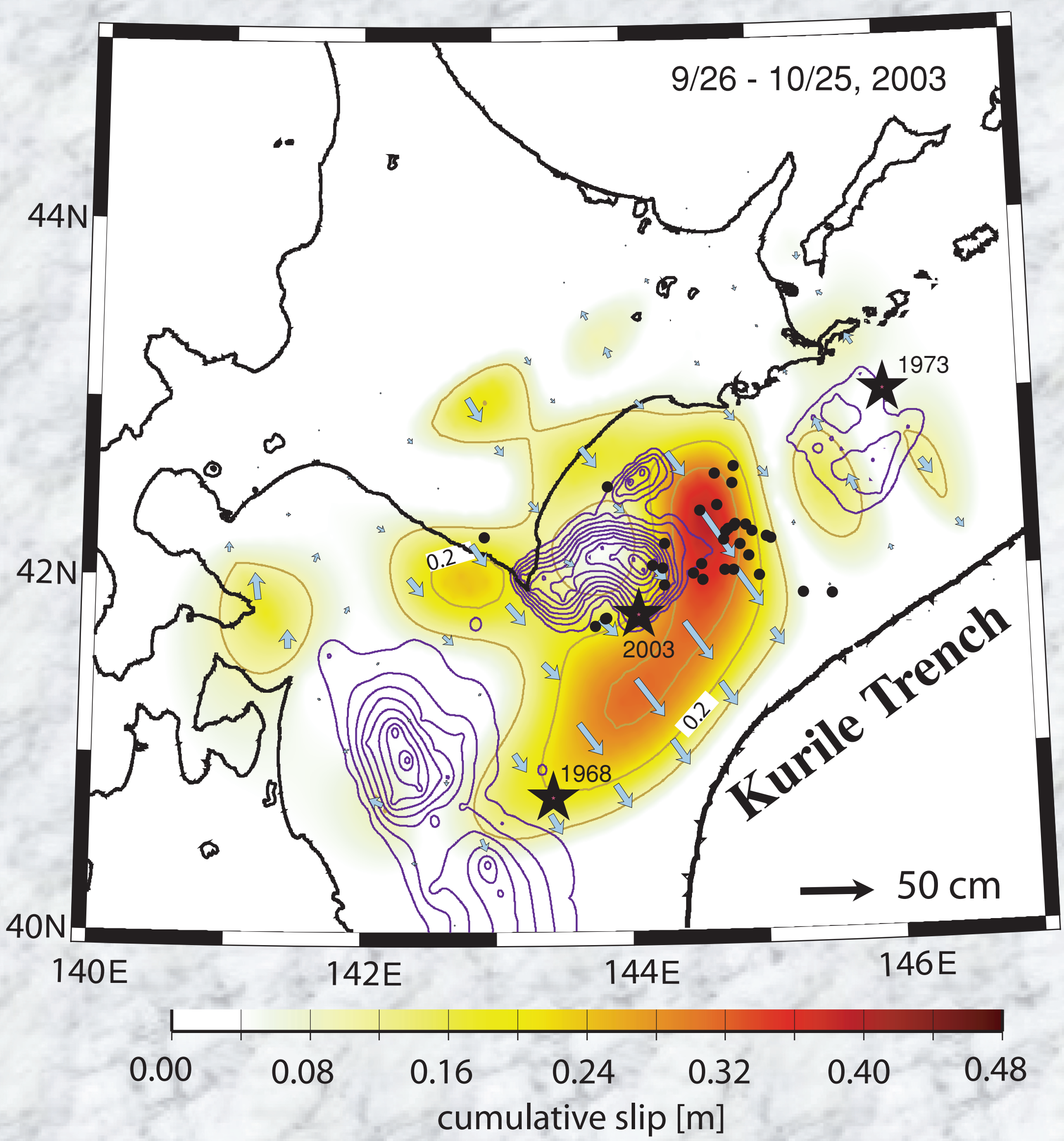
Earthquake Prediction Researches in Japan

The Earthquake Subcommittee of the Coordinating Committee of Earthquake and Volcanic Eruption Prediction Researches



2006

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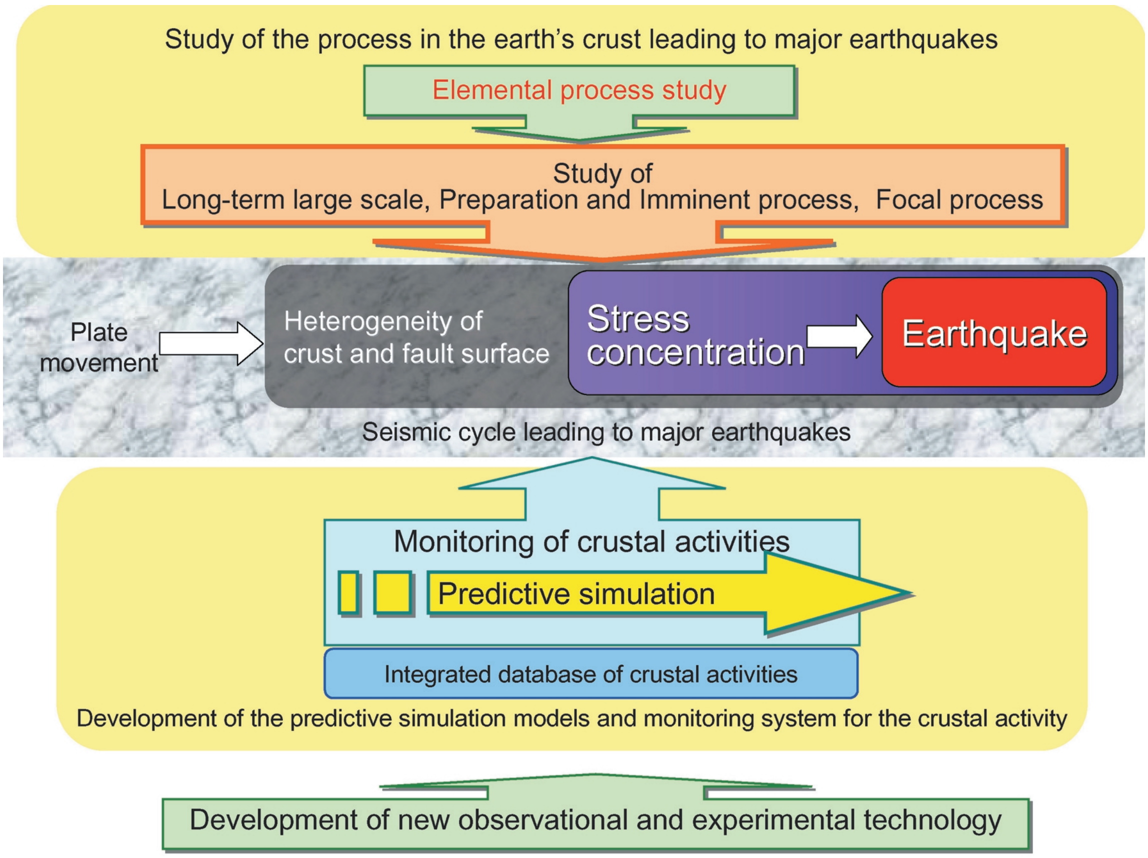
The research program for earthquake prediction has been carried out since 1964 under the proposal of Geodecy Council of Japan. After intensive researches on earthquake precursors for more than 30 years, a comprehensive review on the research program was made to construct a new program. A renovated program named “The New Observation and Research Program for Earthquake Prediction” was proposed by the Geodecy Council of Japan in August, 1998, and successfully executed in a five-year research project that started in 1999. “The Second New Observation and Research Program for Earthquake Prediction” was proposed by the Science and Technology Council of Japan in July, 2003. The proposal aimed for understanding the full process of earthquakes, i.e. from preparation stage through their occurrence. This program also emphasized the importance of earthquake prediction using computer simulation based on the physical model that is constructed by the understanding of physical processes of earthquake in combination with intensive observations for the crustal activities. This brochure will summarize representative results obtained in the new program of earthquake prediction research in Japan.



Recurrence of Earthquakes at Asperities on Plate Boundaries

The Pacific and Philippine Sea Plates subduct beneath the Japanese Islands at a few to ten cm/year, resulting in frictional sliding on the interfaces between the subducting oceanic plates and the overriding plates. Dependent on frictional properties of the plate interfaces, stable sliding occurs without accumulation of elastic strains at some places, and stick-slip occurs at the other places (Figure 1). At the place where stick-slip occurs, the plate interface is locked and strain energy is accumulated during a stick stage, while the strain energy is released during a slip stage, which generates an interplate earthquake. An area where stick-slip occurs is often called an asperity. Asperities of various sizes exist on a plate boundary. Large earthquakes repeatedly occur at large asperities, while small earthquakes occur at small asperities.

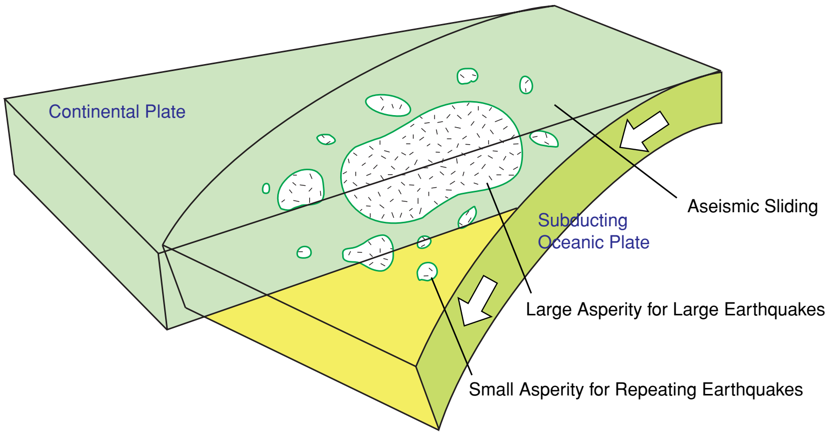


Figure 1. Illustration showing the boundary between a subducting oceanic plate and an overriding plate at a subduction zone.

The 1952 and 2003 Tokachi-Oki earthquakes of magnitudes 8.2 and 8.0, respectively, occurred at a large asperity offshore Hokkaido. Figure 2 shows the spatial distribution of seismic slip of the two Tokachi-Oki earthquakes estimated from seismic waveform analyses. The areas of large seismic slip of the two earthquakes approximately coincide with each other, and these areas are the asperities of the Tokachi-Oki earthquakes. Since relative plate motion accumulates strain energy on an asperity nearly at a constant rate, earthquakes repeatedly occur there nearly at a constant recurrence interval to release strain energy, if the effect of

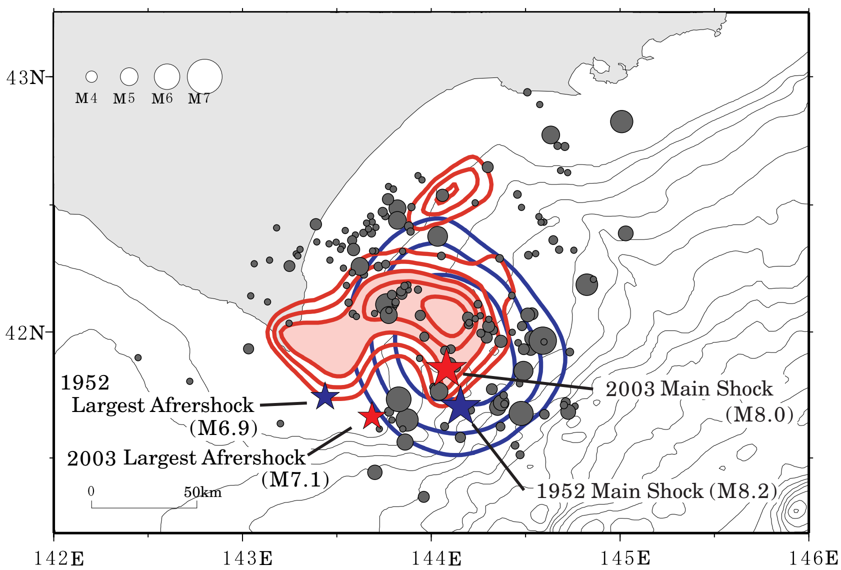


Figure 2. The spatial distributions of coseismic slip of the 1952 Tokachi-Oki earthquake of M8.2 (blue contours of 1 m interval) and the 2003 Tokachi-Oki earthquake of M8.0 (red contours of 1 m interval). Large blue and red stars denote the epicenters of the 1952 and 2003 mainshocks, respectively, and small blue and red stars denote the epicenters of the largest aftershocks. Gray circles stand for aftershocks of the 2003 Tokachi-Oki earthquake.

interaction between asperities is neglected. On the basis of this fact, we can forecast earthquake occurrence. Before the 2003 earthquake, the probability of the occurrence of the Tokachi-Oki earthquake had been evaluated at 60% for the period from 2003 to 2032.

Since coseismic slip is smaller for an earthquake on a smaller asperity, earthquakes recur at shorter time intervals. Off Kamaishi, Iwate Prefecture, nine earthquakes of magnitudes 4.7 to 4.9 at the same asperity have been recorded at a nearly constant time interval since 1957 (Figure 3). The occurrence time and the magnitude of the latest earthquake in 2001 was successfully predicted on the basis of recorded history of the preceding earthquakes.

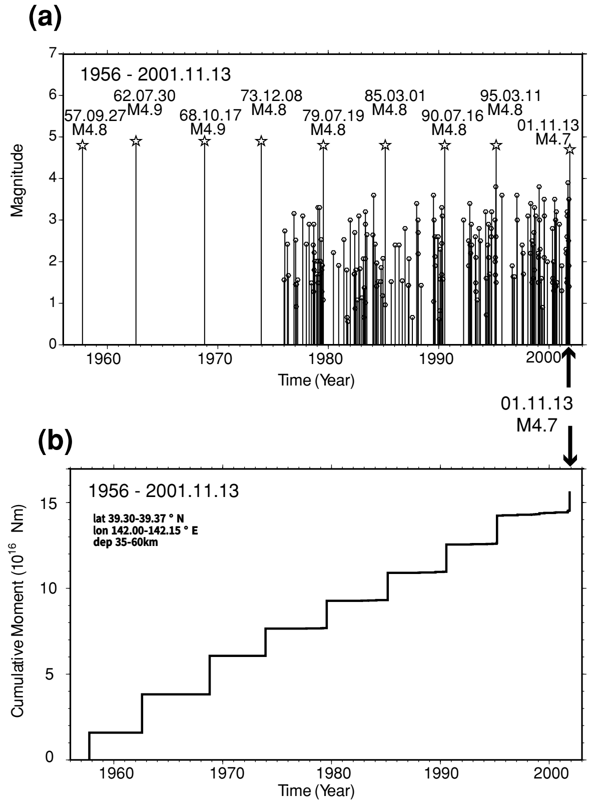


Figure 3. Small repeating earthquakes on a small asperity off Kamaishi, Iwate Prefecture. Magnitudes of earthquakes off Kamaishi versus time since 1956 (top) and the cumulative seismic moment, which is proportional to the strain energy released by earthquakes (bottom).

Aseismic Sliding

While earthquakes repeatedly occur at asperities, stable sliding takes place on the remaining regions of plate boundaries. Since the sliding velocities of stable sliding are too low to generate seismic waves, it is also called aseismic sliding. Characteristics of aseismic sliding have been revealed in the last decade from analyses of data of recently deployed Global Positioning System (GPS), which can detect slow crustal deformation. The figure on the cover shows the spatial distribution of coseismic slip of the 2003 Tokachi-Oki earthquake and postseismic slip (afterslip) for one month from the mainshock estimated from GPS data. Significant postseismic slip took place in the region surrounding the mainshock asperity so as to relax strains due to the mainshock slip.

GPS observations are useful also for mapping aseismic sliding and the locked regions on a plate boundary during an interseismic period (Figure 4).

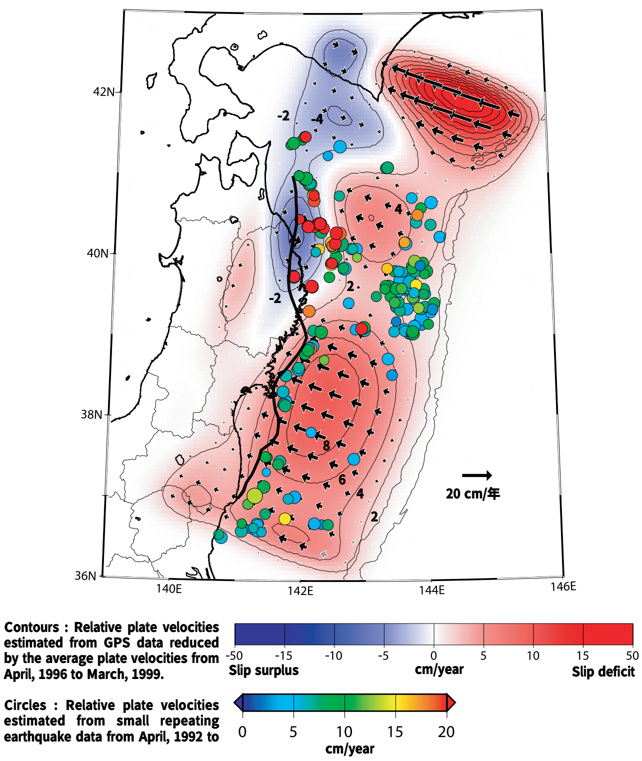


Figure 4. Spatial distribution of aseismic sliding rate on the plate boundary along the Japan trench estimated from GPS data (contours) from April, 1996 to March, 1999 and small repeating earthquakes (circles) from April, 1992 to July, 2000.

At the asperities of the 1994 Sanriku-Oki earthquake (M7.6) and the 2003 Tokachi-Oki earthquake (M8.0), the plate boundary is virtually locked (deep red in Figure 4) and, accordingly, strain energy is accumulated. Aseismic sliding occurs in the regions with light red to blue in Figure 4. If a small asperity exists on an aseismic slip region, small earthquakes repeatedly occur there. These earthquakes are often called small repeating earthquakes. Using the fact that the recurrence interval of earthquakes is inversely proportional to the loading rate, the aseismic slip rate can be estimated from the data of small repeating earthquakes (circles in Figure 4).

Observations of crustal deformation indicate that episodic aseismic slip events have repeatedly occurred on the plate boundary on the deeper extension of the hypothetical source area of the expected Tokai earthquake

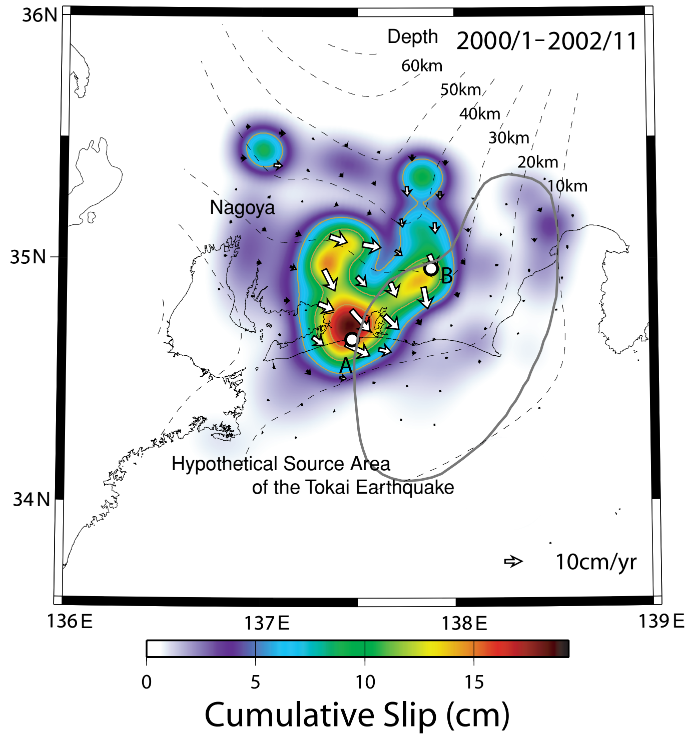


Figure 5. Cumulative slip of an episodic aseismic slip event (slow earthquake) on the deeper extension of the hypothetical source area of the Tokai earthquake estimated from GPS data from January, 2000, to November, 2002.

(Figure 5). Since these aseismic slip events strain the hypothetical source area of the Tokai earthquake, they may be related to the occurrence of the Tokai earthquake. The occurrence of episodic aseismic slip events can be explained by a simple mechanical model, in which the frictional properties at the seismogenic zone and those at the source region of episodic aseismic slip events are assumed to be different from each other (Figure 6).

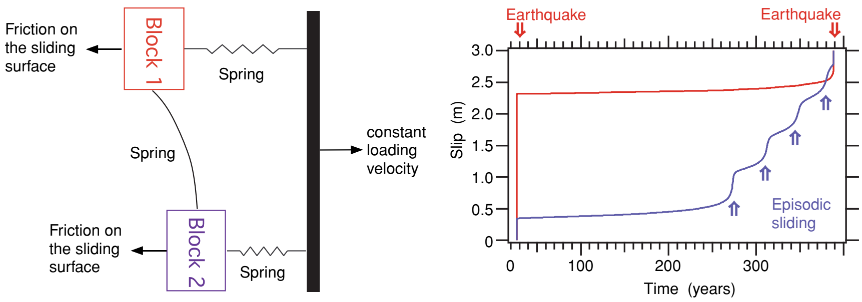


Figure 6. Numerical simulation for episodic aseismic slip events with a simple model consisting of two rigid blocks connected with an elastic spring. The blocks are dragged through springs at a constant rate, which corresponds to relative plate motion, and friction acting on the bases of the blocks corresponding to friction on plate boundaries. By taking appropriate frictional properties at the bases of blocks 1 and 2, we can simulate repeated earthquakes at block 1 and episodic aseismic slip events at block 2.

Numerical Simulation of Earthquake Cycles

As shown for the model of episodic aseismic slip events, a diversity of sliding behavior can be modeled by taking into consideration frictional properties of plate boundaries. Numerous laboratory studies of rock friction have been carried out to understand frictional properties of various rocks under various environmental conditions and to obtain constitutive friction laws. Using the constitutive laws, numerical simulations of sliding behavior on plate boundaries have been performed. During an earthquake cycle, strain energy is accumulated at a locked part (asperity) of a plate boundary, and is suddenly released by the occurrence of an earthquake followed by postseismic sliding mainly in the surrounding region of the seismic slip area. The simulation aims at understanding and modeling the whole earthquake cycle. Figure 7 shows a result of numerical simulation of earthquake cycle along the Nankai trough, southwestern Japan, where magnitude 8 class earthquakes such as the 1944 Tonankai earthquake (M8.0) and the 1946 Nankai earthquake (M8.1) have repeatedly occurred. In past great earthquakes, there were giant earthquakes whose source areas spanned both the source areas of the Tonankai and Nankai earthquakes. The numerical simulation can reproduce the characteristics of such complicated earthquake history along the Nakai trough.

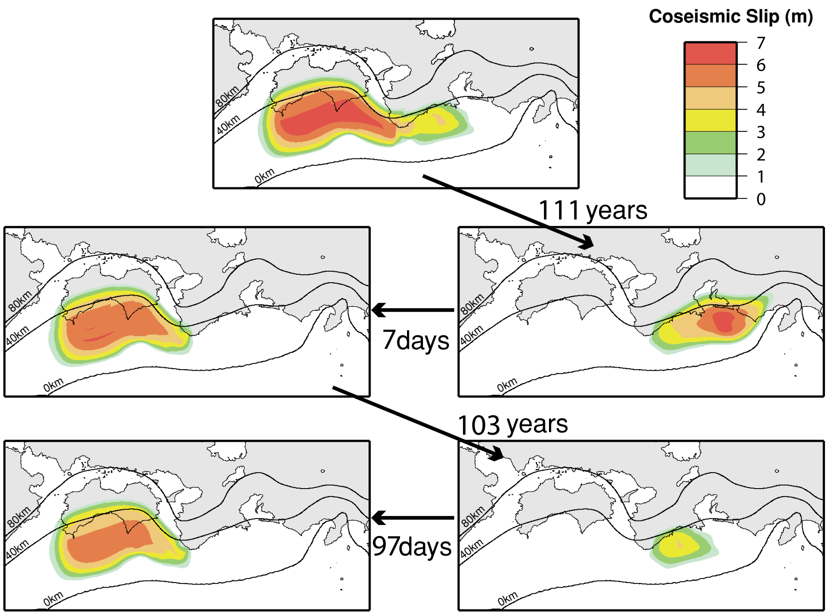


Figure 7. Numerical simulation of earthquake cycles along the Nankai trough, southwestern Japan. Panels show the spatial distributions of coseismic slip of five successive earthquakes in the simulation, demonstrating that the coseismic slip distributions are variable. The Nankai earthquake tends to occur a few to a few tens days after the occurrence of the Tonankai earthquake.

In the simulation using the laboratory-derived constitutive laws of rock friction, an earthquake is preceded by accelerating aseicmic sliding, which is called preseismic sliding or preslip. In friction experiments in the laboratory, preseismic sliding is actually observed. Figure 8 shows a numerical result of preseismic sliding of the coming Tokai earthquake. Since preseismic sliding causes abnormal crustal deformation before earthquake occurrence, it is expected that earthquakes can be predicted. However, it is still controversial whether the amplitude of preseismic abnormal crustal deformation is large enough to be detectable with existing instruments. Further research is necessary to resolve this issue.

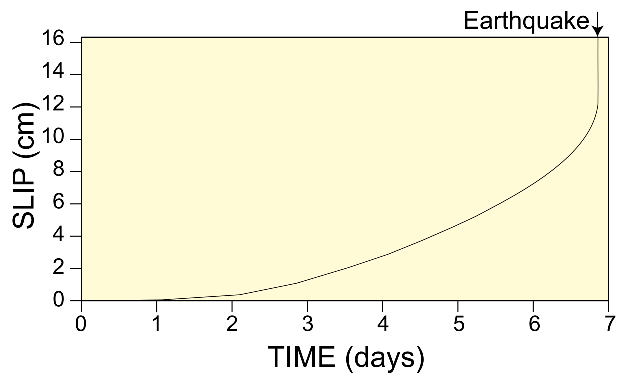


Figure 8. Simulated preseismic sliding of a large interplate earthquake.

Numerical Simulation of Strong Ground Motion

How the ground shakes at the occurrence of an earthquake depends on the rupture process of the earthquake and the underground structure where seismic waves are propagated. Progress of understanding in the earthquake source process and underground structure together with the developments of computation power and technique enable us to perform numerical simulations of realistic strong ground motion of earthquakes. Figure 9 shows a simulation result of strong ground motion when the Tonankai and Tokai earthquakes occur simultaneously, where the earthquake rupture is assumed to propagate from west to east. In the direction of rupture propagation, seismic waves are concentrated to generate larger amplitudes of ground motion. In alluvial plains, seismic waves are amplified due to underground soft materials. These simulation results are used for the evaluation of seismic hazard.

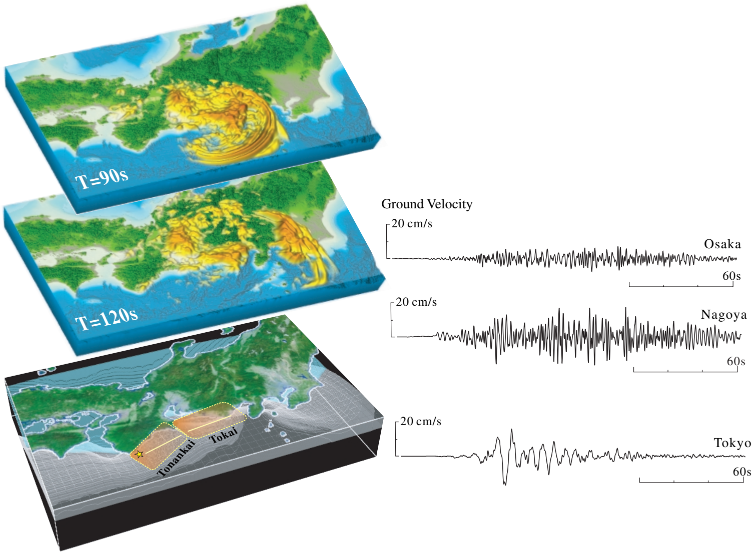


Figure 9. Numerical simulation of strong ground motion from consecutive occurrence of the Tonankai and Tokai earthquakes. Waveforms (right) are the simulated ground velocities at Osaka, Nagoya, and Tokyo.

Structure of Subducting Plate

Understading fine underground structure including the locations of plate boundaries and the spatial distribution of seismic wave speeds is necessary for reliable simulations of earthquake cycles and strong ground motion. Moreover, the research of underground structure is important for understanding where earthquakes occur. The structure beneath the Kinki district estimated from analyses of seismic waveforms from far field earthquakes is shown in Figure 10, and the boundaries where seismic wave speeds abruptly change are clearly illuminated. Figure 10 shows the upper boundary of the subducting Philippine Sea plate and the Moho discontinuity that separates crust and mantle. Many small earthquakes occur in the Philippine Sea plate just beneath the upper boundary of the plate and in the inland upper crust.

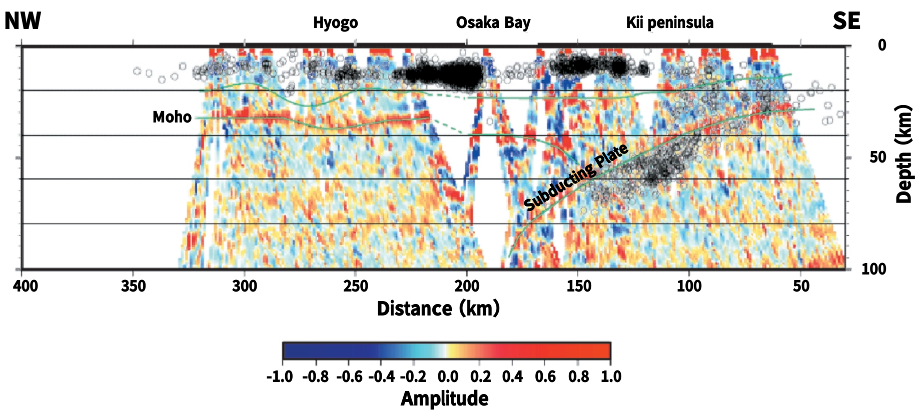


Figure 10. Structure beneath the Kinki district estimated from seismic waveform analyses. The upper boundary of the subducting Philippine Sea plate and Moho, which is the boundary between crust and mantle, are clearly seen. Many earthquakes (black dots) occur in the subducting Philippine Sea plate and inland crust.

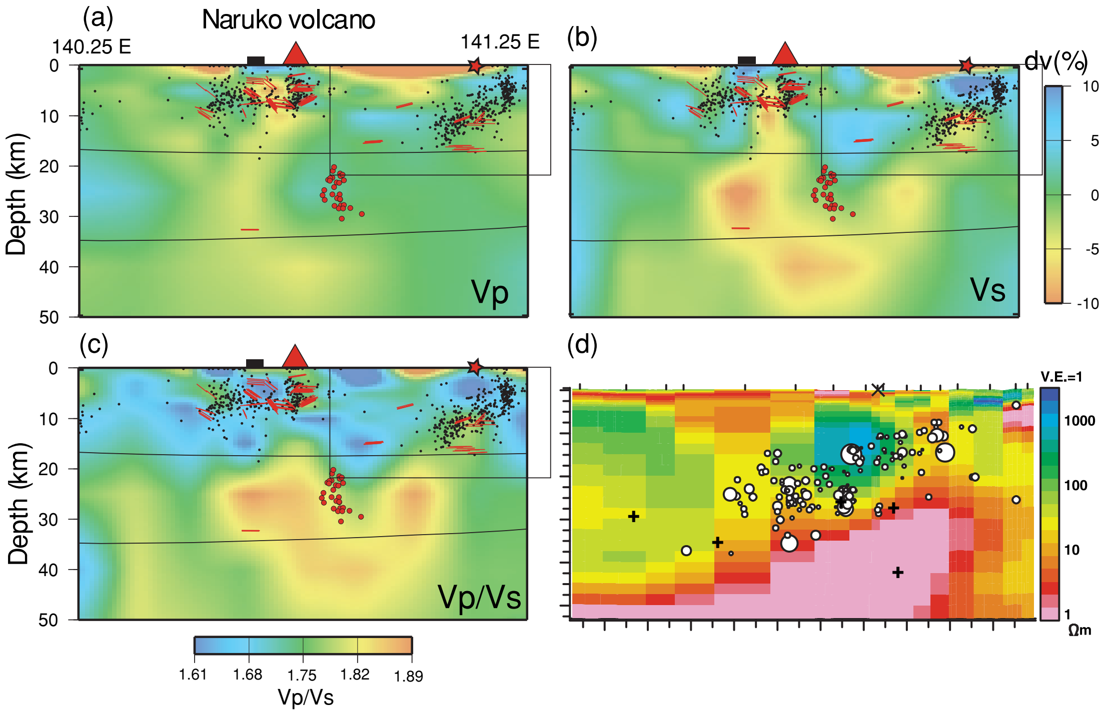


Figure 11. (a)-(c) Distribution of perturbation of seismic wave speeds beneath the Naruko volcano, Miyagi Prefecture, where Vp and Vs represent P- and S-wave speeds, respectively. Bluish and reddish colors indicate high and low velocities, respectively. The upper right frame in each figure shows the region for resistivity structure in (d). (d) The resistivity structure in the focal area of the 1962 Northern Miyagi earthquake (M6.5). Reddish colors indicate low resistivity.

Researches on underground structure are useful also for understanding how earthquakes occur in inland crust. Figure 11 shows seismic wave speed structure beneath the Naruko volcano, Miyagi Prefecture. Figure 11 demonstrates that the seismic wave speeds are relatively lower just beneath the Naruko volcano, suggesting the existence of soft materials. Many S-wave reflectors exist in the same region, and low-frequency microearthquakes occur in a deeper part. These observations suggest the existence of abundant fluids in the region. Low S-wave speeds and some S-wave reflectors are observed near the right corner in Figure 11a-c, where the 1962 Northern Miyagi earthquake (M6.5) occurred. In this region, magnetotelluric surveys were carried out to obtain resistivity structure (Figure 11d). Low resistivity, which also suggests the occurrence of fluids, exists in a region of low S-wave speeds. Synthesizing the above observational results, researchers developed a model for mechanism of inland earthquakes (Figure 12). In regions where high temperature fluids upwell, brittle crustal layer is thinned and, accordingly, earthquake generating stress is concentrated in the thinned crust.

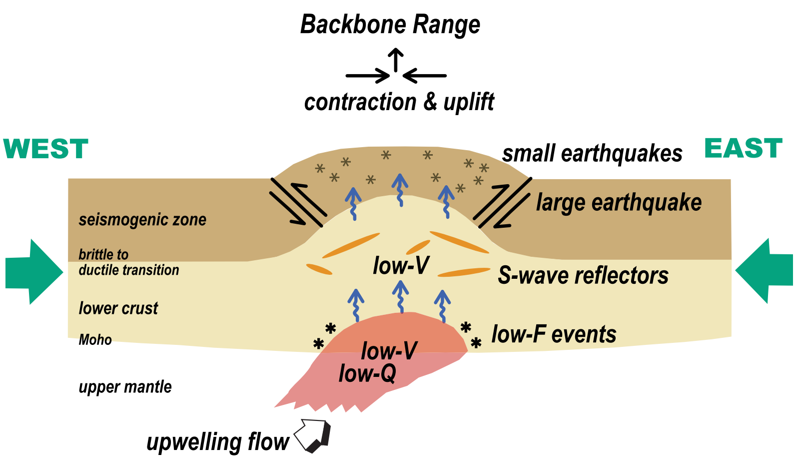


Figure 12. A schematic model of inland deformation and mechanism of inland earthquakes.

The 2004 Mid-Niigata Prefecture Earthquake in the Niigata-Kobe Tectonic Zone

In order to understand the mechanism of the 2004 Mid-Niigata Prefecture earthquake (M6.8), which brought serious damage, researchers observed aftershocks and investigated the structure of the focal region. Figure 13 shows that numerous aftershocks illuminate some planes, which correspond to the faults of the mainshock and some large aftershocks. The mainshock fault plane was laid along the boundary between a region of high seismic wave speeds and a region of low seismic wave speeds.

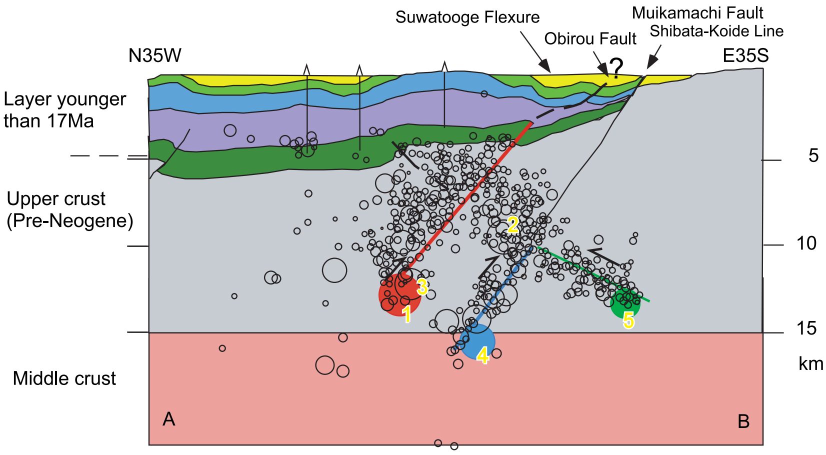


Figure 13. Spatial distribution of aftershocks of the 2004 Mid-Niigata Prefecture earthquake (M6.8). ① denotes the hypocenter of the mainshock, and ② to ⑤ the hypocenters of aftershocks with M≥6. Solid straight lines denote estimated fault planes of the mainshock and the large aftershocks with M≥6.

GPS observations indicate that high strain-rate belt extends from Niigata to Kobe as shown in Figure 14. This high strain-rate belt is now called the Niigata-Kobe Tectonic Zone (NKTZ), where many active faults run and many large earthquakes took place (e.g., the 1995 Kobe earthquake of M7.2 and the 2004 Mid-Niigata Prefecture earthquake of M6.8). Although the origin of NKTZ is controversial, some models have been proposed such as a model in which deformable materials exist beneath NKTZ. Researchers concentrate their efforts on the multipurpose geophysical observation project around the Atotsugawa fault in NKTZ to understand the structure and mechanism of NKTZ.

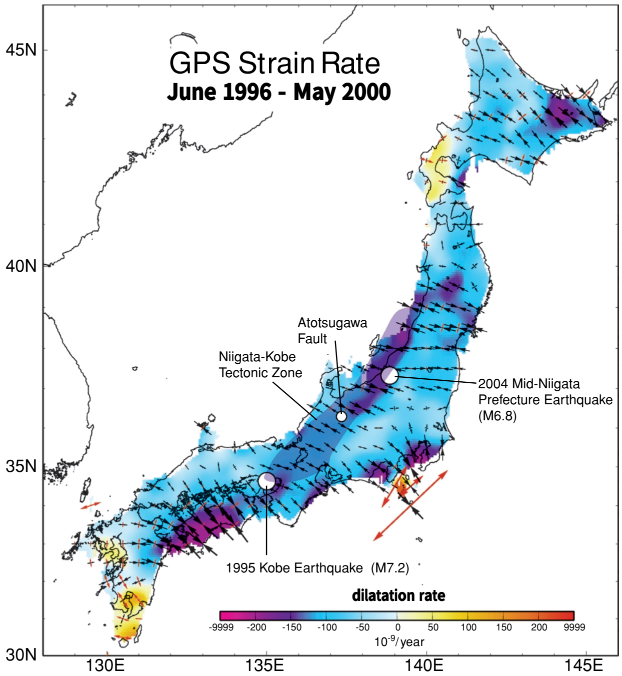


Figure 14. Spatial distribution of areal strain rate in the Japanese islands estimated from GPS data from June, 1996, to May, 2000. High strain-rate belt from Niigata to Kobe is the Niigata-Kobe Tectonic Zone (NKTZ), in which the 1995 Kobe earthquake (M7.2) and the 2004 Mid-Niigata Prefecture earthquake (M6.8) occurred.

Monitoring the State of Fault Surfaces

Understanding the state of the surfaces of plate boundaries and active faults may be useful for forecasting sliding behavior. Figure 15 shows an experimental result of seismic wave transmission through a fault in a rock sample, and indicates that the amplitude of the transmitted seismic wave decreases with an increase in sliding velocity. This is caused by that the degree of contact between sliding surfaces decreases with increasing sliding velocity. The degree of contact is expected to be weakened prior to earthquake occurrence because of preseismic sliding. Accordingly, observing seismic waves through fault zones may be useful for earthquake prediction. To accurately monitor the state of fault surfaces with seismic waves, the amplitudes and the frequencies of input seismic waves must be constant. For this purpose, a vibrator that generates seismic waves of the identical waveform was developed, and the vibrators were installed at some test sites to monitor the state of fault surfaces.

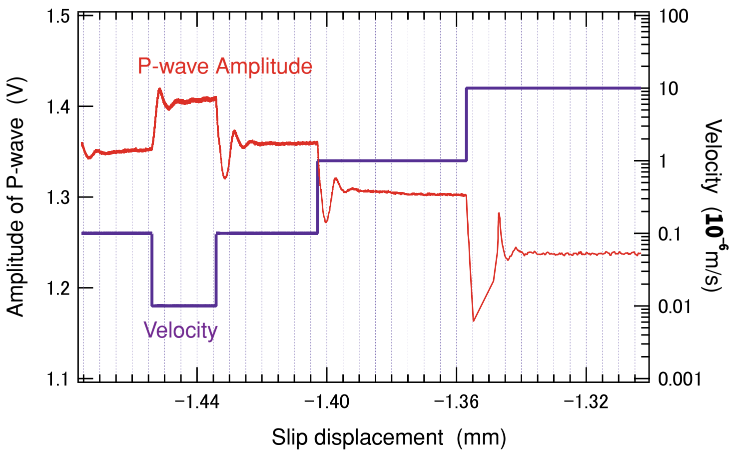


Figure 15. The amplitude of transmitted P-wave through an artificial fault in a rock sample in the laboratory. The amplitude decreases with increasing sliding velocity of the fault.

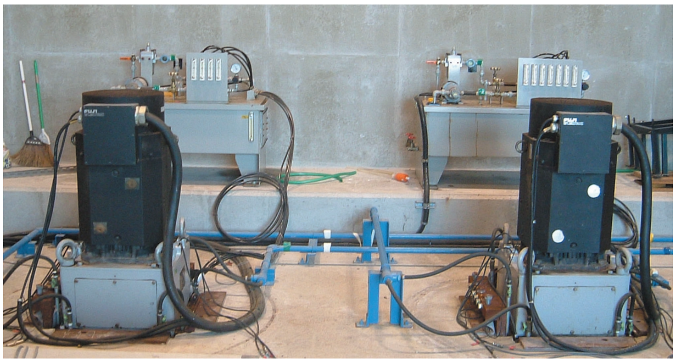
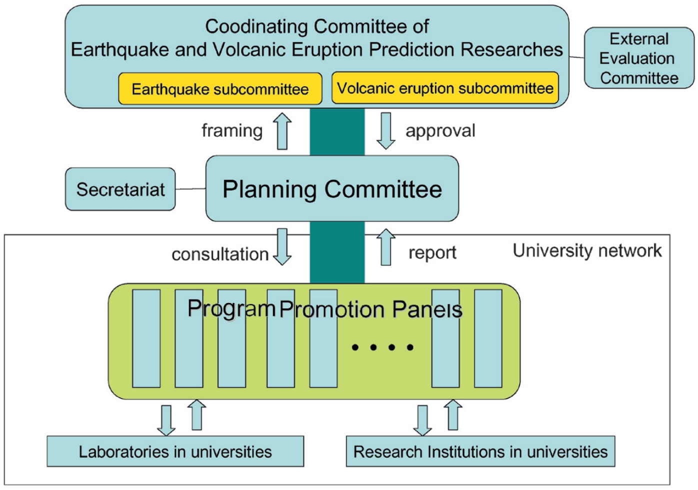


Figure 16. A vibrator for generating identical seismic waveforms for monitoring underground structure.

Organization to Promote Earthquake Prediction Research in Japanese Universities



The Coordinating Committee of Earthquake and Volcanic Eruption Prediction Researches (CCEVPR) is organized with heads of the institutions related to seismology and volcanology in Japanese universities. Prediction-related researches are promoted under the leadership of CCEVPR with a system that is open for many researchers covering interdisciplinary research fields. CCEVPR was established by reorganizing the former two committees concerning earthquake prediction and volcanic eruption prediction researches to have closer cooperation between the two fields. A Planning Committee and Program Promotion Panels are formed to make effective and quick administration on the research promotion.

The Planning Committee presides at workshops and symposia to oversight the research program. Annual achievements of the research projects by all of the concerning institutions are to be discussed in the end-year symposium hosted by CCEVPR and other government-supported institutions. Annual achievements are also published by the Promotion Committee for Earthquake Observation and Research under the Council for Science and Technology, and appeared on a web of the Ministry of Education, Culture, Sports, Science and Technology.

Eight program promotion panels are responsible for eight different research divisions of earthquake prediction research, i.e.

1) Long-term, large-scale crustal activity.
2) Preparation or imminent processes in the crust leading to large earthquakes.
3) Focal processes and generation of strong ground motions.
4) Elemental processes of earthquake generation.
5) Development of predictive simulation models for the crustal activity.
6) Development of monitoring system for the crustal activity.
7) Development of integrated database of the crustal activity.
8) Development of new technology on observation and experiment.

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Institute of Seismology and Volcanology, Graduate School of Science, Hokkaido University
Earthquake and Volcano Observatory, Faculty of Science and Technology, Hirosaki University
Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University
Faculty of Engineering and Resource Science, Akita University
Earthquake Research Institute, The University of Tokyo
Graduate School of Science, The University of Tokyo
Laboratory for Earthquake Chemistry, Graduate School of Science, The University of Tokyo
Graduate School of Science and Engineering, Tokyo Institute of Technology
Volcanic Fluid Research Center, Tokyo Institute of Technology
Research Center for Seismology, Volcanology and Disaster Mitigation, Graduate School of Environmental Studies, Nagoya University
Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University
Faculty of Engineering, Tottori University
Kochi Earthquake Observatory, Faculty of Science, Kochi University
Institute of Seismology and Volcanology, Graduate School of Sciences, Kyushu University
Nansei-Toko Observatory for Earthquakes and Volcanoes, Faculty of Science, Kagoshima University

Planning Committee
Coordinating Committee of Earthquake and Volcanic Eruption Prediction Researches
Earthquake Research Institute, The University of Tokyo
1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, JAPAN
Phone +81-3-5841-5712

Front Cover: Spatial distributions of coseismic slip (purple contours) of the 2003 Tokachi-Oki earthquake (M8.0) and its postseismic sliding (color) for one month from the earthquake together with the spatial distributions of coseismic slip of the 1968 Tokachi-Oki earthquake (M7.9) and the 1973 Nemuro-Hanto-Oki earthquake (M7.4). Solid stars denote the epicenters of the earthquakes, and small solid circles denote aftershocks of the 2003 Tokachi-Oki earthquake.