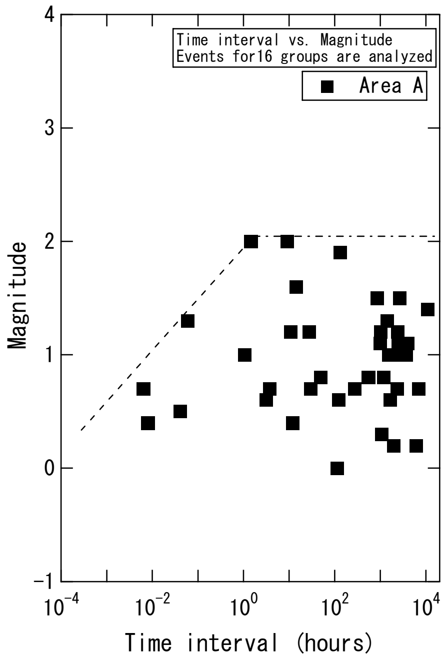
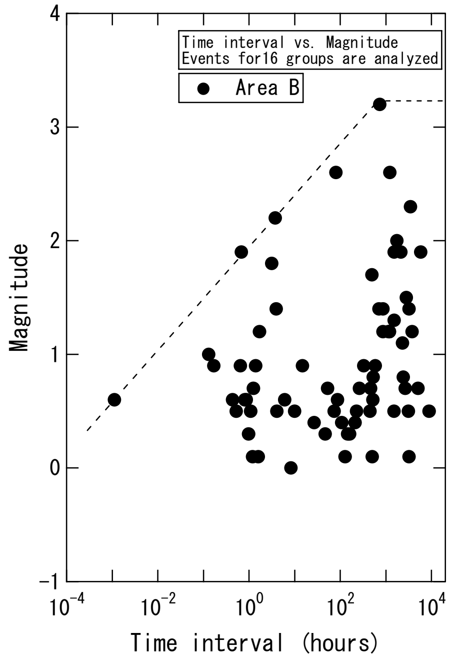


Figure 5. Plot of the distance to the next earthquake as a function of the magnitude of the previous event for each consecutive pair of similar earthquakes.



(a)



(b)

Figure 6. Magnitude and time interval of event occurrence for each consecutive pairs of similar earthquakes. (a) at Area A and (b) at Area B.

SUMMARY

In this paper, similar earthquakes in Horonobe area were relocated by multiplet-clustering analysis to reveal the mechanisms of earthquake swarms in this district. The seismic clusters revealed after the relocation allowed two high seismicity areas to be identified, at 10–20 km and around 25–30 km depth. The relationships between magnitude and the distance to the next event, and magnitude and the time interval between event occurrence were investigated. A cutoff line was seen in the relationship between magnitude and distance to next event, suggesting that the distance between the source locations depends on the event magnitude and that the source areas of similar earthquakes do not overlap. The relationships between them have suggested that earthquake seismic clusters would be induced by continuous strain accumulation along faults and its subsequent release as a result of plate tectonic movements. These results have given us the key knowledge that the asperities on the delineated faults intermittently release strain energy as similar earthquakes, and that the feature of similar earthquake occurrence such as relationship between magnitude and time interval is different depending on the seismic clusters.

ACKKOWLEDGEMENT

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