PROCEEDINGS, Twenty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 2003
SGP-TR-173

EFFECT OF NORMAL STRESS AND SLIP VELOCITY ON ACOUSTIC EMISSION ACTIVITY ASSOCIATED WITH SHEAR SLIP

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ABSTRACT

The model experiments that simulate shear slip of preexisting fracture have been conducted under a confining pressure condition in order to investigate the controlling parameters of “aseismic” fracture. In this paper, we discuss the normal stress and the slip velocity as the possible controlling parameters of AE (Acoustic Emission) occurrence and efficiency. The effects of these parameters on AE activity are investigated through the observation of AE events associated with the stable slip of artificially prepared fracture planes, which are made using split rock specimens. The AE activity during stable slip was evaluated as AE event rate and m-value for statistical evaluation. It has been suggested that the normal stress acting on the fracture plane has less effect on AE event rate and m-value, and that slip velocity has negative effect on AE event rate as well as m-value. The mechanism of the effect of normal stress is explained with the normal stress insensitivity of surface contact condition on the fracture, while the effect of slip velocity has not yet been clarified.

INTRODUCTION

A measurement of subsurface fractures is important for development and monitoring for maintenance of a geothermal reservoir, especially for enhanced geothermal systems. AE technique using microseismic events associated with hydraulic fracturing or stimulation is most powerful tool to estimate subsurface fractures (Niitsuma, et al., 1999).

The recently developed high-resolution mapping methods enable us to determine the location of fractures precisely, and which make it possible to compare the source location with the well logging data for further understanding of reservoir characteristics. Through the analysis of induced microseismic events, it has been revealed that some preexisting fractures do not radiate enough seismic energy expected from the measured shear displacement along the fracture. This observation implies that the shear slip on the preexisting occurred aseismically (Cornet, et al., 1997). In addition, it has been also reported that few AE events were observed around the permeable fractures, which were confirmed by flow logging and identified as major fluid flow paths, although many AE events were located at other regions (Tezuka and Niitsuma, 1997).

These observations of aseismic phenomenon implies that a result of AE source locations does not necessarily indicate fractures which behave as major fluid flow paths that would determine reservoir characteristics as heat exchanger. Therefore, it is essential to understand the mechanism of the aseismic phenomenon for a measurement of reservoir using induced microseismicity, and this study is indispensable to understand physical characteristics of reservoirs enhanced by hydraulic stimulation.

In this paper, we describe model experiments of shear slip using a granite specimen with a simulated fracture in order to make clear the controlling parameters on the characteristics of AE events associated with the slip. We focus on normal stress applied to the fracture surface and slip velocity as the possible controlling parameters for AE activity. The results of the model experiments are described and the dependence of AE event rate and m-value, which indicates a statistics characteristic of the observed AE, on normal stress and slip velocity is discussed in order to understand aseismic phenomenon.

MODEL EXPERIMENTS FOR CHARACTERLIZATION OF AE ON STABLE SLIP

Rock specimen with simulated fracture

Figure 1 shows the photograph of rock specimen used for the experiments. Rock type is Iidate granite with grain size of approximately 1mm. The size of cylindrical specimen is 30 mm in diameter and 92 mm in axial length. The specimen has a precut surface split in half with an angle of 30 degrees from the axial direction. This precut surface was carefully lapped by hands with #16 grit silicone carbide abrasive (the mean particle size is 1mm). A borehole of 3 mm in diameter was drilled along the axis in the lower half of the specimen to reach to the simulated fracture. Specimen was saturated with water using a vacuum pump prior to the experiment and was used under the condition for the fracture being filled in water during the experiment.

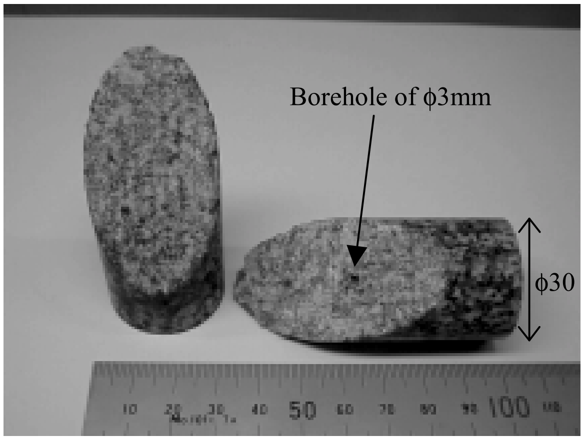

Figure. 1. Rock specimen with bore hole. Simulated fracture was lapped with #16 silicon carbide abrasive by hands. The left in the figure is upper part of sample, and the right one is lower part. The borehole of 3 mm in diameter was drilled with the lower part of the sample.

Setup and condition for experiment

All of the experiments were conducted at the constant confining pressure in the room temperature. The slip of constant velocity was actuated by a hydraulic servo-controlled uni-axial loading machine (INSTRON 8803). The maximum loading capacity of this machine is 500□kN and the stiffness is 1066 kN/mm.

The specimen, which was jacketed with rubber tube and attached with the upper and lower end cap, was placed in the pressure vessel. After the fracture was filled with water, confining pressure was applied into the vessel with a hand pump. Then, the specimen was held for 30 minutes to stabilize the applied confining pressure. After that, we made a small amount of slip on the fracture as an initial sliding for 0.5 mm and hold this condition for an hour to stabilize the surface contact state. After the holding for one hour, we made slip for 10 to 11mm.

Two series of stable slip experiments were conducted to investigate the effect of normal stress and that of slip velocity on AE activity during stable slip. The effect of normal stress has been investigated in the first series of experiments, where the confining pressure was kept constant for 5, 10, 15 and 20 MPa, respectively, and slip velocity was constant as 11.5 μm/s. The normal stress during stable slip in each experiment was calculated as 7.5, 14.5, 21 and 28 MPa, respectively. In the second series, slip velocity was kept constant as 1.15, 11.5, 115 and 1155 μm/s to investigate effect of slip velocity during the slip at constant confining pressure of 10 MPa, thus normal stress of 14.5 MPa. Pore pressure, which indicates the pressure of water filled in the fracture in this paper, was 0 MPa (atmospheric pressure) in all of the experiments.

Measurement of parameters during stable slip

We measured axial load, confining pressure, axial displacement as mechanical data. The axial load was measured with the load cell attached on the piston of the pressure vessel. The axial displacement was measured by a pressure-proof displacement transducer (LVDT) which was attached to the lower end cap with the mount (No.9 in Figure 2). These data were filtered using low pass filter with cutoff frequency of 80 Hz, and digitized with sampling frequency of 200 Hz. Normal and shear stress on the simulated fracture were calculated with the recorded axial load and confining pressure. Slip displacement along the fracture was calculated as a component along the slip fracture of the axial displacement measured by the LVDT.

AE events associated with the stable slip were detected by broadband-type piezoelectric AE sensor (Fuji-ceramics, 1045S, frequency band of 100 kHz to 1 MHz) mounted in the cavity of the upper steel end cap that placed on the upper half of the sample. Pre-amplifier of 40 dB and main amplifier of 30 dB amplified the signal from AE sensor. After applying band pass filter from 200 kHz to 1 MHz, the signal from AE sensor was digitized and recorded by sampling frequency of 5 MHz. Then, characteristic parameters of AE events such as the triggered time and the maximum amplitude of each event were picked up and recorded by the data acquisition system (NF, 7600 module). We regarded the number of triggers per unit slip displacement as the AE event rate on unit slip. The mechanical data such as axial load, axial displacement and confining pressure, and the AE event rate were recorded with two different data acquisition systems respectively and were synchronized on slip displacement by referring a commonly recorded signal after each experiment.

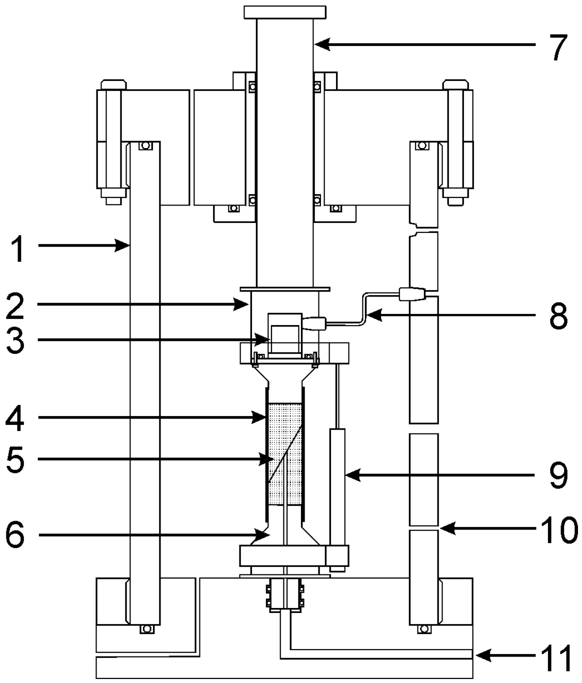

Figure. 2. Schematic figure of the pressure vessel used for the model experiments. 1. Pressure vessel, 2. Upper end cap, 3. Piezoelectric AE sensor, 4. Rubber tube jacket, 5. Granite specimen with borehole, 6. Lower end cap, 7. Loading piston, 8. Cupper feed through for AE sensor, 9. Pressure-proof displacement transducer (LVDT), 10. Water inlet for confining pressure, 11. Water inlet for pore pressure.

EXPERIMENTAL RESULTS

General feature of observed data

Figure 3 shows an example of the result of the experiment where the confining pressure is 15 MPa and the slip velocity is 11.5 μm/s. As shown in Figure 3(b), the normal stress and shear stress are changing during the initial stage of slip. On the other hand, the normal and shear stresses are stable after the initial sliding, and which means that we can control the mechanical parameters and perform the stable slip.

Friction coefficient, μ (=τ/σ_n, where, τ is shear stress and σ_n is normal stress applied to the fracture plane, which are calculated by the axial load and the confining pressure measured during experiment.) during stable slip shows the value of 0.5 ~ 0.6 in all the experiments. On the other hand, AE event rate on unit slip decreases with the slip displacement within a several millimeters and stabilized. This phenomenon is called the evolution process (Sammonds and Ohnaka, 1998).

The m-values of every slip for 1 mm have been evaluated for each experiment (Figure 3(a)). For estimation of the m-value, we used the events whose amplitude was -0.3 to 0.7 in the range of the logarithmic maximum amplitude. The m-value represents the amplitude distribution of the detected AE events. In the case of Figure 3, the estimated m-values are ranging from 1.5 to 2.5, and gradually increased with the cumulative slip.

EFFECT OF NORMAL STRESS

Figure 4(a) shows the AE event rate versus slip displacement changing the normal stress, where the normal stress is changed from 7.5 MPa to 28 MPa. The significant difference among them cannot be identified in this figure. Figure 4(b) shows the mean value of the AE event rate during the stable portion after initial sliding. It is suggested that the AE event rate does not change with the normal stress magnitude. This result means that the normal stress has little effect on the AE event rate. Figure 4(c) shows the m-values of every 1 mm versus slip displacement changing the normal stress magnitude, and Figure 4(d) describes the median of the m-value versus normal stress. The notable change and trend can not be seen in Figure 4(d). These results suggest that the dependence of AE characteristics, which are represented by AE event rate and m-value, on the normal stress acing on the fracture surfaces is not significant in the range of above stress magnitude.

EFFECT OF SLIP VELOCITY

Figure 5(a) shows the AE event rate versus slip displacement as a function of slip velocity, where the slip velocity is changed from 1.15μm/s to 1155μm/s. Figure 5(b) shows the mean value of AE event rate during the stable portion of AE event rate. The offset values of the curves of AE event rate decrease according to the increase of slip velocity as shown in Figure 5(a). The mean value of the AE event rate is also decreased, and which would suggest that the slip velocity has the negative effect on AE event rate.

The m-values of every 1 mm has also been compared on the slip velocity. Figure 5(c) shows the relationship of the m-value in each experiment to the slip velocity. Figure 5(d) shows the median of the m-values plotted as a function of slip velocity. In Figures 5(c) and 5(d), we can find that the m-value changes with the slip velocities, and which suggests that the slip velocity has negative effect on the occurrence of AE events during the stable slip.

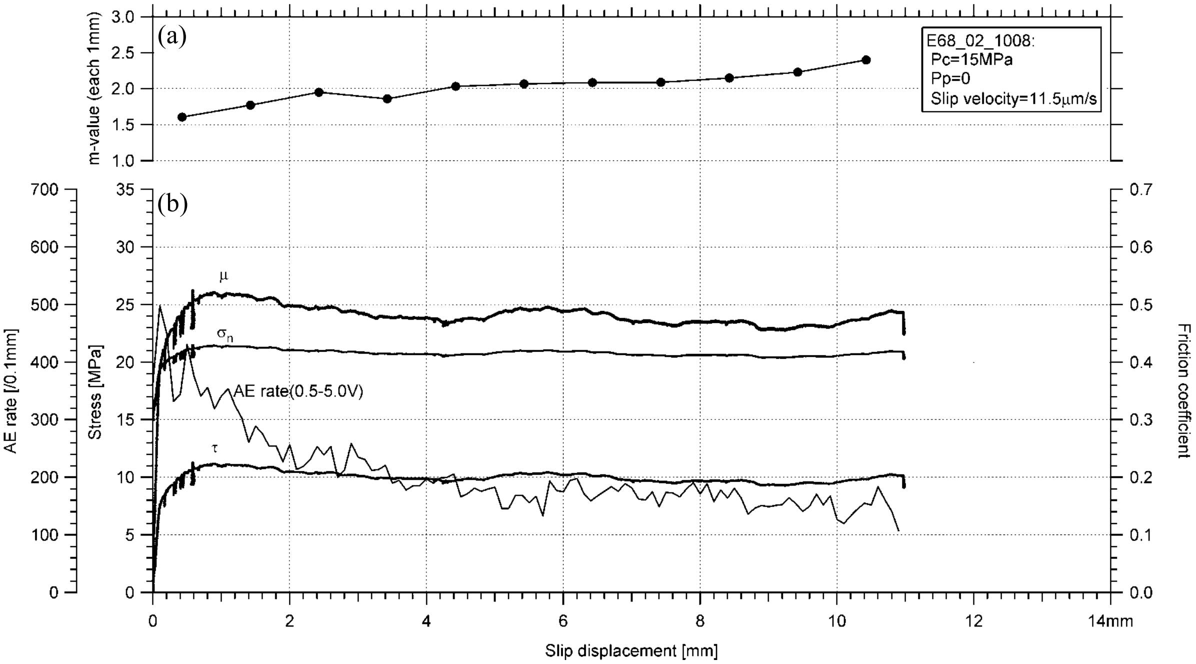

Figure.3. An example of the result of the stable slip experiment under the condition that confining pressure of 15 MPa, pore pressure of zero (= atmospheric pressure) and slip velocity of 11.5 μm/s. (a): The curve of the m-values evaluated for every 1 mm is shown. It increases gradually with the increase of slip displacement. (b): Normal stress, σ_n , shear stress, τ, friction coefficient,μ and AE event rate on unit slip displacement versus slip displacement are shown. Normal stress, shear stress and friction coefficient were almost constant during the slip except for the beginning of the slip as a small preliminary slip. AE event rate was decreasing with the increase of slip displacement.

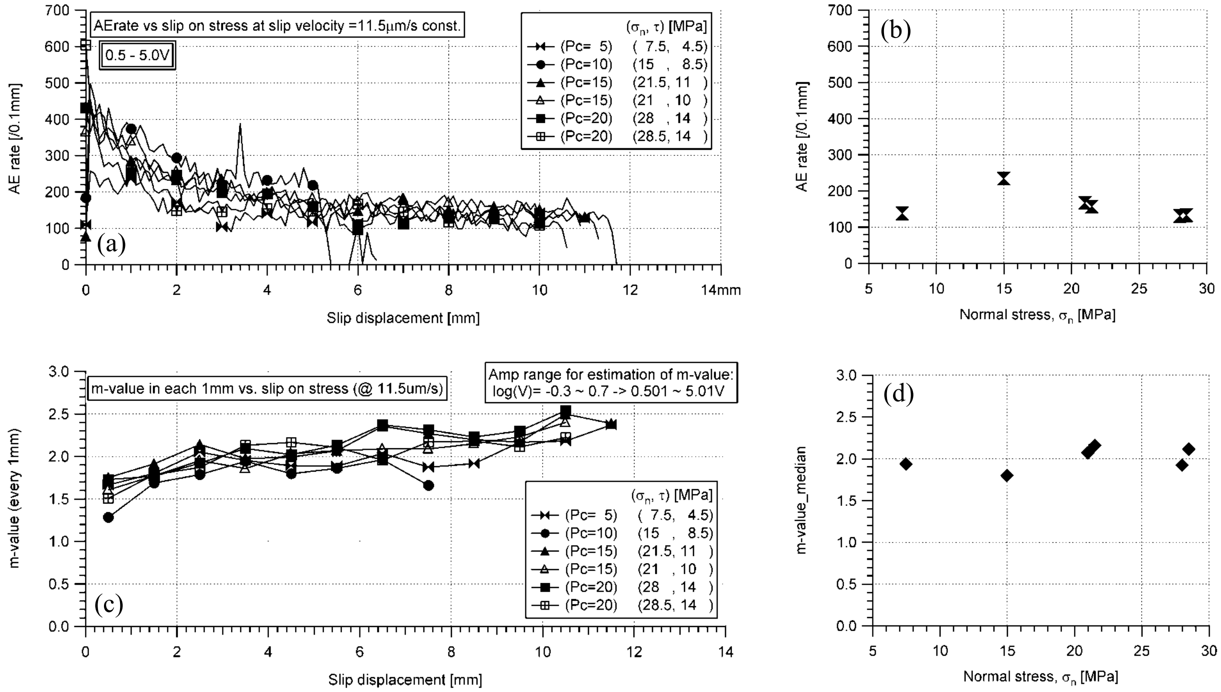

Figure 4. (a): Comparison of the relationship between AE event rate and slip displacement on normal stress applied to the simulated fracture surface. (b): Effect of normal stress on the stable portion of the AE event rate. (c): Comparison of the relationship between the m-values of every 1 mm and slip displacement on normal stress. (d): Effect of normal stress on the median of the m-values of every 1 mm. Significant difference or trend of the AE event rate and the m-value to the applied normal stress can't be seen in all the figures.

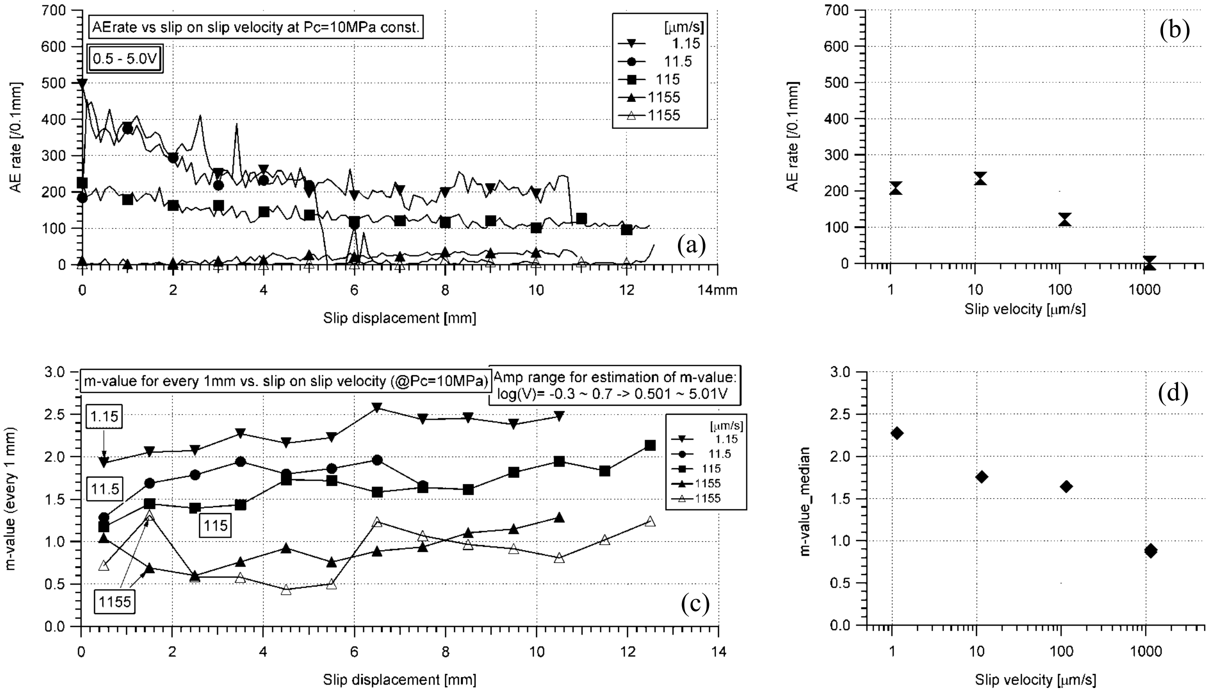

Figure 5. (a): Comparison of the relationship between AE event rate and slip displacement on slip velocity. (b): Effect of slip velocity on the stable portion of the AE event rate. (c): Comparison of the relationship between the m-values of every 1 mm and slip displacement on slip velocity. (d): Effect of slip velocity on the median of the m-values of every 1 mm. The AE event rate and the median of the m-values decrease with the increase of slip velocity.

DISCUSSION

It has been revealed that the normal stress has almost no effect on the AE event rate and the m-value in this series on experiments, where the normal stress is changed from 7.5 MPa to 28 MPa. It is reasonable that AE activity associated with slip is related to the condition of the fracture surfaces because two rough surfaces are contacted or bonded with asperities on the surfaces (*e.g.* Bowden and Tabor, 1964). Dieterich and Kilgore (1996) showed that the real contact area distribution on roughened surface did not significantly varied with the applied static normal stress by the rigorous observation of real contact area on roughened quartz plate, although the real contact area increased with the normal stress. In addition, the result of direct observation of surface contact by Dieterich and Kilgore (1996) seems for us that the number of contact points has been insensitive to the normal stress, although the real contact area of each contact increases with the normal stress. Therefore, the explanation of the result could be that the number of contact points between two surfaces, which would be approximately proportional to the number of AE events or the AE event rate, did not significantly change due to the increase of the normal stress in our experiment.

The m-value reflects the distribution of amplitude of the detected AE events. That is, the m-value becomes smaller if the AE events have similar amplitudes. The distribution of real contact area on the surface would reflect the amplitude distribution of the generated AE events. That is, each contact surface at asperities could be considered as each AE source and the contact surface area characterizes the maximum amplitude of the AE event during the stable slip. Therefore, we would be able to interpret the insensitivity of m-value to the normal stress by introducing the explanation that the change of the distribution of real contact area is not sensitive to the normal stress (Dieterich and Kilgore, 1996).

The effect of slip velocity has not been clarified so far. The decrease of m-value reflects that the number of AE events with small amplitude is relatively decreased or that the number of AE events with large amplitude is increased. In the case of this experiment, the number of events with smaller amplitude seems to decrease according to the increase of slip velocity. Then, one possible explanation is that the large events masked the small events. This masking effect would occur when slip velocity is higher. Therefore the results where the slip velocity is 1155 μm/s in the Figure 5 could be ignored because of the low AE event rate due to the masking effect. On the other hand, the number of AE events would be enough to evaluate the m-value at the slip velocity less than 115 μm/s. Nevertheless in that case, we can still recognize the negative effect of slip velocity. In the experimental seismology, the investigation of the effect of the slip velocity on AE activity is carried out using a dry granite specimen under bi-axial compression condition at room temperature in order to reveal the mechanism of subduction zone (Yabe, 2002). The result of this experiment has also suggested the negative effect on the m-value. He pointed out the possibility of the effect to micromechanics of the asperity contact. However, the reason for the negative effect on AE activity has not been clarified in detail.

CONCLUSION

We have conducted the model experiments that simulate shear slip of preexisting fracture in order to reveal the controlling parameters of "aseismic" fracture. The normal stress and the slip velocity have been studied as the possible controlling parameters of AE occurrence and efficiency, where the effect of these parameters on AE activity has been investigated through the observation of induced AE events during the stable slip of artificial fracture. It has been suggested that the normal stress acting on the fracture surface has less effect on AE event rate and m-value, and that the slip velocity has the negative effect on the AE rate as well as the m-value. The mechanism of the less effect of normal stress on the AE event rate and the m-value has been explained with the insensitivity of the number of contacts and the distribution of the real contact area on the surface, respectively. However, the mechanism of the negative effect of slip velocity has not been clarified.

ACKNOWLEDGEMENTS

We would like to appreciate helpful and suggestive discussions with Mr. Y. Yabe, Graduate school of science, Tohoku University.

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