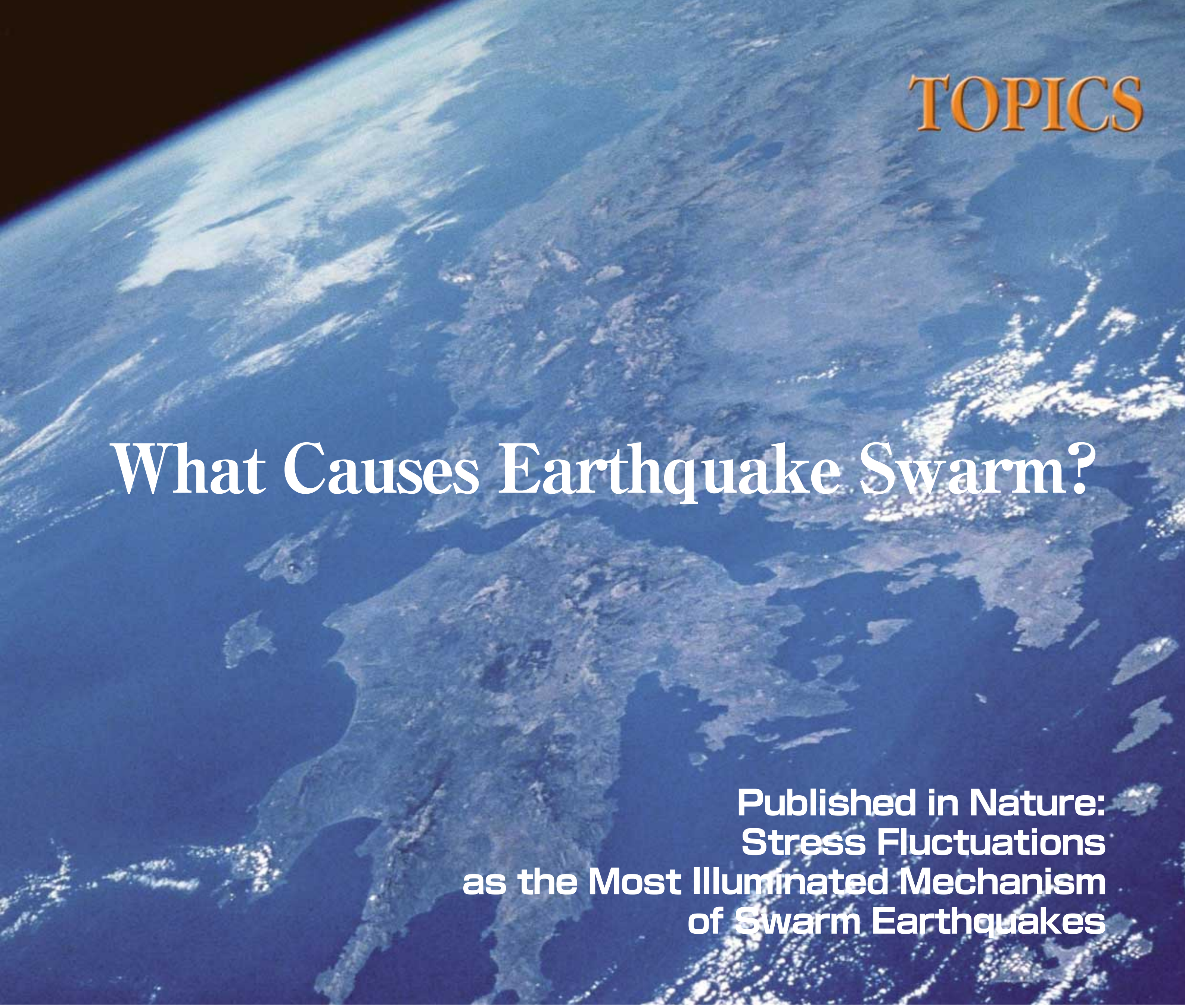

What Causes Earthquake Swarm?

Published in Nature: Stress Fluctuations as the Most Illuminated Mechanism of Swarm Earthquakes

● Cover of the Nature, 5 September 2002 issue (courtesy of the Nature Japan)

Seismic activities can be classified into either a major quake followed by aftershocks or an earthquake swarm. In general, within major earthquakes a maximum-scale quake is followed by a number of minor aftershocks. Meanwhile, the swarm earthquake is a series of the quakes of a similar scale to the mainshock. The pace of subsidence in such earthquake occurring is gradual relative to aftershocks in normal earthquakes, and the seismic activities are protracted.

The AD 2000 Izu islands earthquake that struck the northern Izu islands showed one of the most energetic swarms ever recorded. We analysed the seismicity data as well as the land survey of this swarm to demonstrate that the sustained crustal deformation and increase in stressing rate largely contribute to the occurrence of earthquake swarms.

Earthquake Swarms Produced by the Change in Stressing Rate

Earthquake swarm has been considered to be "an exceptional phenomena" which differs from the normal earthquakes. Dominant hypotheses that explain the occurrence of the swarm include the immediate influence of magma and ground water (ex. intrusion to the fault), peculiar inhomogeneity of crustal structure and so on. As shown below, in the AD 2000 Izu islands earthquake swarm, we found that the seismic activities were produced by stress transfers due to crustal deformation, that was incited by magma intrusions and extrusions. Although the mechanism of each earthquake is the same as that of normal earthquake, an extraordinarily high stress generated for a relatively short period rapidly elevates the rate of earthquake occurrence, resulting in distinctive seismological behaviour. The research result was published in Nature, the issue of September 5th, 2002 (co-authored with Dr. Takeshi Sagiya, Geographical Survey, Japan and Dr. Ross Stein, US Geographical Survey).

Analysis of the AD 2000 Izu Islands Earthquake Swarm

The swarm that struck the northern Izu islands from June to August 2000 was one of the largest earthquakes ever recorded in the land territory and surrounding areas, producing 7,000 shocks with magnitude ≧ 3 including five magnitude ≧ 6 shocks. In addition to its enormous scale, a great deal of attention was attracted to the detailed data of the seismic activities obtained through thorough observations conducted by the researchers of Japan Meteorological Agency and Tokyo University, as well as the continuous GPS (Global Positioning System) observation by Geographical Survey Institute. The displacement of the ground surface in relation to the seismicity was monitored in almost real time (see Fig.1).

Swarm Moved the Islands - Laboratory-based Observation Using the Growth Model of Magma -

As a result of GPS observation, it was calculated that the distance between Niijima and Kozujima islands was extended by approximately 80cm whilst that between Nijima and Toshima islands was drawn closer by 20cm during the 2 months from June 26 to August 23, when the seismicity was active. From longitudinal data analysis of displacement, although abrupt changes of about several centimeters were produced by shocks over magnitude 6, it was made clear that the distance between the two islands were gradually extended for the two months. In order to give an explanation to such crustal deformation, we assumed that a vertical dyke spread 15 km long by 5 km wide in the waters off Miyakejima continuously propagated for 2 months (dyke model hereinafter). The dyke eventually opened by 20m. Based on this dyke model, the shear stressing rate of the surrounding earth's crust was calculated as

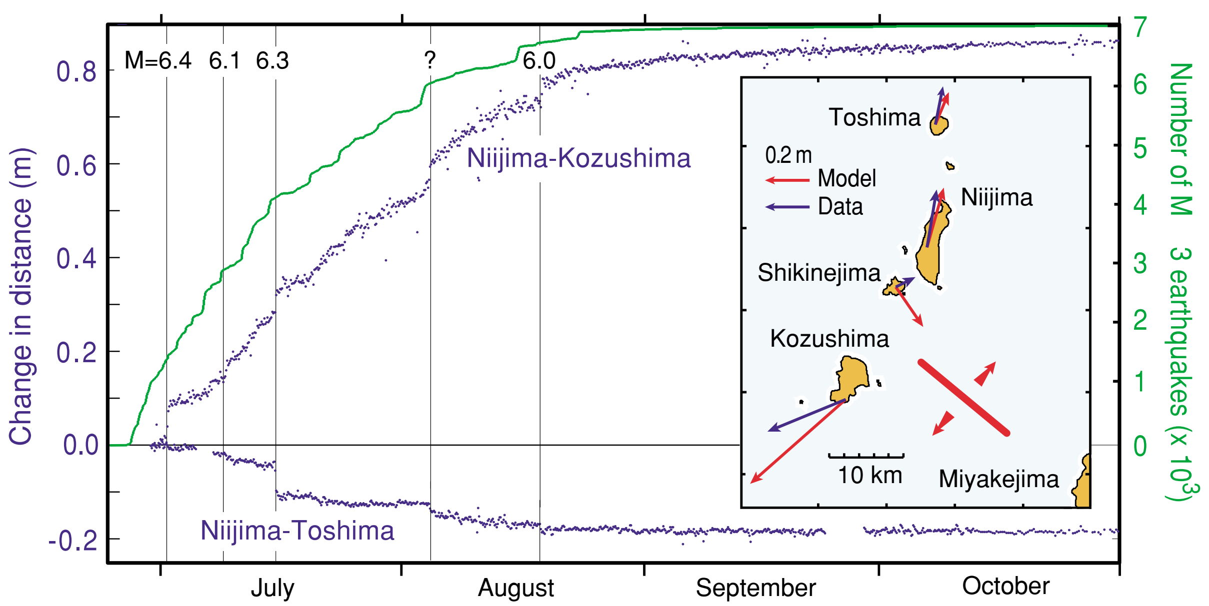

Fig.1 GPS line-length changes and cumulative earthquakes during the swarm.

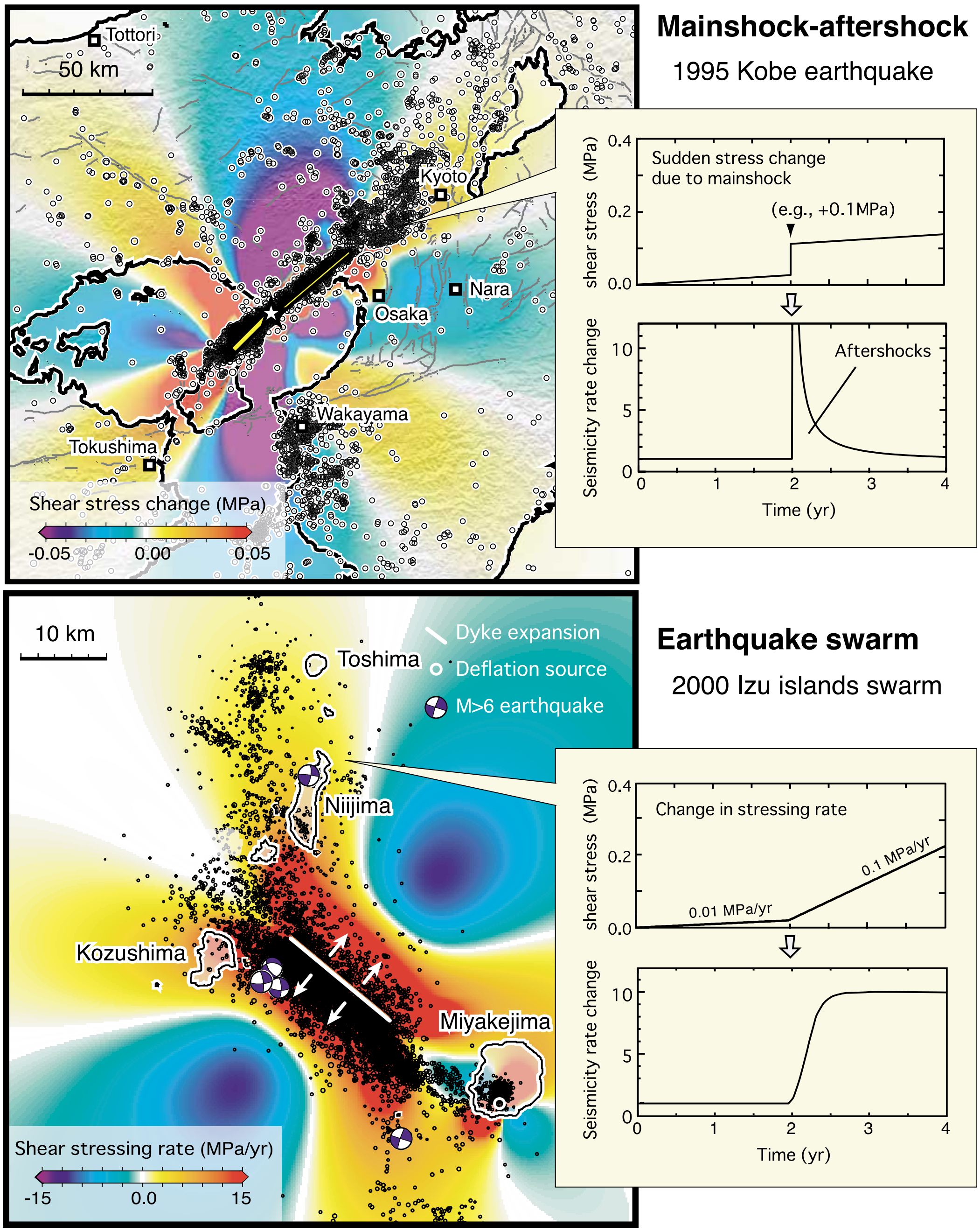

Fig.2 Two types of seismicity produced by a stress step or an increase of stress rate.

a strike-slip fault that is common in the most earthquakes. Consequently, the area was divided into two in accordance with the resulting variation of stressing rate (Fig.2 bottom The warm and cold colors indicate the increase and decrease of the stressing rate, respectively.). We estimated that the stressing rate in the offshore of Miyakejima, close to the dyke was 10Mpa/year or over and it reached several Mpa a year even on Nijima island, away from the dyke. Based on the GPS observational data for the several years before the seismic activities, the normal stressing rate is estimated at 0.01Mpa/year. That means, more than a 1000-fold increase in stressing rate occurred in the area of north west offshore of Miyakejima whilst a several hundred fold increase occurred in the surrounding area of Nijima. The sustained stressing rate was higher than normal. Meanwhile, most of the observed shocks occurred in the area of increased stressing rate (Fig. 2 bottom). Comparing the occurrence rate to that of the normal earthquakes, it was observed that the change of the seismicity rate is more proportional to the stressing rate variation. This finding conforms to a theory obtained from the fault friction experiment. This theory, although being quite straightforward, was verified for the first time by our study, suggesting the possibility to apply it to prediction of an earthquake. Through the observation of the swarm of this time, it was revealed that:

1. The area of seismic activities expanded over time;
2. The duration of aftershocks of earthquakes magnitude ≧ 6 was extremely short.

These results also confirmed our laboratory-based fault friction theory.

Increase in Stressing-rate and Seismicity

As shown in the study of the Izu islands earthquake swarm, it has become easier to calculate the shift of crustal stress by means of the computer assisted numerical analysis, in spite of the difficulty in calculation/estimation of the absolute stress value. Another major clustering element of seismic activities, that is "majorshock and aftershocks" can also been explained by the similar analysis.

Conventionally, the academic attention has been drawn to the aftershocks provoked on the source fault. However, recent findings indicate the influence of majorshock to the seismic activity away from the earthquake source. The shift of seismic activities in the areas away from the epicenter that was developed before-and-after the mainshock is not necessarily consistent. We observed both increase and decrease in seismic rate, depending on the area. In case of the Izu islands swarm, where the deformation was produced by dyke intrusion, the remote triggering of the seismic center can be explained by the calculation of static stressing rate changes. In the example of the Kobe earthquake in 1995, the stressing rate changes extended to the latent shear faults in the surrounding crust that were triggered by the mainshock were calculated as shown in Fig. 2, top. The earthquakes that occurred during the following 18 months (aftershocks in a broad sense) were also plotted.

Although there are exceptions, an earthquake is likely to occur frequently in the area where the stressing rate increased. In contrast, the area where the stressing rate decreased, reduced earthquake activity is observed. It should be noted that even the slightest variation in stressing rate (less than atmospheric pressure) can cause a significant change in seismic activities. This suggests the sensitivity of constitutive balance of the crust that may be hovering around the critical level. The achievements of the similar researches upon the other major earthquakes around the world have manifested the correlation between the abrupt change of stressing rate produced by the mainshock and seismic activities.

Possibility of Earthquake Prediction

As indicated above, the chain earthquake can be categorised into two groups depending on the type of stressing rate change (Fig.2) .

1. Mainshock-aftershocks type: The sudden increase in stressing rate triggers temporal bursts of seismic activities, i.e. aftershocks which decay over time.
2. Earthquake swarm type: The seismic activities increase in proportion to the gradual and sustained increase in stressing rate.

These properties of stressing rate and seismic behaviors can be applied to the probabilistic prediction of sequencing seismic activities such as aftershocks and swarms. The experimental attempt of aftershock prediction has already started. Earthquake prediction/forecast has still a long way to go for contemporary geoscience. However, we are approaching the perception any earthquake occurrences are not individual phenomenon acting in isolation but rather being interrelated to one another within the crust. In that sense, there is plenty of scope for anticipating the realization of earthquake prediction in the future.

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