Development of a Predictive Simulation System for Crustal Activities in and around Japan

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The aim of our research program (CAMP) is to develop a physics-based predictive simulation system for long-term crustal deformation and earthquake generation cycles in and around Japan. The total simulation system consists of a crust-mantle structure model, a quasi-static tectonic loading model, a dynamic rupture propagation model, and a data assimilation module. In 2003 we have carried out 1) upgrading the 3D standard plate interface model developed in 2002, 2) optimizing the code to compute viscoelastic slip responses for the structure model, 3) computing the long-term crustal deformation due to steady plate subduction in and around Japan, 4) inverting GPS data to estimate the slip-deficit distributions at plate interfaces, and 5) numerically simulating the entire process of earthquake generation at the 1968 Tokachi-oki seismogenic region, northeast Japan, on the Pacific-North American plate interface.

Keywords: plate subduction, earthquake generarion cycles, crustal deformation, geodetic data inversion, predictive simulation.

1. Introduction

Japanese Islands are in a very complex tectonic setting (Fig. 1). In the northeastern part the Pacific plate is descending beneath the North American plate, in the southwestern part the Philippine Sea plate is descending beneath the Eurasian plate, and in the central Kanto area these four plates are interacting with each other in a very complicated way. Interaction between the oceanic and the continental plates at subduction zones produces the periodic occurrence of large earthquakes, coseismic, postseismic and interseismic crustal movements, and long-term crustal deformation of the island arc-trench system. The aim of our program (CAMP) is to develop a physics-based predictive simulation system for long-term crustal deformation and earthquake generation cycles in and around Japan [1].

The basic equations governing the entire process of earthquake generation cycles consist of a viscoelastic slip-response function and a fault constitutive law. The driving force of this system is relative plate motion. The total simulation system consists of a crust-mantle structure model, a tectonic loading model, a dynamic rupture model, and a data assimilation module [2].

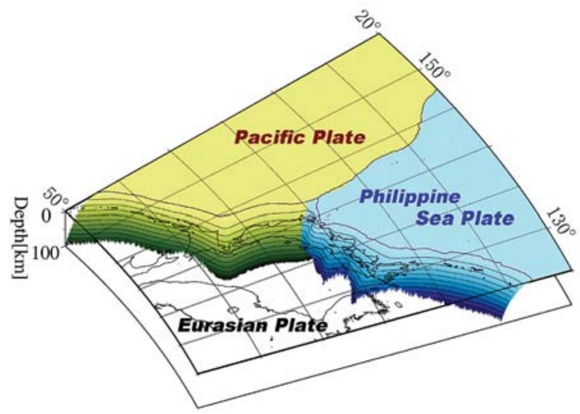

Fig. 1 3D geometry of plate interfaces in and around Japan (Hashimoto, Fukui & Matsu'ura, 2004).

2. Upgrading the 3D standard plate interface model

In 2002 we developed a realistic 3D model of plate interfaces in and around Japan by applying an inversion technique to the ISC hypocenter distribution data [3]. As shown in Fig. 1, the 3D configuration of plate interfaces is very complex in the Kanto area, where the Philippine Sea plate is descending beneath the North American plate to the north-

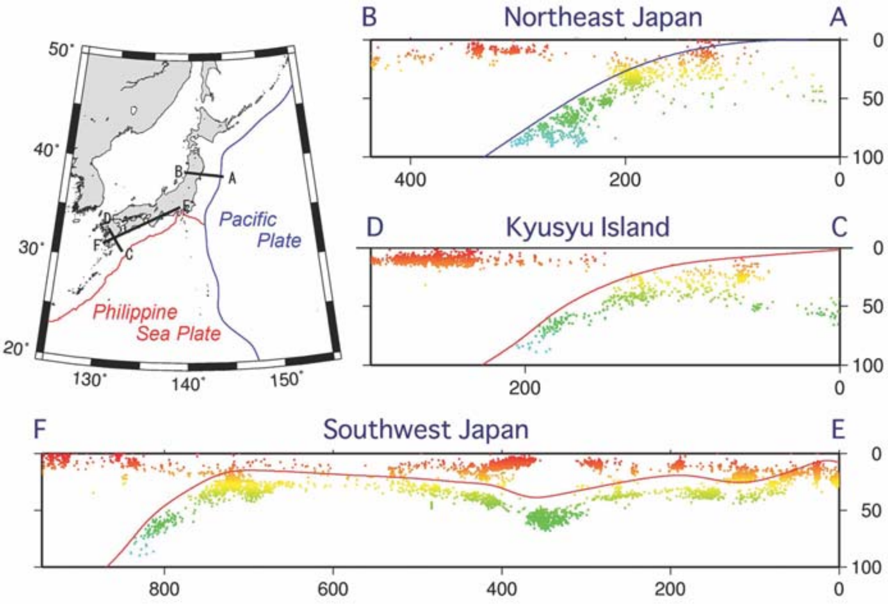

Fig. 2 Comparison of the modeled plate interfaces (solid curves) with the observed hypocenter distributions at three representative vertical cross sections (Hashimoto, Fukui & Matsu'ura, 2004).

west along the Sagami trough, and the Pacific plate is descending beneath both the plates to the west along the Japan trench. We examined the validity of the 3D standard model developed in 2002 through the comparison of it with the JMA unified hypocenter data, and slightly improved the interface geometry in the south Kanto area. In order to efficiently compute viscoelastic slip responses for this structure mode, which is the most time-consuming part in simulation, we have completely done vectorization and parallelization of the code of viscoelastic slip-response functions.

3. Long-term crustal deformation due to steady plate subduction

With the 3D structure model, given the steady slip rates at plate interfaces calculated from NUVEL1-A, we can compute long-term crustal deformation caused by steady subduction of the Pacific and the Philippine Sea plates [3]. The computed results in Fig. 3 show that the steady plate subduction brings about steep uplift at island arcs, sharp subsidence at ocean trenches, and gentle uplift at outer rises. The maximum uplift rate is 1.5 mm/yr both in northeast and southwest Japan. The maximum subsidence rate is 2.5 mm/yr at the Japan trench and 1.5 mm/yr at the Nankai trough.

In Fig. 4 we calculated the increasing rates of free-air gravity anomalies from the vertical displacement rates by integrating gravitational effects of mass excess or deficit at the surface, and compared it with observed free-air gravity anomalies [4]. Good agreement between them indicates that the dynamic origin of free-air gravity anomalies is in subduction of oceanic plates.

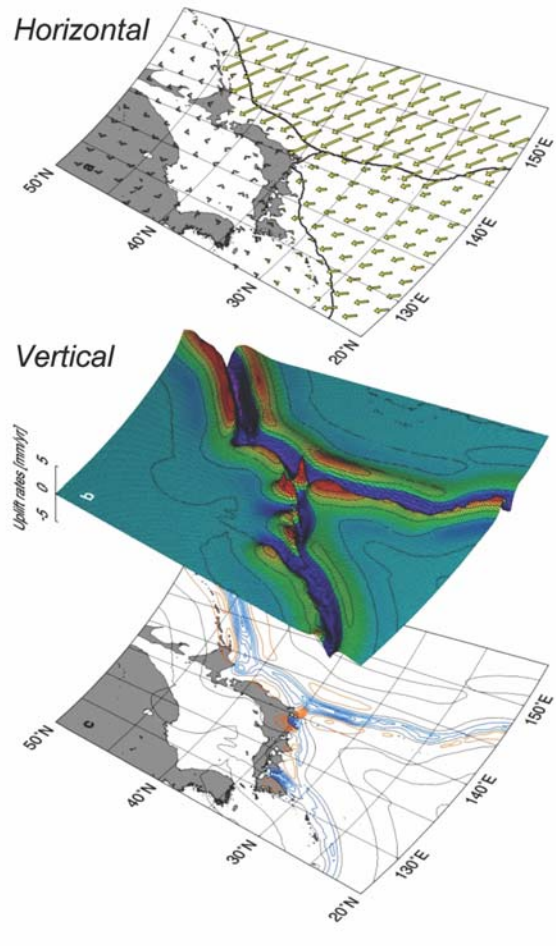

Fig. 3 Long-term crustal deformation due to steady plate subduction (Hashimoto, Fukui & Matsu'ura, 2004). Top: a vector map showing horizontal displacement rates. Middle and bottom: stereographic and contour-map representations of vertical displacement rates.

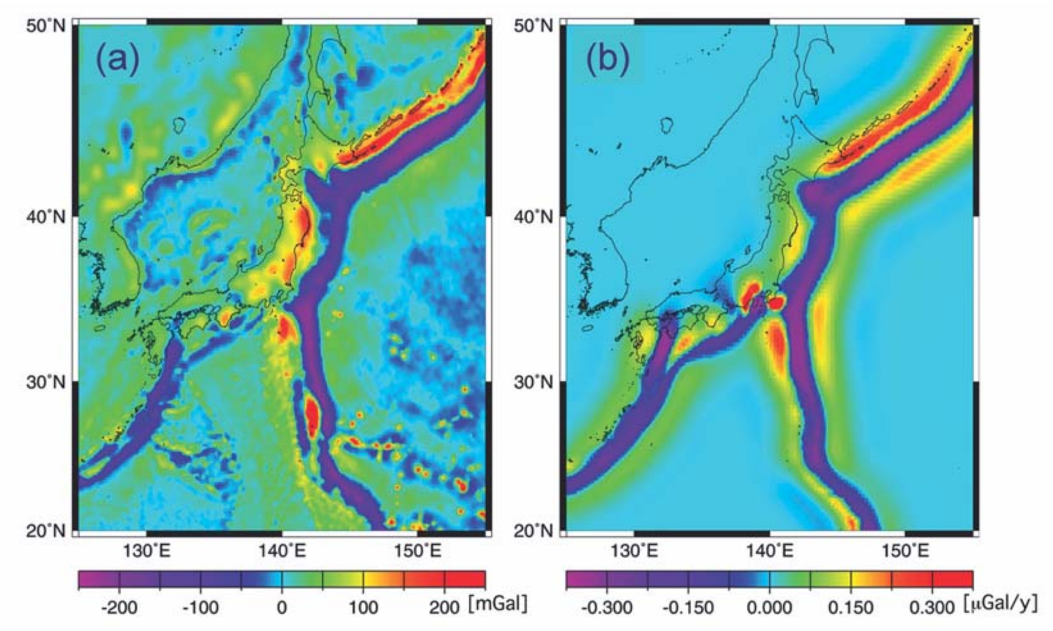

Fig. 4 Comparison of (b) the computed pattern of free-air gravity anomaly rates (Hashimoto & Matsu'ura, 2004) with (a) the pattern of observed free-air gravity anomalies (Sandwell & Smith, 1997).

4. The slip-deficit distributions at plate interfaces inverted from GPS data

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 [2]. Outputs of this simulation model are the crustal deformation and internal stress change associated with seismic and/or aseismic slip at 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 plate interfaces by using an inversion technique [5]. Figure 5 shows spatial distribution of slip excess and deficit at plate interfaces, estimated from the inversion analysis of GPS data [6]. The slip deficit causes stress accumulation in and around a locked portion on plate interfaces.

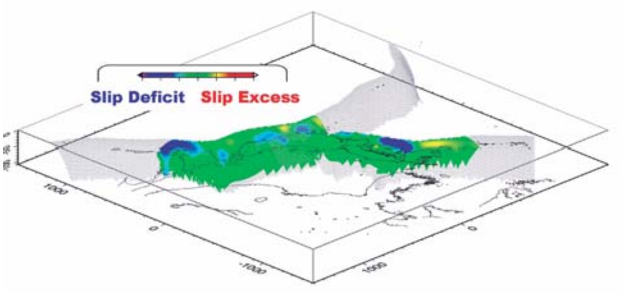

Fig. 5 Spatial distribution of slip excess and deficit at plate interfaces, estimated from the inversion analysis of GPS data (Sagiya, Hashimoto & Matsu'ura, 2003).

5. Predictive simulation of earthquake generation at the 1968 Tokachi-oki seismogenic region

Combining the quasi-static earthquake cycle model and the 3D dynamic rupture model developed in 2002 on the same structure model, we can construct a unified simulation model for the entire process of earthquake generation cycles [2]. 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 with this unified model. In Fig. 6, as an example of predictive simulation, we show the quasi-static stress accumulation process at the 1968 Tokachi-oki seismogenic region on the Pacific-North American plate interface, and the subsequent process of rupture initiation, propagation and stop there [7]. As a result of relative plate motion, shear stress accumulates in and around the seismogenic region and is suddenly released by earthquake rupture. In this simulation we forced dynamic rupture to start by giving artificial stress drop at t = 35 yr. 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, of course. In this case, seismic waves with high amplitudes are radiated from the source and propagated into the surrounding elastic medium.

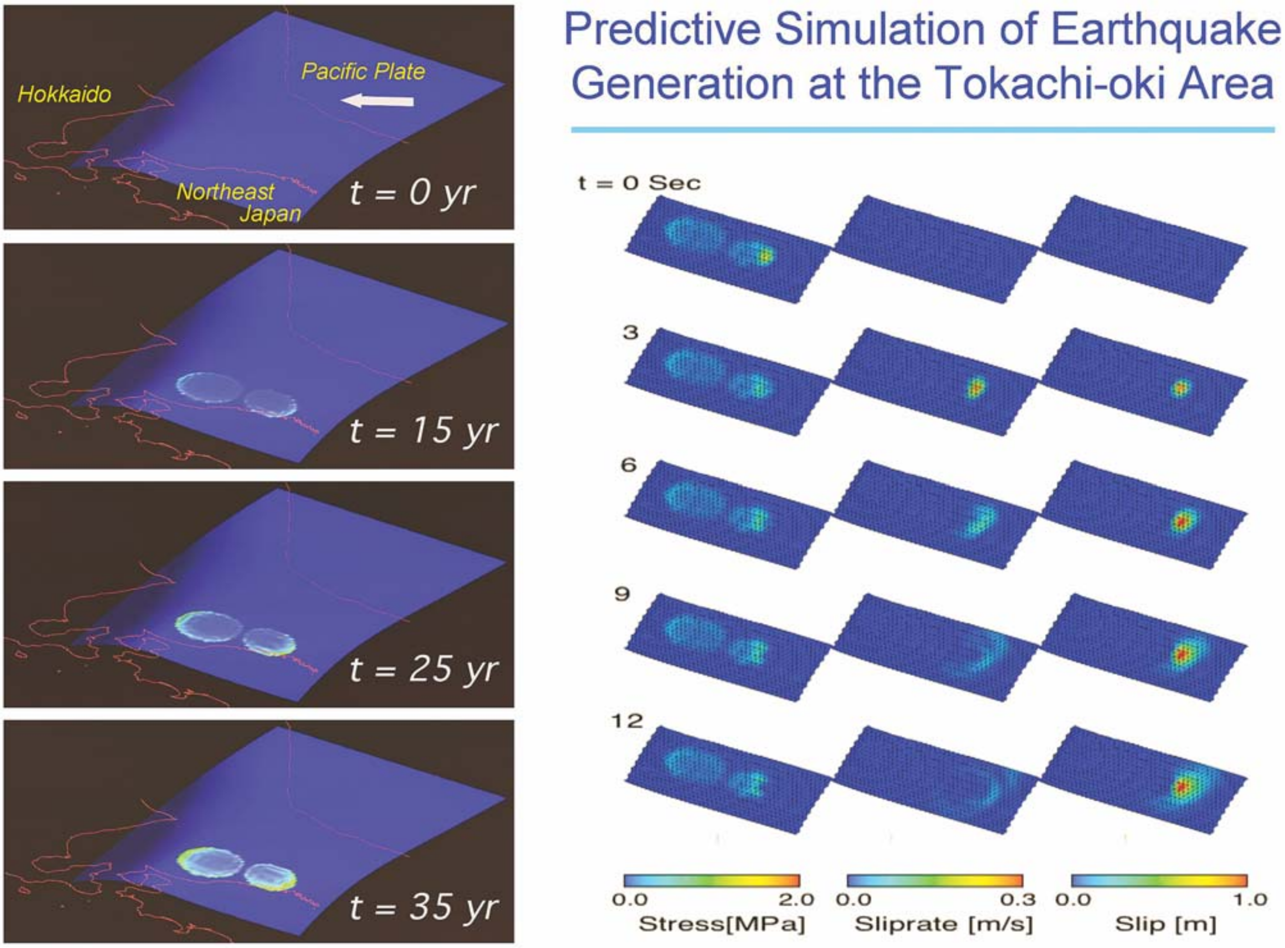

Fig. 6 Predictive simulation of earthquake generation cycles at the source region of the 1968 Tokachi-oki area, northeast Japan, on the Pacific-North American plate interface (Matsu'ura, Hashimoto & Fukuyama, 2003). Left: a series of snapshots showing quasi-static stress accumulation at and around the source region. Right: a series of snapshots showing 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 stae is not in a critical level.

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