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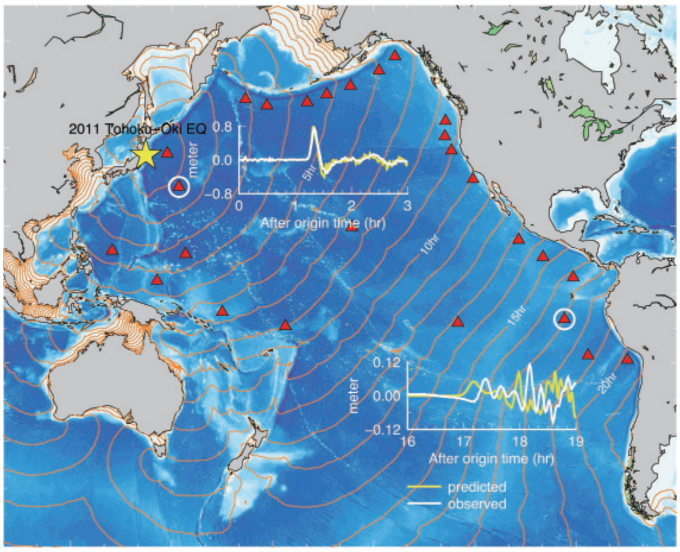
TRAVEL TIME DELAY OF DISTANT TSUNAMIS CAUSED BY ELASTIC GRAVITATIONAL COUPLING TO THE SOLID EARTH



2011 Tohoku earthquake tsunamis crossing the Pacific Ocean. Simulated (in yellow line) and observed (in white line) waveforms are compared. A yellow star indicates the earthquake and red triangles are the deep-ocean tsunami-meters.

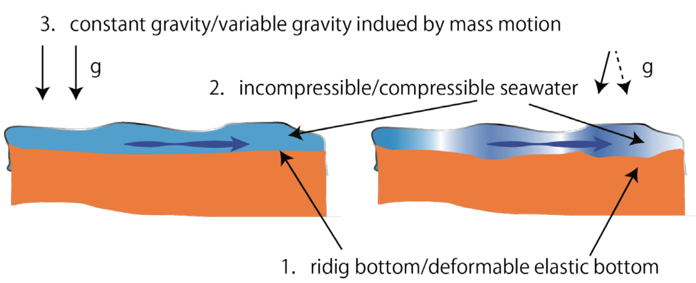
Large shallow submarine earthquakes often cause tsunami, which is a long wave in the ocean, and its propagation speed is determined by the ocean depth. The analyses of tsunami records at short distances from the earthquake successfully revealed quantitative source properties of mega-earthquakes.

After the 2004 Indian Ocean earthquake and tsunami, deep ocean tsunami-meters were deployed in the Pacific Ocean for tsunami early warning. Tsunami waves from the 2010 Chilean and 2011 Tohoku-Oki earthquakes were recorded at these tsunami-meters. Tsunami scientists and engineers quickly realized that tsunami simulation at trans-oceanic distances cannot reproduce the observed travel times.

Systematic delays of tsunami travel time up to 15 min. compared to the numerically simulated long waves from the two mega-earthquakes were observed at deep ocean tsunami-meters. Furthermore, Watada and co-authors found that enigmatic small negative phases preceding the main peak appeared commonly only at trans-oceanic locations.

Precise measurements of propagation speed of distant tsunamis revealed that the tsunami phase velocity becomes slower than the conventional long-wave tsunami speed by 1-2% depending on period; i.e., long-period tsunami phase velocity is dispersive. A new tsunami propagation theory with compressible seawater, elastic sea bottom, and gravity change associated with mass motion during tsunami propagation explains the measured dispersive tsunami phase velocity.

With a newly developed fast computation method of distant tsunami waveforms including these three effects for real bathymetry, the accuracy of tsunami waveform prediction crossing the Pacific Ocean has been greatly improved. We recently demonstrated that with only 4 deep ocean tsunami-meter records near the 2010 Chilean earthquake the tsunami waveforms and arrival times near the Japan coast can be accurately forecasted.



A cartoon showing tsunami propagation over the solid Earth. Three effects causes the delay and phase reversal of distant tsunamis.

MIGRATING SHALLOW LOW-FREQUENCY TREMOR IN HYUGA-NADA, NANKAI SUBDUCTION ZONE: SEISMOLOGICAL EVIDENCE FOR EPISODIC SLOW SLIP OF SHALLOW SUBDUCTION INTERFACE

During the last decade, discovery of various slow earthquakes including the seismic tremor on the downward extension of the seismogenic megathrust boundary at subduction zones have revealed the transitional behavior from shallow brittle failure to deeper creeping motion. Our joint research group, comprising the University of Tokyo, Kyushu University, Kagoshima University, and Nagasaki University, has carried out a temporal ocean bottom seismological observation using 12 ocean bottom seismometers installed on the seafloor of Hyuga-nada, for a period of 3 months in 2013, in order to monitor of offshore seismicity and understand the coupling state of the plate boundary.

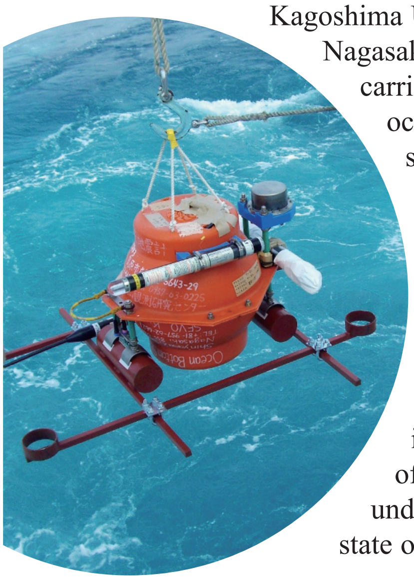


Fig. 3 Ocean bottom seismometer.

One of the most important result of our research was the finding of "migrating" shallow low-frequency tremor occurring at a shallow plate interface. It is the first observation of shallow tremor as a complete episode. Near site observation clarified common characteristics between shallow and deep tremor in migration modes and association with very low-frequency earthquakes (VLFEs), which provides the first seismological evidence for the occurrence of episodic slow slip event (SSE) in the shallow subduction interface.

These new findings provide important insight into slip behavior at a shallow subduction interface and will improve understanding and modeling of subduction megathrust earthquakes and tsunamis in the future. For details, please refer the paper published in Science on May 8th, 2015.

Since 2014, we have started broad-band long-term ocean bottom observation in the same area using short-period seismometer, broad-band seismometer, and pressure gauge to understand relationship among shallow tremor, VLFE, and episodic SSE (Research project for compound disaster mitigation on the great earthquakes and tsunamis around the Nankai trough region).

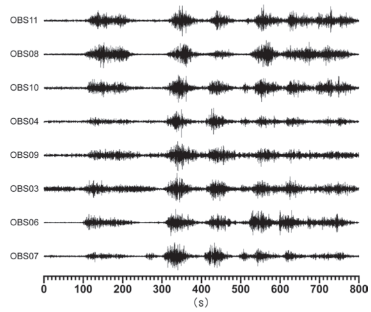


Fig. 2 Example waveform of shallow tremor observed by ocean bottom seismometers. Each trace was UD component and normalized by maximum amplitude. The OBSs location are shown in Fig 1.

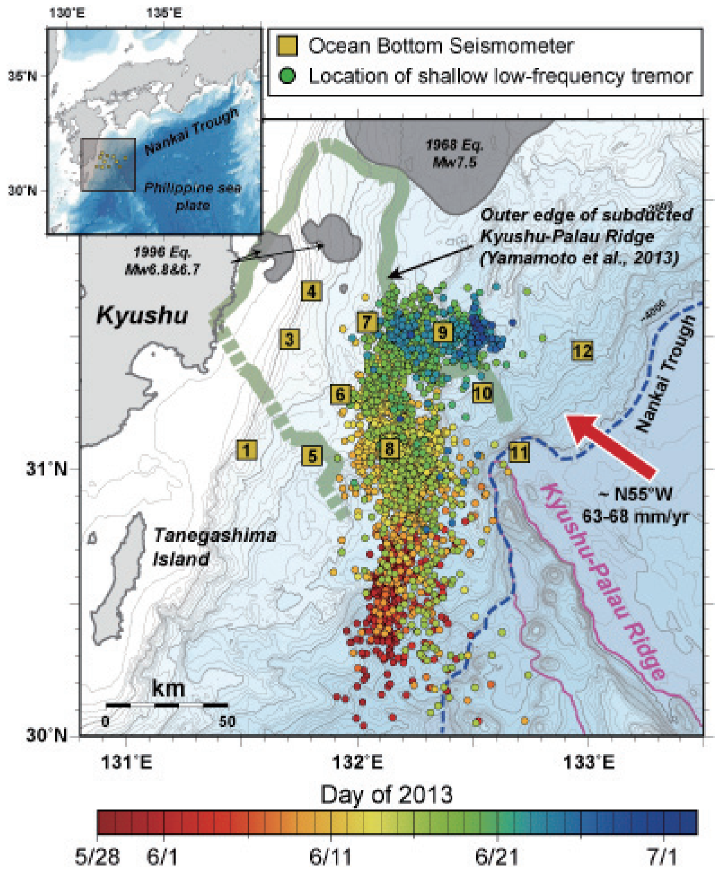


Fig.1 Distribution of shallow low-frequency tremors detected by ocean bottom seismometers.

“COMPREHENSIVE SIMULATION OF AN EARTHQUAKE ENHANCED BY HEROIC SUPERCOMPUTING”

An urban earthquake disaster consists of earthquake wave propagation, soil amplification, the seismic structural response, and evacuation/recovery. Evaluations based on physics-based comprehensive simulations of these processes should improve the reliability of urban earthquake disaster estimation, but this has not been accomplished due to the huge computing cost involved. Using heroic supercomputing on K computer (the best supercomputer in Japan), we conducted a comprehensive earthquake simulation far beyond the state-of-the-art. Application at such scale is a groundbreaking accomplishment and is expected to significantly improve the quality of earthquake disaster estimation and contribute to society. Our achievement was accepted as the 2014 & 2015 ACM Gordon Bell Prize finalist, which is one of the highest awards in high performance computing.

Reference: *Tsuyoshi Ichimura, Kohei Fujita, Pher Errol Balde Quinay, Lalith Maddegedara, Muneo Hori, Seizo Tanaka, Yoshihisa Shizawa, Hiroshi Kobayashi and Kazuo Minami, Implicit Nonlinear Wave Simulation with 1.08T DOF and 0.270T Unstructured Finite Elements to Enhance Comprehensive Earthquake Simulation, SC15: International Conference for High Performance Computing, Networking, Storage and Analysis, 2015. doi: 10.1145/2807591.2807674*

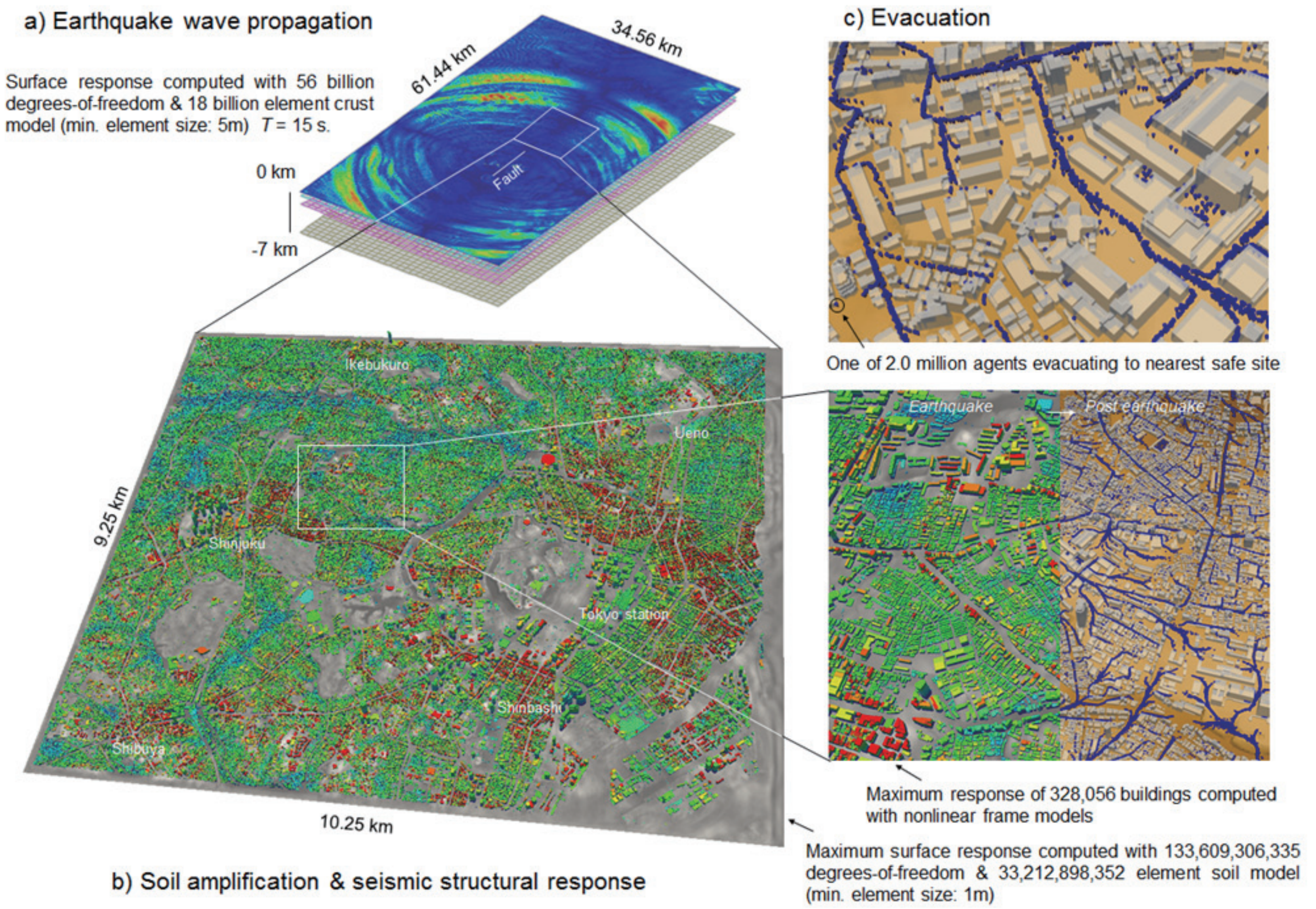


Fig1: Comprehensive simulation of an earthquake in Tokyo. a) A snapshot of the computed motion of the ground surface. b) Snapshots of the computed motion on the ground surface and structural seismic responses. c) A snapshot of individuals evacuating with complicated behaviors.

SUPERPLASTICITY OF THE EARTH'S MANTLE

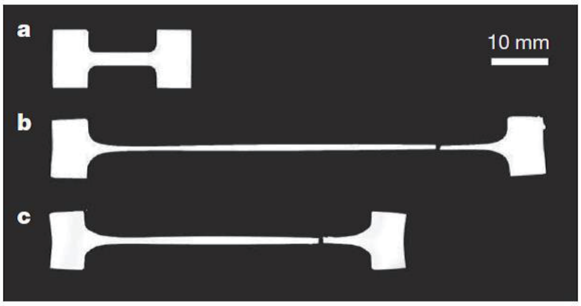


Fig. 1 Specimens before (a) and after tensile deformation experiments (b and c). (a) Starting sample of Fo+10vol% periclase. (b) Fo+10vol% periclase sample after 515% elongation. (c) Forsterite + enstatite+diopside sample after 315% elongation.

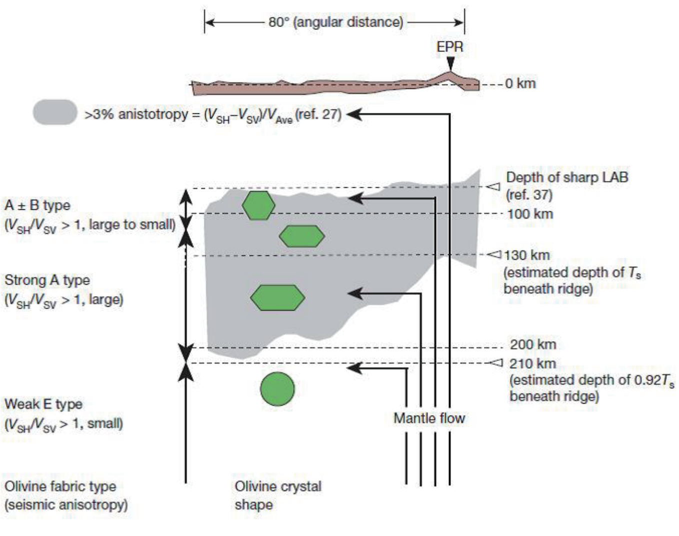


Fig. 2 Proposed depth distributions of olivine crystal shape and fabrics during diffusion-accommodated GBS creep of peridotite in the mantle asthenosphere. Seismic anisotropy profile beneath the Pacific basin is added. Circular, tabular and hexagonal grains represent olivine appearing at low, high and above solidus temperatures, respectively. Characteristics of seismic anisotropy are estimated from the olivine fabric types and intensity. LAB, lithosphere?asthenosphere boundary; [V_{Ave}], average shear-wave velocity;[V_{SH}], velocity of horizontally polarized shear wave; [V_{SV}], velocity of vertically polarized shear wave.

To understand rheological properties of the Earth's interior, we have been developing a technique to synthesize highly dense and fine-grained mineral aggregate, and used them for creep experiments at high temperature and room pressure conditions. Using this novel technique, deformation properties under very low stress, relationships among stress/strain rate/grain size/ fraction of secondary phase, and superplastic nature of the earth's materials were explored.

In material science, the term "super-plasticity" refers to large strain tensile deformation without failure. This character often appears at high temperature, fine-grained and low stress conditions which has been speculated to occur in the Earth's interior for decades. We succeeded in demonstrating more than 500% tensile strain of forsterite aggregates providing a direct evidence for mantle superplasticity (Fig. 1).

The crystallographic preferred orientation (CPO) of olivine, produced during dislocation creep, is considered to be the primary cause of elastic anisotropy in Earth's upper mantle and is often used to determine the direction of mantle flow. However, a remaining fundamental question is whether the alignment of olivine crystals is uniquely produced by dislocation creep. We showed the development of CPO in iron-free olivine (i.e. forsterite) during diffusion creep; the intensity and pattern of CPO depend on temperature and the presence of melt, which control the appearance of crystallographic planes on grain boundaries. Grain boundary sliding on these crystallography-controlled boundaries accommodated by diffusion contributes to grain rotation, resulting in a CPO. We show that strong radial anisotropy is anticipated at temperatures corresponding to depth where melting initiates to depths where strongly anisotropic and low seismic velocities are detected. Conversely, weak anisotropy is anticipated at temperatures corresponding to depths where almost isotropic mantle is found (Fig. 2). We propose diffusion creep to be the primary means of mantle flow.