Reproducing Core-Mantle Dynamics and Predicting Crustal Activities Through Advanced Computing

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Abstract The solid Earth is a very complex nonlinear system, consisting of the crust, mantle and core that are different, both physically and chemically, from each other. Our vision in solid Earth science is to develop an integrated simulation model for reproducing the core-mantle dynamic processes such as geodynamo, mantle convection and global plate motion, and for predicting the diverse crustal activities such as earthquake occurrence, volcanic eruption and mountain building. Recent advances in high performance computer technology and numerical simulation methodology are bringing this vision within reach.

Keywords: predictive simulation, geodynamo, mantle convection, plate dynamics, earthquake generation.

1. Introduction

The solid Earth consists of the crust, mantle and core that are different, both physically and chemically, from each other. To short time-scale disturbances such as seismic waves, for example, the Earth system behaves like an elastic body, except for the outer core that is composed of liquid iron. To intermediate time-scale changes such as inter-seismic loading or post-glacial unloading, the Earth's surface layer, called the lithosphere, still behaves like an elastic body, but the underlying uppermost mantle layer, called the asthenosphere, now behaves like a viscous fluid. To long time-scale tectonic loading, the whole Earth system behaves like a fluid but with different viscosities in depth. The average viscosities of the lithosphere, the asthenosphere, the mesosphere (the main part of the mantle), and the outer core are about 10^{24} Pas, 10^{19} Pas, 10^{21} Pas, and 10^{-2} Pas, respectively (Fig. 1). Because of such a remarkable contrast in viscosity, the solid Earth operates as three coupled convective systems of the fluid outer core, the subsolidus mantle, and the outermost solid shell.

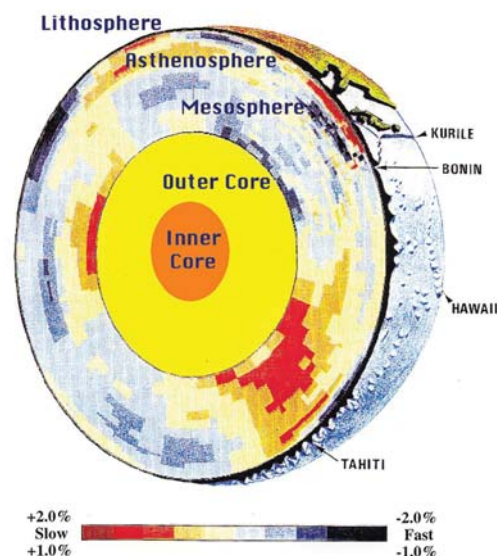| Compo-sition	Rheology	Viscosity
Crust	Lithosphere	10^{24} Pa s
Mantle	Asthenosphere	10^{19} Pa s
	Mesosphere	10^{21} Pa s
Core	Outer Core	10^{-2} Pa s
	Inner Core	----

Fig. 1 A 3D tomographic image obtained from the inversion analysis of seismic data and the rheological structure of the Earth's interior. The tomographic image was reproduced by courtesy of Yoshio Fukao, ERI, University of Tokyo.

These three convective motions are driven essentially by the flow of thermal energy from the Earth's deep interior to the surface. The ultimate sources of the thermal energy are radioactive decay and cooling of the planet. Gravitational instability caused by the non-equilibrium thermal state in the Earth's interior generates convective motions in the outer core and the mantle. The magneto-hydrodynamic convection in the outer core generates the Earth's magnetic field. The thermal convection in the mantle is responsible for the global plate motions with accretion of new plate areas at ocean ridges and consumption of old plate areas at ocean trenches. Diverse crustal activities such as earthquake occurrence, volcanic eruption and mountain building can be ascribed to dynamic interaction at plate interfaces.

Our vision in solid Earth science is to reproduce the present core-mantle dynamics and predict the future crustal activities by integrating theoretical models and observations. In order to realize this vision, realistic numerical simulations based on physical models are crucial as well as more precise and denser observations with new technology. For realistic simulations in solid Earth science we need a very large-scale, high-speed computer system. In Japan, recently, a high performance, massively parallel-processing computer system, called the Earth Simulator, has been completed at the Yokohama Institute, JAMSTEC. Advanced computing on the Earth Simulator enables us to develop a multi-scale, multi-physics solid Earth simulation system, named the Solid Earth Simulator.

2. Architecture of the Solid Earth Simulator

Since the solid Earth is a multi-scale complex system, we design the Solid Earth Simulator as a composite of three sub-systems corresponding to long-term global simulation of core-mantle dynamics, intermediate-term regional simulation of crustal activities due to relative plate motion, and short-term local simulation of earthquake rupture and strong ground motion. These three sub-systems with different simulation algorithms are connected with each other through a platform on the Earth Simulator.

On a long-term global scale, the solid Earth operates as three coupled convective systems of the fluid outer core, the subsolidus mantle, and the outermost solid shell. In the fluid outer core magneto-hydrodynamic dynamo action generates the Earth's magnetic field. In the subsolidus mantle, in addition to the global-scale thermal convections that would be responsible for plate tectonics, there exist local-scale thermal plumes that cause hot-spot volcanism. In the outermost solid shell gravitational forces arising from thermal contraction by cooling drive global plate motions with accretion of new plate areas at

ocean ridges and consumption of old plate areas at ocean trenches. The aim of developing a long-term global scale simulation model for core-mantle dynamics is to quantitatively understand the interaction between these convective systems and to reproduce the dynamic processes in the Earth's interior.

On an intermediate-term regional scale, plate tectonics, the surface manifestations of mantle convection, brings about earthquakes, volcanic eruptions, and crustal deformations at plate boundary zones. On a long-term average, plates move steadily relative to each other. The occurrence of large interplate earthquakes is regarded as the perturbations of the steady plate motion. Thus, crustal deformation during one earthquake cycle can be decomposed into two parts: the secular change due to steady slip over the whole plate interfaces and the cyclic change due to stick-slip motion in seismogenic regions. At present we can precisely determine the 3D geometry of plate interfaces from seismological observations and the relative velocities among plates from space-based geodetic measurements such as GPS, SLR, and VLBI. Therefore, a rational representation of plate-to-plate interaction, which is the origin of diverse crustal activities, is to specify the increasing rates of tangential displacement discontinuity (fault slip) across the plate interface [1]. The force system equivalent to tangential displacement discontinuity has no net force and no net torque. Such a property must be satisfied for any force system acting on plate interfaces, since it originates from a dynamic process in the Earth's interior. As a result of relative plate motion, shear stress accumulates in and around a seismogenic region and is suddenly released by earthquake rupture. The aim of developing an intermediate-term regional simulation model for crustal activities is to understand the physical process of earthquake generation driven by relative plate motion and to examine the possibility of earthquake prediction.

On a short-term local scale, the dynamic propagation of earthquake rupture along a complex fault system radiates elastic waves. These elastic waves are propagated in a 3-D heterogeneous medium and strongly amplified by the interaction of various phases in a sedimentary layer with complicated structure. The aim of developing a short-term local simulation of earthquake rupture and strong ground motion is to understand the interacting effects of the source process and the seismic wave propagation and to precisely estimate strong ground motion in a realistic situation.

3. Reproducing the Dynamic Processes in the Earth's Interior

The origin of the Earth's magnetic field is one of the most interesting unsolved problems in Earth science. At

present it is widely recognized that the Earth's magnetic field is generated and maintained by dynamo action that operates in the fluid outer core, but the details of the self-regenerating process of dynamo and its variation still remain far from understood.

Modern geomagnetic field observations show that the main component of the Earth's magnetic field (the magnetic dipole positioned at the Earth's center and aligned with the rotation axis) has decayed by 5–10 percent for the past 150 years. This decay rate suggests the possibility of geomagnetic polarity reversal in near future. Paleomagnetic observations show that such geomagnetic reversals occurred, though with great variability, about once every half million years on average [2].

Is the geomagnetic field really reversing? To answer this question advanced numerical simulations of geodynamo with a high-performance computer such as the Earth Simulator are necessary. In numerical dynamo simulation we must solve intensively coupled magneto-hydrodynamics equations. The essential dimensionless parameters that characterize the coupled magneto-hydrodynamics equations are the Ekman number (E) and the Rayleigh number (Ra). In particular the Ekman number, which describes the ratio of viscous force to Coriolis force, is quite important, because difference of E leads to a drastic change in characteristics of the convective system. The Ekman number of the Earth's outer core has been estimated to be less than 10^{-9}. So far the values of E used in dynamo simulation have been limited to greater than 10^{-5} because of the ability of computers. The difference of four orders of magnitude in E is too large to discuss the possibility of geomagnetic reversal on the basis of simulation results. To bring the simulation results closer to the real process in the Earth's outer core, we must decrease the value of E in dynamo simulation. Recently, such attempts have started with the Earth Simulator [3]. Figure 2 shows an example of 3D simulation of a MHD dynamo (right) and the generated Earth's magnetic fields (left) in the case of $E = 10^{-6}$. Progress in numerical dynamo simulation will advance greatly our understanding of the mechanism of magnetic reversal.

Global convective motion in the 2900-km thick mantle plays a major role of thermal energy transport from the deep Earth's interior to the surface. Whether mantle convection occurs in one or two separate layers still remains as a fundamental question. Understanding mantle convection is also important in the following two senses; 1) plate tectonics, which is responsible for seismicity, volcanism and mountain building, is the surface manifestations of mantle convection, and 2) mantle convection strongly affects the self-regenerating process of dynamo in the outer core through thermo-mechanical coupling at the core-mantle boundary.

Present-day global plate motion, which is the surface manifestations of mantle convection, can be now directly observed by using space-based technology. High-resolution mantle seismic tomography is producing 3D images of seismic velocity anomalies, which may correlatable to
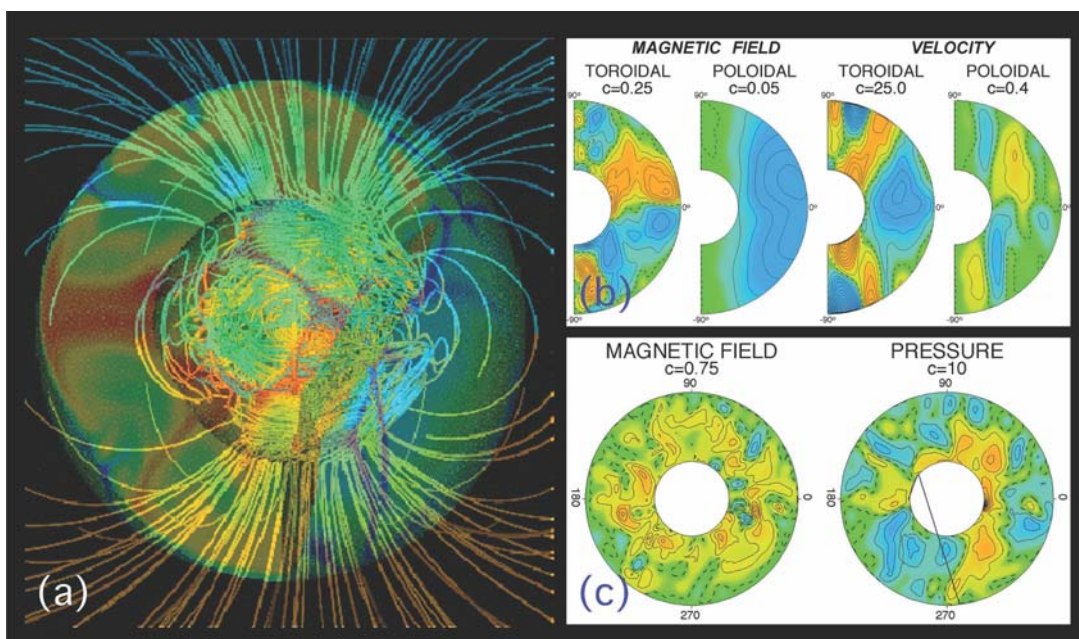

Fig. 2 3D simulation of a MHD dynamo and geomagnetic fields. (a) The magnetic field generated by a MHD dynamo that operates in the fluid core. (b) Magnetic and velocity fields at the meridian cross section. (c) Magnetic and pressure fields at the equatorial cross section. All the figures were reproduced by courtesy of Yozo Hamano and Ataru Sakuraba, DEPS, University of Tokyo.
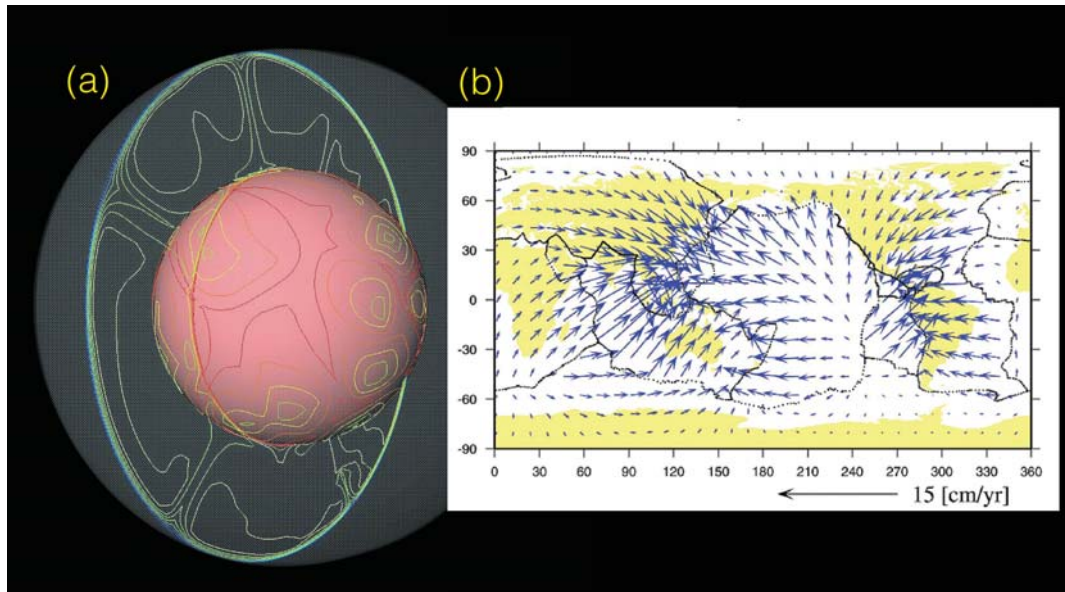
Fig. 3 3D simulation of mantle convection and global plate motion. (a) Isotherm contours showing convection patterns in the mantle. (b) Reproduced global plate motion. All the figures were reproduced by courtesy of Satoru Honda, ERI, University of Tokyo.

the density anomalies that directly drive convective motions [4]. The global geoid anomalies observed by satellite altimetry also provide integrative measure of the mantle density anomalies. Thus, at present, we have a rough image of global-scale mantle convection, but we lack information about the flow patterns in the deep Earth's interior and the distribution of mantle plumes, which are closely related to the core-mantle coupling. Furthermore, we do not know how mantle flow is coupled to the motions of tectonic plates. We have poor understanding of the mechanism for initiation of new subduction. To resolve these problems advanced numerical simulations of mantle dynamics are necessary.

Most difficulties in the realistic simulation of mantle dynamics arise from the complexity in rheological properties of mantle material. At present we have not enough knowledge about the mantle rheology to describe the real state of the Earth's interior. Then, there may be two possible approaches to numerically reproduce the convective motions in the crust-mantle system. In the first approach we reproduce the observed global plate motion by numerically solving the basic equations governing the crust-mantle convective system [5]. Figure 3 is an example of such attempts, demonstrating the good agreement of simulated plate motions to observations. In this simulation the geometry of plate boundaries characterized by low viscosity are given *a priori* as the boundary conditions based on observations. In the second approach we reproduce the 3D tomographic images related to mantle convection by numerically solving the basic equations for the observed global plate motion that gives the boundary

conditions to be satisfied at the Earth's surface. For totally understanding the convective motion of the crust-mantle system, we need to combine these two approaches.

4. Predicting Crustal Activities in and around Japan

Plate subduction at ocean trenches causes diverse crustal activities such as earthquake occurrence, volcanic eruption, and the formation of island arc-trench system. Among them, earthquake occurrence may be the most interesting and serious phenomena for us. From the standpoint of earthquake prediction, our target is limited to large earthquakes. The essential difference between large and smaller events is in their stress accumulation-release processes. The large events that completely break down the seismogenic zone may be regarded as the process of tectonic stress release, while the smaller events that break down only a part of the seismogenic zone should be regarded as the redistribution process of local stress. Thus, only to large events, we can apply the concept of earthquake cycle, which generally consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, and fault strength restoration.

In the last decade there has been great progress in the physics of earthquake generation; that is, the introduction of laboratory-based fault constitutive laws as a basic equation governing earthquake rupture and the quantitative description of tectonic loading driven by plate motion. We can now quantitatively describe the entire process of earthquake generation cycle by a coupled non-
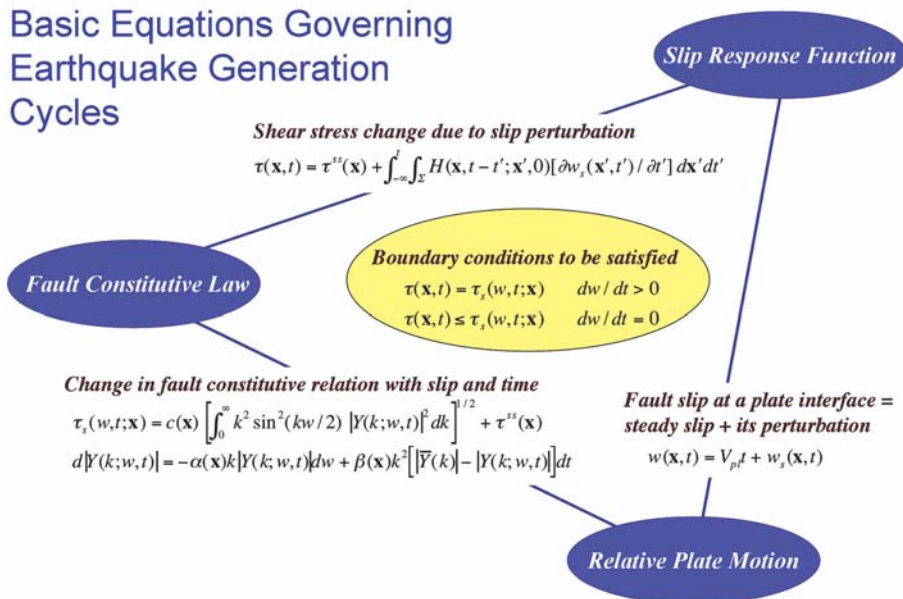
Basic Equations Governing Earthquake Generation Cycles

Slip Response Function

Shear stress change due to slip perturbation

$$\tau(\mathbf{x},t) = \tau^{ss}(\mathbf{x}) + \int_{-\infty}^{t}\int_{\Sigma} H(\mathbf{x},t-t';\mathbf{x}',0)[\partial w_s(\mathbf{x}',t')/\partial t']\, d\mathbf{x}'dt'$$

Fault Constitutive Law

Boundary conditions to be satisfied

$$\tau(\mathbf{x},t) = \tau_s(w,t;\mathbf{x}) \qquad dw/dt > 0$$
$$\tau(\mathbf{x},t) \le \tau_s(w,t;\mathbf{x}) \qquad dw/dt = 0$$

Change in fault constitutive relation with slip and time

$$\tau_s(w,t;\mathbf{x}) = c(\mathbf{x})\left[\int_0^{\infty} k^2 \sin^2(kw/2)\, |Y(k;w,t)|^2\, dk\right]^{1/2} + \tau^{ss}(\mathbf{x})$$
$$d|Y(k;w,t)| = -\alpha(\mathbf{x})k|Y(k;w,t)|dw + \beta(\mathbf{x})k^2\left[|\overline{Y}(k)| - |Y(k;w,t)|\right]dt$$

Fault slip at a plate interface = steady slip + its perturbation

$$w(\mathbf{x},t) = V_{pl}t + w_s(\mathbf{x},t)$$

Relative Plate Motion

Fig. 4 A diagram showing the relation between the basic equations that govern the entire processes of earthquake generation cycles.
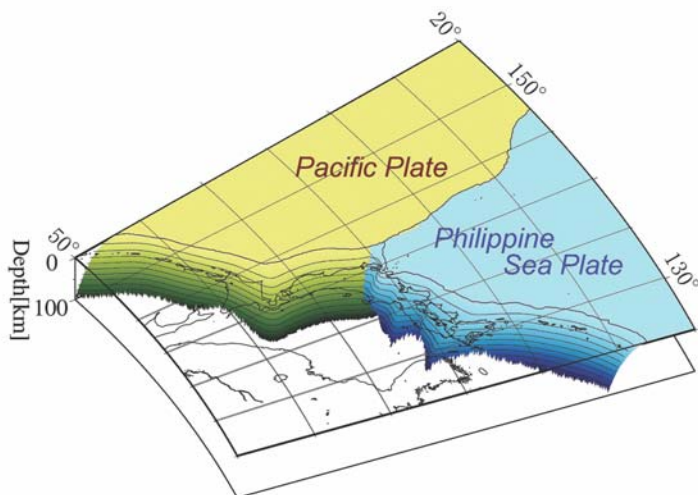

Fig. 5 3D geometry of plate interfaces in and around Japan (Hashimoto, Fukui & Matsu'ura, 2004).

linear system, which consists of a slip-response function that relates fault slip to shear stress change and a fault constitutive law that prescribes change in shear strength with fault slip and contact time (Fig. 4). Here, in modeling the earthquake generation cycle, the slip-response function should be viscoelastic, since we cannot neglect the effects of stress relaxation in the asthenosphere on the time scale of several tens years. Furthermore, as to the fault constitutive law, it must have an inherent mechanism of strength restoration. The driving force of this system is observed relative plate motions. The system to describe the earthquake generation cycle is conceptually quite simple. The complexity in practical modeling mainly comes from complex structure of the real Earth.

The Crustal Activity Modeling Program (CAMP) started in 1998 is one of the three main programs composing the Solid Earth Simulator project promoted by the Science and Technology Agency (now the Ministry of Education and Science) of Japan. The aim of CAMP is to develop a physics-based, predictive simulation system for the entire process of earthquake generation cycles in and around Japan, where the four plates of Pacific, North American, Philippine Sea, and Eurasian are interacting with each other in a very complicated way. The total simulation system consists of a crust-mantle structure model, a tectonic loading model, and a dynamic rupture model.

Figure 5 shows a realistic 3D model of plate interface geometry in and around Japan, constructed by applying

an inversion technique to ISC hypocenter distribution data [6]. The 3D geometry of plate interfaces is represented by the superposition of bi-cubic B-splines with 8 km equally spaced local supports. A 40 km thick elastic surface layer overlying a Maxwellian viscoelastic half-space models the crust-mantle rheological structure. With this structure model, given relative velocities among the plates, we can compute long-term crustal deformation due to steady subduction of the Pacific and the Philippine Sea plates [6]. The computed deformation pattern in Fig. 6 demonstrates that the steady subduction of oceanic plates brings about steep uplift at island arcs, sharp subsidence at ocean trenches, and gentle uplift at outer rises.

Incorporating a fault constitutive law with inherent strength-restoration mechanism into the steady plate subduction model, we can develop a quasi-static earthquake cycle model driven by relative plate motion [7]. Recently, by integrating microscopic effects of abrasion and adhesion at contacting rock surfaces, a rational fault constitutive law, called the slip- and time-dependent law, has been theoretically derived [8]. This constitutive law consistently explains three basic experimental results for rock friction; that is, the slip weakening in high-speed rupture, the log *t* strengthening in stationary contact, and the slip-velocity weakening in steady-state slip. Therefore, we can use the slip- and time-dependent constitutive law as a basic equation governing the entire process of earthquake generation. On the other hand, by applying the boundary integral equation method, a simulation model for dynamic rupture propagation on a 3D curved plate interface has been also developed. Thus, combining the quasi-static stress accumulation model and the dynamic rupture propagation model on the same structure model, we can construct a unified simulation system for the entire process of earthquake generation cycles [9].

Outputs of the simulation system are the crustal deformation, internal stress change and seismic wave radiation associated with seismic and/or aseismic slip at the plate interfaces. From comparison of these computed data with observed data, we can extract useful information to estimate the past slip history and the present stress state at the plate interfaces by using an inversion technique [10]. Given the past slip history and the present stress state, we can predict the next step fault-slip motion and stress change through computer simulation.

In Fig. 7, as an example of predictive simulation, we show the quasi-static stress accumulation process at the 1968 Tokachi-oki seismogenic region, northeast Japan, on the Pacific-North American plate interface (left), and the subsequent process of rupture initiation, propagation and stop there (right). In this simulation we forced dynamic rupture to start by giving artificial stress drop. Then, unstable rupture started, but it was not accelerated. This means that the dynamic rupture is not accelerated, if the stress state has not reached to a certain critical level. If the stress state is critical, the started dynamic rupture is accelerated to a high-speed terminal velocity. In this case, seismic waves with high amplitudes are radiated from the source and propagated into the surrounding elastic medium. A sophisticated model to simulate this process and to estimate strong ground motion in a realistic situation has been already developed [11]. Figure 8 is an example of good performance of strong motion simulation in the case of the hypothetical Nankai-trough earthquake. The propagation of strong velocity pulses is indicated by red and orange colors.
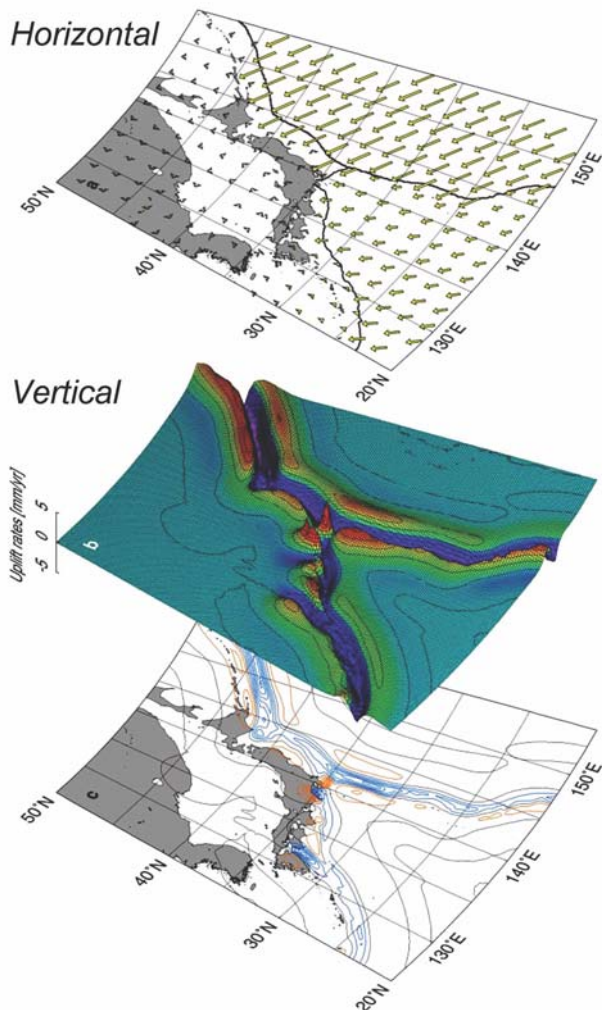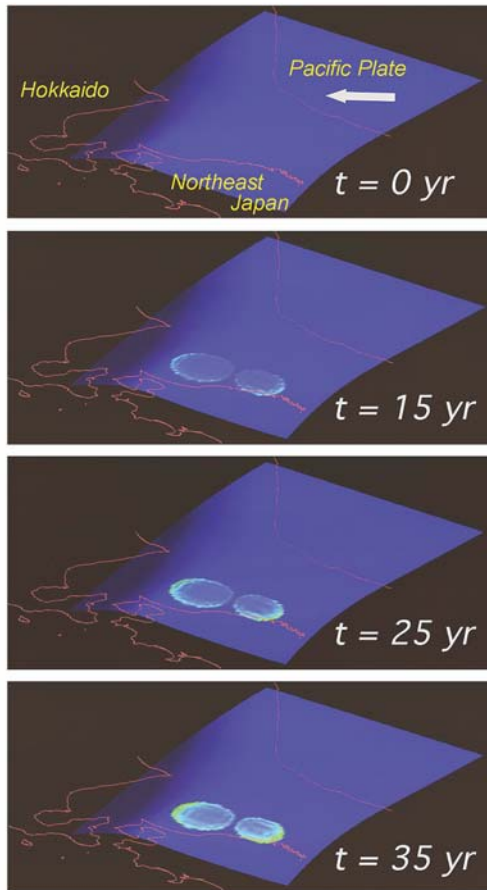

Fig. 6 Long-term crustal deformation due to steady plate subduction in and around Japan (Hashimoto, Fukui & Matsu'ura, 2004). Top: a vector map showing horizontal displacement rates. Middle and bottom: stereographic and contour-map representations of vertical displacement rates.

Predictive Simulation of Earthquake Generation at the Tokachi-oki Area
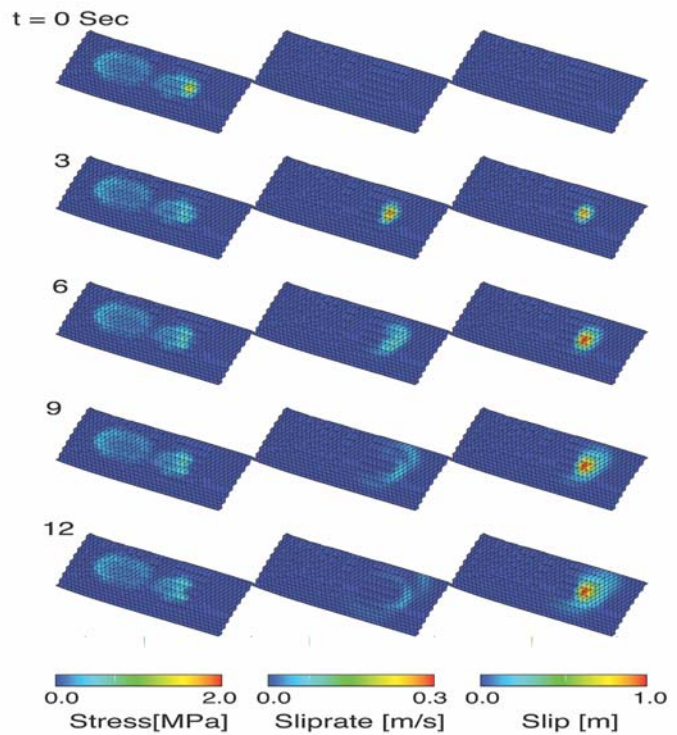
Fig. 7 Predictive simulation of earthquake generation cycles at the source region of the 1968 Tokachi-oki area, northeast Japan, on the Pacific-North American plate interface (Matsu'ura, Hashimoto & Fukuyama, 2003). Left: a series of snapshots showing the quasi-static stress accumulation process at and around the source region. Right: a series of snapshots showing the changes in shear stress, slip velocity, and fault slip after the initiation of dynamic rupture. In this case, the dynamic rupture is not accelerated, because the stress state is not in a critical level.
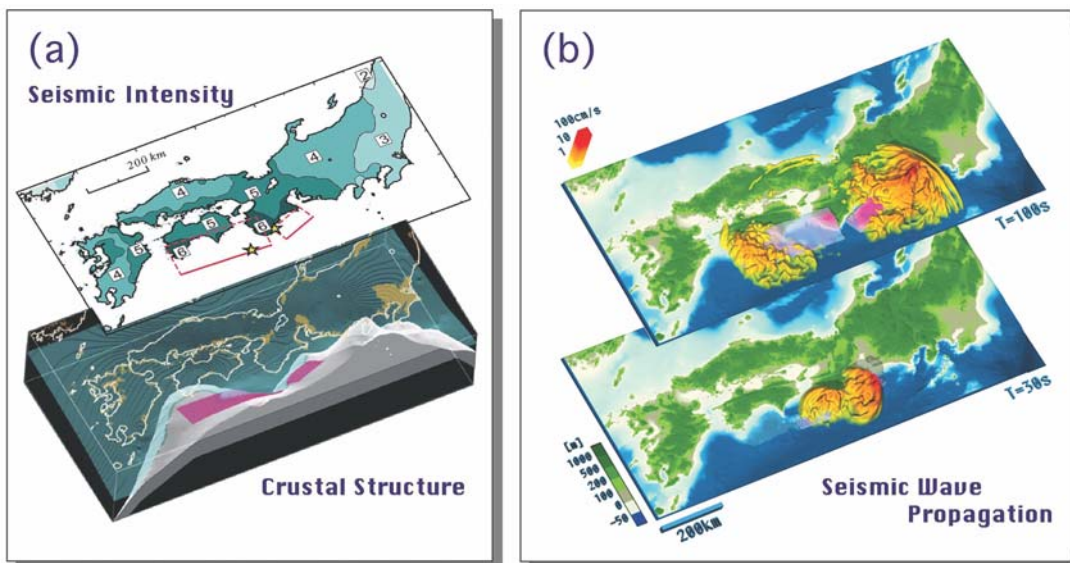

Fig. 8 3D simulation of seismic wave propagation in a realistic heterogeneous medium. (a) Top: a fault model of the hypothetical Nankai-trough earthquake and the expected seismic intensity distribution. Bottom: the crustal structure model in southwest Japan, used for the computation. (b) Propagation of seismic waves radiated from the source region of the hypothetical Nankai-trough earthquake. All the figures were reproduced by courtesy of Takashi Furumura, ERI, University of Tokyo.

5. International Collaboration for Solid Earth Simulation Study

The development of an integrated simulation model for reproducing core-mantle dynamics and predicting diverse crustal activities is our vision in solid Earth science. Although recent advances in high performance computer technology and numerical simulation methodology are bringing this vision within reach, there still exist many problems to be solved both in solid Earth science and computer science to reach the final goal. In order to overcome these problems, interdisciplinary collaboration becomes important more and more. For example, international collaborations that bridge solid Earth science and computer science have been carried out through the APEC Cooperation for Earthquake Simulation (ACES) since 1998. Furthermore, the Earth scientists and computer scientists who focus on modeling the dynamic processes of the solid Earth system are now developing the International Solid Earth Research Virtual Observatory (iSERVO), which will let scientists seamlessly merge multiple data sets and models and create new queries [12]. Such a direction in solid Earth simulation study will create a new research field called the predictive Earth science.

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